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The Consequences of Uncertainty: Climate Sensitivity and Economic Sensitivity to the Climate

John Hassler,[1,2,3,4] Per Krusell,[1,2,3,5] and Conny Olovsson[6]

[1]Institute for International Economic Studies, S-106 91 Stockholm, Sweden; email: john@hassler.se, per.krusell@iies.su.se

[2]Department of Economics, University of Gothenburg, S-405 30 Gothenburg, Sweden

[3]Center for Economic and Policy Research, London, United Kingdom

[4]Society for Economic Measurement, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA

[5]National Bureau of Economic Research, Cambridge, MA 02138, USA

[6]Sveriges Riksbank, S-103 37 Stockholm, Sweden; email: conny.olovsson@riksbank.se

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Abstract

We construct an integrated assessment model with multiple energy sources—two fossil fuels and green energy—and use it to evaluate ranges of plausible estimates for the climate sensitivity, as well as for the sensitivity of the economy to climate change. Rather than focusing explicitly on uncertainty, we look at extreme scenarios defined by the upper and lower limits given in available studies in the literature. We compare optimal policy with laissez faire, and we point out the possible policy errors that could arise. By far the largest policy error arises when the climate policy is overly passive; overly zealous climate policy (i.e., a high carbon tax applied when climate change and its negative impacts on the economy are very limited) does not hurt the economy much as there is considerable substitutability between fossil and nonfossil energy sources.

1. INTRODUCTION

The economy–climate nexus involves three large blocks: how the economy works, how the climate is determined, and how emitted carbon circulates between different reservoirs (the carbon cycle). These blocks interact. The key links are that the economy feeds carbon dioxide into the atmosphere, where it enters the carbon circulation system; atmospheric carbon then constitutes a key input into the determination of the climate, which in turn affects how our economies work. Thus, human welfare is affected. The description of the joint system is often referred to as integrated assessment modeling, and in this review, we employ an integrated assessment model to address one of the key issues in this area: uncertainty. In particular, there is imperfect knowledge about the climate system, the carbon cycle, and the economic damages caused by climate change, as well as about how these systems interact. We focus on two of these uncertainties here: the climate system and the economic damages.

A key feature of our analysis is that, unlike the previous literature on this issue, we do not formally model uncertainty. Rather, we look at the range of estimates and focus on the extremes. The extremes are naturally defined as upper and lower bounds of intervals given in the literature. (True tails events, occurring with extremely low probability, are not considered in this review.) First, we look at how sensitive global temperature is to carbon dioxide in the atmosphere and select two extreme values: an upper bound and a lower bound. These are selected from the Intergovernmental Panel on Climate Change's (IPCC's) 2013 report (IPCC 2013), which states a range of values for climate sensitivity—the change in the global mean temperature after a doubling of the atmospheric carbon dioxide concentration—within which the outcome will likely land, i.e., will land with a probability that the IPCC considers to be higher than approximately two out of three. For economic damages, we rely on the recent meta-study by Nordhaus & Moffat (2017) and select upper and lower bounds in a similar manner to these authors. We then combine these into four distinct possibilities, thus combining the bounds into four logically possible outcomes. We find this approach to be more easily interpretable, and arguably even more relevant, than an approach that formally examines uncertainty since we perceive the main issue to be a concern with extreme outcomes (both good and bad) rather than with random fluctuations within the range defined by the extreme cases. Thus, we do not think that it is the imperfect consumption smoothing that is worrisome in the climate–economy area, but rather fears of a highly damaging outcome, either because insufficiently aggressive policy is undertaken when the damages of emission turn out to be large or because of policy that is too aggressive when carbon emission by itself (through climate change) does not harm economic welfare much (for examples of studies of risk and uncertainty, see, e.g., Cai et al. 2013, Gollier 2013, Jensen & Traeger 2016, Lemoine 2010, Weitzman 2011).

Our integrated assessment model is based on that of Golosov et al. (2014). It is also related to recent work in which Hassler et al. (2017a; for more detail on energy supply, see Hassler et al. 2017b) endogenize technology. Our framework is highly tractable and yet quantitatively specified, i.e., it is specified based on a specific (optimal neoclassical growth) structure that can be straightforwardly tied to empirical estimates of utility- and production-function-based parameters. The model is augmented to include some richness on the side of energy supply and to include a carbon cycle and a climate model. One of the key features of this framework is that it captures the sensitivity of climate to atmospheric carbon dioxide concentration jointly with the economic damages inflicted by global warming in one parameter: γ. This parameter has a concrete interpretation: the percentage loss in the flow of world GDP from a one-unit increase in the carbon dioxide concentration in the atmosphere (thus baking together how carbon creates warming, which in turns causes economic damages). In the calculations, one unit is expressed as 1,000 gigatonnes of carbon (GtC) in the global atmosphere. Thus, we look at four values of γ defined by the four combinations of high and low climate sensitivity and high and low economic sensitivity. Conveniently for policy analysis, the optimal carbon tax is proportional to γ.

To begin with, then, one interesting issue is whether the uncertainty, as expressed by the ranges in the two studies we refer to [by the IPCC (2013) and by Nordhaus & Moffat (2017)], generates a larger span of values for γ due to the uncertainty about climate sensitivity than that due to uncertainty about economic sensitivity, or the other way around. We find the following: Low–low (climate–economic) sensitivities yield a γ of 0.27, low–high sensitivities yield a value of 1.79, high–low sensitivities yield a value of 1.44, and high–high sensitivities yield a value of 10.39. Thus, the effects are not additive—they interact somewhat nonlinearly—but, roughly speaking, the difference between high and low climate sensitivities amounts to a factor of about 5.5 in the γ, whereas the uncertainty due to economic sensitivities amounts approximately to a factor of 7 in γ. Thus, these uncertainties are of the same order of magnitude. Clearly, it is hard to argue that the bounds selected from the two studies represent exactly the same amount of uncertainty, but we note at least that there is significant economically relevant uncertainty both about the climate and about the economy. Our prior was that the former would be swamped by the latter, which turned out not to be correct.

When we compute optimal taxes, we obtain values that are in line with numbers in the literature, and we then use these to simulate eight scenarios: For each of the four γ cases, we look both at the laissez-faire market outcome and at optimal policy. We see, in brief, that the negative welfare effects of carbon emission are sizable unless both the climate and economic sensitivities are low. We also see, however, that the optimal tax is quite potent in containing climate change and its economic effects. In terms of energy supply, we see that coal use will grow significantly in all of the scenarios except the worst outcome—with both sensitivities being high and under the corresponding optimal tax. Finally, we look at the kinds of errors that arise if one adopts a climate policy in a way that is poorly matched to the actual sensitivities. In this case, we see that the negative consequences of erroneously adopting a high tax—computed optimally based on the assumption that both the climate and economic sensitivities are high) are not very large, chiefly because energy substitution is quite effective: Using green energy (which would be the equilibrium implication of a high tax on carbon) when coal really should be used more is not very costly for the economy as the two are rather close substitutes. However, incorrectly adopting a low tax, which is appropriate if both sensitivities are low, when they are actually high is very costly.

In Section 2, we describe the economy–climate model. Section 3 then shows how we calibrate the model, and Section 4 covers the results. We offer some concluding remarks in Section 5.

2. MODEL

In this section, we describe our benchmark model, block by block, and then discuss the tax assumptions implemented in the market economy.

2.1. Economy

Overall, our framework is an integrated model of the economy and the climate: These two systems have a feedback between them. As such, it is a close relative of Nordhaus & Boyer's (2000) DICE and RICE models. However, and for focus, we consider a world economy that is highly stylized in a number of ways and, in that sense, is much simpler than some of the existing leading models. First, the world has two regions, defined by whether they are oil consuming or oil producing. Second, there are three types of energy sources: oil, which is produced at zero marginal cost; coal, which is produced at a constant marginal cost measured in terms of the final good; and green, which is also produced at a constant marginal cost. The amount of oil is finite, and the amounts of coal and green are infinite (for coal, this is a simplification but not a severe one, since there is a very large amount of coal and, thus, a very small associated rent). Third, the only trade between the regions is intratemporal: oil for consumption (there is a homogeneous consumption good). We take technology trends as given and only consider policy in the form of a carbon tax, which, if used properly, would suffice to render the world equilibrium Pareto optimal. The implications of endogenous technical change in a similar setting are explicitly analyzed by Hassler et al. (2017b), who, in turn, build on the simpler endogenous technology of Hassler et al. (2017a). We use a simple utility and production-function specification to obtain closed-form solutions as far as possible.

Both regions are inhabited by representative consumers; these have preferences given by

$$E_0 \sum_{t=0}^{\infty} \beta^t \log(C_t). \qquad 1.$$

Below, we use C_t to denote consumption in the oil-consuming region and $C_{o,t}$ to denote consumption in the oil-producing region.

The oil-consuming region has an aggregate production function for the final good Y_t that is given by

$$Y_t = A_t L_t^{1-\alpha-\nu} K_t^{\alpha} E_t^{\nu},$$

where A_t is total-factor productivity (TFP), L_t is labor used in final-good production, K_t is the capital stock, and E_t is energy services.

The assumption that the elasticity of substitution between energy and the other inputs (capital and labor) is unity is hard to defend when a time period is short—in that case, a much lower elasticity is called for. However, for longer time periods—and, indeed, our focus here is on the long run—the Cobb-Douglas assumption does not appear unreasonable. In fact, as demonstrated for this particular application by Hassler et al. (2017a), one can express the higher long-run substitutability between inputs in terms of endogenous technology choice. Suppose, namely, that the production function is of a constant elasticity of substitution (CES) form between energy services and a Cobb-Douglas capital–labor composite and that technology choice involves the ability to choose input saving in the form of two technology parameters multiplying these two inputs, subject to a constraint. Under these circumstances, if that constraint is specified as a log-linear relationship, the outcome is a reduced-form production function in the basic inputs that are Cobb-Douglas, regardless of the degree of short-run substitutability between these inputs.[1]

Energy services, in turn, are provided by firms that act competitively with a constant-returns-to-scale production function in n distinct energy inputs:

$$E_t = \mathcal{E}(e_{1,t}, \ldots, e_{n,t}) = \left[\sum_{k=1}^{n} \lambda_k \left(e_{k,t} \right)^{\rho} \right]^{\frac{1}{\rho}}. \qquad 2.$$

In this case, $e_{1,t}$ is the import of oil in period t. The other energy sources $\{e_{2,t}, \ldots, e_{n,t}\}$ are energy sources assumed to be produced and supplied entirely domestically within the oil-consuming region. The associated production technology is linear in the final good; in particular, to produce $e_{k,t}$ units of energy source $k \in \{2, \ldots, n\}$, $p_{k,t}$ units of the final good are required. Thus, we allow

[1]This statement holds so long as the CES function has an elasticity parameter less than or equal to one, i.e., $\rho \leq 0$ (this is the empirically reasonable case for this application). For $\rho > 0$, the result is complete specialization: The production function becomes linear in one of the inputs.

for these marginal costs to change over time. Final goods not engaged in energy production are consumed or invested in a standard neoclassical way. In sum, the resource constraint for the final good reads

$$C_t + K_{t+1} = A_t L_t K_t^{\alpha} E_t^{\nu} - p_{1,t} e_{1,t} - \sum_{k=2}^{n} p_{k,t} e_{k,t} + (1-\delta) K_t.$$

We take the world market price of oil $p_{1,t}$ to be expressed in units of the global final good.

The oil-producing region, finally, produces oil without any resource cost. Its constraints are

$$\begin{aligned} R_{t+1} &= R_t - e_{1,t}, \\ R_t &\geq 0 \forall t, \\ C_{o,t} &= p_{1,t} (R_t - R_{t+1}), \end{aligned} \qquad 3.$$

where R_t is the remaining stock of oil in the ground at the beginning of period t.

2.2. The Carbon Cycle

The use of energy leads to carbon emission in the form of CO_2. Specifically, emissions in period t are given by

$$M_t = \sum_{k=1}^{n} g_k e_{k,t},$$

where g_k measures how dirty energy source k is. We measure fossil energy sources in terms of their carbon content, implying that, for each of them, $g_{k,t} = 1$. Conversely, purely green energy sources have $g_{k,t} = 0$. We could also, but do not currently, have intermediate cases.

We use the structure of Golosov et al. (2014), so we assume that the law of motion for the atmospheric stock of carbon S_t in excess of its preindustrial level is given by

$$S_t = \sum_{s=0}^{t} (1 - d_s) M_{t-s},$$

where

$$1 - d_s = \varphi_L + (1 - \varphi_L) \varphi_0 (1 - \varphi)^s$$

captures how much carbon remains in the atmosphere s periods after it was emitted: The share of emissions that remains forever in the atmosphere is φ_L, the share that leaves the atmosphere within a period is $1 - \varphi_0$, and the remainder $(1 - \varphi_L) \varphi_0$ depreciates geometrically at rate φ.

2.3. The Climate and the Economic Damages Therefrom

The climate is affected by the atmospheric carbon concentration through the well-known greenhouse effect. Changes in the climate, in turn, have effects on the productivity of the economy. The effect of atmospheric carbon concentration on TFP can thus be thought of in two steps. In step one, there is a logarithmic effect of CO_2 on the Earth's energy budget and, thus, on global warming. This effect has been known since the work of Arrhenius (1896). It can be expressed using T_t, which denotes the global mean temperature (in excess of its preindustrial level), and the stock of carbon in the atmosphere can be expressed as

$$T_t = \frac{\lambda}{\ln 2} \ln \left(\frac{S_t + \bar{S}}{\bar{S}} \right). \qquad 4.$$

In this equation, λ represents the climate sensitivity, and $\bar{S}$ represents the preindustrial atmospheric carbon stock. We abstract from dynamics in the relationship between S_t and T_t and assume that the long-run equilibrium temperature associated with a level of carbon concentration is achieved immediately. In this sense, we exaggerate the direct effect of emissions on temperature (it would be straightforward to include dynamics, and we leave them out mostly for convenience).

Step two is the effect of changes in the global mean temperature on the economy. This mechanism appears in a variety of forms and is highly heterogeneous across geographic space. In contrast to step one, step two is typically modeled as convex—marginal global damages increase in temperature. Golosov et al. (2014) demonstrate that, at least relative to the literature, the combination of a concave step one and convex step two yields an overall effect of CO_2 concentration on productivity that is quite well captured by a simple log-linear specification. Specifically, they use a specification for TFP that reads

$$A_t = e^{z_t - \gamma_t S_{t-1}}, \tag{5.}$$

where z_t is exogenous technical change and γ_t captures the possibly time-varying sensitivity to atmospheric CO_2 concentration.

2.4. Markets and Equilibrium

All agents in our model are price takers. Consider the oil-producing region first. We thus assume that there are many oil producers operating under perfect competition, with the representative oil producer choosing how much oil to store for next period, R_{t+1}, taking the world market price of oil as given. Using the last part of Equation 3 to substitute out $C_{o,t}$ in Equation 1 and taking the first-order condition with respect to R_{t+1} then yields

$$\frac{1}{R_t - R_{t+1}} = E_t \frac{\beta}{R_{t+1} - R_{t+2}}.$$

This second-order difference equation, which really represents an Euler equation for consumption of the oil producer, is easily solved: It delivers $R_{t+1} = \beta R_t$, implying $C_{o,t} = p_{1,t}(1-\beta) R_t$. Note, in particular, that even if $p_{1,t}$ is stochastic, it has no effect on oil supply. The reason for this is simply that the income and substitution effects exactly cancel with logarithmic preferences. Conversely, note that our setup allows us to side-step the Hotelling price formula, by which the price of oil—in a case in which its marginal production cost is zero and there is no monopoly power—would have to rise at the real rate of interest. The reason for this is that oil producers cannot invest their proceeds from an oil sale (say, in case of an oil price hike) at a global rate of interest, since they do not have access, by assumption, to the global capital market. This assumption is, of course, unrealistic in its extreme form, but the notion that there are at least some restrictions on these kinds of trade should not be controversial. In any case, it has been very difficult to reconcile the Hotelling price formula with emperical observations (see, e.g., Hart & Spiro 2011).

We may now write the behavior of energy service providers as the solution to the cost-minimization problem

$$\min_{e_{k,t}} \sum_{k=1}^{n} p_{k,t} e_{k,t} - \Lambda_t \left\{ \left[\sum_{k=1}^{n} \lambda_k \left(e_{k,t}\right)^{\rho} \right]^{\frac{1}{\rho}} - E_t \right\}. \tag{6.}$$

In this equation, we note that, by construction, the Lagrange multiplier is given by $\Lambda_t = P_t$, the price index of energy services.

The first-order condition for $e_{k,t}$ yields, for $k \in \{2, n\}$,

$$e_{k,t} = E_t \left(\frac{P_t \lambda_k}{p_{k,t}} \right)^{\frac{1}{1-\rho}}, \tag{7.}$$

and similarly, oil consumption satisfies

$$e_{1,t} = E_t \left(\frac{P_t, \lambda_1}{p_{1,t}} \right)^{\frac{1}{1-\rho}}. \tag{8.}$$

Using this finding in the expenditure function, we arrive at

$$P_t = \left(\sum_{k=1}^{n} p_{k,t}^{\frac{\rho}{\rho-1}} \lambda_k^{\frac{1}{1-\rho}} \right)^{\frac{\rho-1}{\rho}}. \tag{9.}$$

Producers of the final good maximize profits while taking the oil price as given, so that

$$P_t = \nu \frac{A_t L_t^{1-\alpha-\nu} K_t^{\alpha} E_t^{\nu}}{E_t}.$$

This can be solved for energy service demand:

$$E_t = \left(\nu \frac{A_t L_t^{1-\alpha-\nu} K_t^{\alpha}}{P_t} \right)^{\frac{1}{1-\nu}}.$$

The output net of energy expenses reads $(1-\nu) Y_t \equiv \hat{Y}_t$. Note, however, that the shares of spending on the different energy sources are not constant unless $\rho = 0$, i.e., unless the overall production function is Cobb-Douglas in all inputs.

Households in the oil-consuming economy supply labor inelastically; we normalize its value to unity. The households thus maximize Equation 1 subject to the budget constraint

$$C_t + K_{t+1} = w_t L_t + r_t K_t + (1-\delta) K_t.$$

In this equation, $w_t = (1-\alpha-\nu) \frac{Y_t}{L_t}$ and $r_t = \alpha \frac{Y_t}{K_t}$, so that $w_t L_t + r_t K_t = \hat{Y}_t$.

We take one time period to be long enough that we can make the assumption that $\delta = 1$. Define the savings rate out of net output to be $s_t = \frac{\hat{Y}_t - C_t}{\hat{Y}_t}$. We can then write the Euler equation for the households as

$$\begin{aligned} \frac{C_{t+1}}{C_t} &= \beta \frac{\partial Y_{t+1}}{\partial K_{t+1}}, \\ \frac{(1-s_{t+1})(1-\nu) Y_{t+1}}{(1-s_t)(1-\nu) Y_t} &= \beta \frac{\alpha Y_{t+1}}{s_t (1-\nu) Y_t}. \end{aligned}$$

By inspection, we see that the savings rate must be constant over time at $s = \frac{\alpha\beta}{1-\nu}$.

Proposition 1. In each period, the allocation is determined by the state variables K_t, R_t and S_{t-1} such that (*a*) the capital savings rate is constant at $\frac{\alpha\beta}{1-\nu}$, (*b*) oil supply is $(1-\beta)R_t$, (*c*) energy price is $P_t = \left(\sum_{k=1}^{n} p_{k,t}^{\frac{\rho}{\rho-1}} \lambda_k^{\frac{1}{1-\rho}} \right)^{\frac{\rho-1}{\rho}}$, (*d*) energy service demand is $E_t = \left[\nu \frac{e^{(z_t - \gamma_t S_{t-1})} L_t^{1-\alpha-\nu} K_t^{\alpha}}{P_t} \right]^{\frac{1}{1-\nu}}$, (*e*) domestic fuel demand is $e_{k,t} = E_t \left(\frac{P_t \lambda_k}{p_{k,t}} \right)^{\frac{1}{1-\rho}}$, and (*f*) oil demand is $e_{1,t} = E_t \left(\frac{P_t \lambda_1}{p_{1,t}} \right)^{\frac{1}{1-\rho}}$. The price of oil is determined from equilibrium at the world oil market $e_{1,t} = (1-\beta) R_t$. The laws of motion for the state variables are $K_t = \alpha\beta Y_t$, $R_{t+1} = \beta R_t$, and $S_t = \sum_{v=0}^{t} (1 - d_{t-v}) M_t$.

Two things are noteworthy in this case. First, the allocation is determined sequentially without any forward-looking terms; this is a result of the combination of functional forms that allow income and substitutions effects to cancel. Second, conditional on a world market price of oil, all equilibrium conditions have closed-form solutions. Finding the equilibrium in any period t is therefore only a matter of finding the equilibrium oil price, where supply is predetermined to be $(1-\beta)\,R_t$ (as a result of optimal oil extraction).

2.5. Taxation

A key goal of this analysis is to analyze the consequences of taxing fossil fuels and, in particular, to assess the effectiveness of less than fully optimal taxation. With this aim, we allow the oil-consuming region to tax the users of fossil energy inputs. A carbon tax rate τ_t is thus imposed, implying that the total cost for the energy service provider of using energy type k becomes $(1+\tau_t g_k)\,p_{k,t}$.

The immediate result of adding taxes is that the price of energy and the mix of fuels change. These changes are straightforward to calculate. The prices $p_{1,t}$ and $p_{k,t}$ are simply replaced by tax-inclusive prices in Equations 7, 8, and 9. The aggregate use of energy services is still given by

$$E_t = \left(\nu \frac{A_t L_t^{1-\alpha-\nu} K_t^{\alpha}}{P_t}\right)^{\frac{1}{1-\nu}},$$

but now the tax-inclusive energy price is used.

The only complication resulting from taxes is that how the government revenues are handled matters for outcomes. Due to the implied income effects, if the revenues are redistributed lump sum to households, the savings rate will no longer be exactly $\alpha\beta/(1-\nu)$. However, our numerical analysis suggests that the quantitative effect of this effect is negligible, essentially because the income share of energy is small (ν is on the order of a few percent): Energy taxes simply cannot generate much revenue, as measured as share of GDP. An alternative is to assume that the revenues from taxing fossil fuel are wasted or spent on goods the consumption values of which do not interfere with how consumption is determined. However, if tax revenues are wasted, then the calculation of optimal taxes will be biased. To maintain tractability, we opt for the former assumption along with savings rules that remain at $\alpha\beta/(1-\nu)$, which imply that consumers do not smooth consumption fully optimally over time (conditional on their revenues). This is unlikely to lead to a sizable bias compared to the bias that would arise if the tax revenues were wasted. Given this approach, all the other features of Proposition 1 remain intact.

3. CALIBRATION

We describe, first, how we calibrate the benchmark model and, then, how the key uncertainty is captured.

3.1. Basic Model Parameters

We use a discount factor of 0.985^{10} with the understanding that a period is a decade. In the final-good production function, we set $\alpha = 0.3$ and the fuel income share ν to 0.055. We assume that labor input is constant and normalize it to one.

The production of energy services is calibrated as follows. For the elasticity of substitution between the three sources of energy, we use a meta-study (Stern 2012) of 47 studies of interfuel substitution. The unweighted mean of the oil–coal, oil–electricity, and coal–electricity elasticities is 0.95, i.e., slightly below unity. This elasticity implies $\rho = -0.058$, which we use as the main case. Note, in this context, that the meta-study is based on substitution elasticities for different time horizons. At the same time, Hassler et al.'s (2017a) arguments, discussed above, suggest that a nearly Cobb-Douglas elasticity is likely a reasonable outcome from endogenous input-saving technology choice.

To calibrate the λ's, we need prices and quantities of the three fuel types. We follow Golosov et al. (2014), who use a coal price of \$74/ton and a carbon content of 71.6%. The (pre–financial crises) oil price was \$70/barrel, corresponding to $\$70 \cdot 7.33$ per ton and a carbon content of 84.6%. This implies a relative price between oil and coal in units of carbon of 5.87 (oil being worth more per carbon unit).

We then use the same source for the global ratio of oil to coal use in carbon units, namely 0.916. Using Equations 7 and 8, we find that $\frac{\lambda_1}{\lambda_2} = 5.348$. For green energy, we use data for the sum of nuclear, hydro, wind, waste, and other renewables, also from Golosov et al. (2014), and retain their assumption of a unitary relative price between oil and renewables. This delivers $\frac{\lambda_1}{\lambda_3} = 1.527$. Along with the normalization $1 = \lambda_1 + \lambda_2 + \lambda_3$, this implies that $\lambda_1 = 0.543$, $\lambda_2 = 0.102$, and $\lambda_3 = 0.356$. We also need a value for the initial stock of conventional oil. Again following Golosov et al. (2014), it is set to 300 GtC.

For the carbon cycle parameters, we also follow Golosov et al. (2014) and set $\varphi_L = 0.2$, $\varphi_0 = 0.393$, and $\varphi = 0.0228$. We take the year 2010's stock of excess atmospheric carbon (221 GtC) as an initial condition. Of that, 104 GtC is not depreciating but stays in the atmosphere indefinitely. The preindustrial stock of carbon ($\bar{S}$ in Equation 4) is set to 581 GtC.

We assume that initial global GDP is \$75 trillion per year and set initial productivity and capital so that the economy is on a balanced growth path. Productivity in final-goods production, e^{z_t}, is assumed to grow at 1.5% per year, and we assume that the cost of producing coal and green fuel is constant in terms of the final good. This rate of productivity increase implies an annual GDP growth rate of approximately 2%.

3.2. Climate and Damage Uncertainty

As discussed in the introduction, the purpose of this review is to explore the range of economic outcomes at the endpoints of a range of plausible estimates for (*a*) the sensitivity of the climate to the carbon concentration and (*b*) the sensitivity of the economy to the climate. For the former, we use the range given in a 2013 IPCC report, which states that the equilibrium climate sensitivity (λ) is "likely in the range 1.5 to 4.5°C" (IPCC 2013, p. 81).[2] Since we are interested in the end points of the ranges, denoted λ_H and λ_L, we set $\lambda_H = 4.5$ and $\lambda_L = 1.5$.

To provide a similar range for the sensitivity of the economy to global warming, we build on the recent paper by Nordhaus & Moffat (2017). The authors provide a rather comprehensive survey of studies of global damages from climate change. They also argue that the different studies should not be given equal weight in trying to distill a representative estimate of the aggregate effects of global warning. One particularly convincing argument for the unequal weights is that some studies are derivatives of earlier studies. Their approach is somewhat judgmental, but they operationalize it by assigning a weight between zero and one, representing reliability and/or originality, to each of the studies. In all, they find 36 usable estimates of damages, expressed as percentages of global

[2] The report also makes explicit that "likely" should be taken to mean a probability of 66–100%.

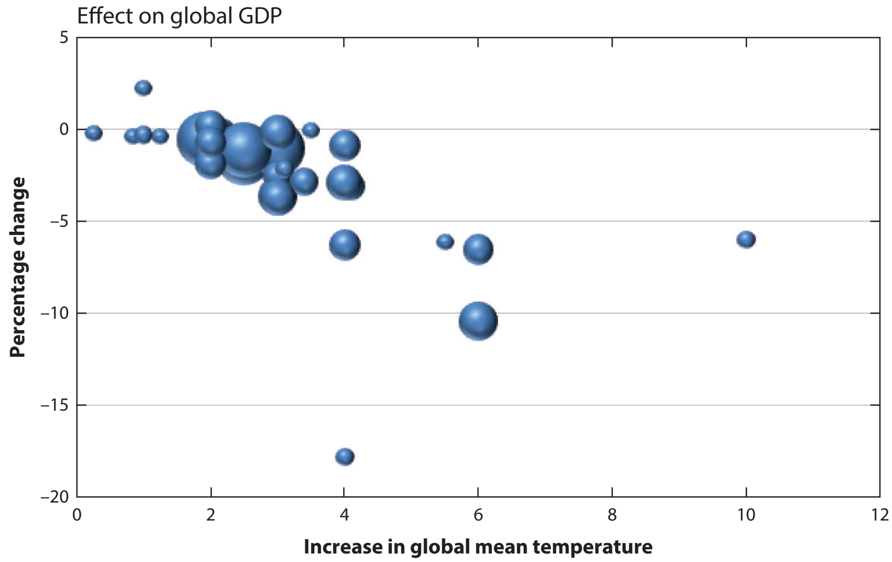

Figure 1

Results of the Nordhaus & Moffat (2017) meta-study. The x axis measures the increase in the average global temperature and the y axis represents the percentage of loss in world GDP; the size of bubbles indicates the attached weight.

GDP, for different temperatures; they then construct their ranges based on these 36 studies. In **Figure 1**, we show the estimates reported by Nordhaus & Moffat (2017).

We use the estimates of Nordhaus & Moffat (2017) to calibrate the likely range of economic sensitivity translated into our damage-function formulation. In our formulation, we thus need to derive a range for the parameter γ in Equation 5. To accomplish this, we first observe that, given a value of λ, the Arrhenius equation (Equation 4) can be inverted to yield S as a function of T:

$$S(T;\lambda) = \bar{S}\left(e^{\frac{T\ln 2}{\lambda}} - 1\right).$$

By assumption, the damage associated with a given amount S of excess atmospheric carbon concentration in our formulation is

$$1 - e^{-\gamma S}.$$

Thus, let $\hat{\Delta}_i(T_i)$ be a particular estimate of the effect on GDP at a temperature T_i. Then, for a given climate sensitivity λ, each of the 36 estimates implies an estimate $\hat{\gamma}_i$ that satisfies

$$\hat{\gamma}_{i;\lambda} = -\frac{\ln\left[1 - \hat{\Delta}_i(T_i)\right]}{S(T_i;\lambda)}.$$

For each of the two climate sensitivities under consideration, λ_H and λ_L, we thus obtain a set of damage elasticities $\hat{\gamma}_{i;\lambda}$. Within each of the sets, we define two subsets, high- and low-damage elasticities, denoted $\Gamma_{H,\lambda}$ and $\Gamma_{L,\lambda}$, respectively. These are constructed as follows. Let $\pi_i, i \in \{1, \ldots, 36\}$ denote the weight that Nordhaus & Moffat (2017) assign to the different studies on global climate damages. The set of high-damage elasticities is defined as the smallest set of the highest $\hat{\gamma}_{i;\lambda}$ such that

$$\sum_{i\in\Gamma_{H,\lambda}} \pi_i \geq 0.2 \sum_{i=1}^{36} \pi_i .$$

The set of low-damage elasticities is defined by, instead, collecting the lowest damage elasticities. Finally, our endpoint elasticities are defined as the weighted average value in the respective sets. Our result is that, for λ_L, the endpoints, denoted γ_{L,λ_L} and γ_{H,λ_L}, are 0.27 and 1.79. For λ_H, we obtain $\gamma_{L,\lambda_H} = 1.44$ and $\gamma_{H,\lambda_H} = 10.39$, all expressed as percentage (of global GDP) per 1,000 excess atmospheric GtC.

4. RESULTS

We now describe and discuss our results, beginning with optima tax calculations and then looking at outcomes (for the economy and the climate) under different scenarios.

4.1. Optimal Taxes

The methodology starts with an optimal tax calculation (or, equivalently, the calculation of an optimal marginal damage externality, which equals the optimal tax in a standard Pigou manner). Thus, given any value of γ, we can use the formula of Golosov et al. (2014) for an optimal tax—the setting in this section is a special case of that described by Golosov et al. This formula reads

$$\tau_t = \gamma Y_t \left[\frac{\varphi_L}{1-\beta} + \frac{(1-\varphi_L)\varphi_0}{1-(1-\varphi)\beta} \right], \qquad 10.$$

where we note that all parameters are expressed for a period length of a decade. Note that the optimal tax is proportional to global GDP with only three kinds of parameters, representing discounting (β), carbon depreciation (the φs), and damages (γ).

We maintain the carbon depreciation parameters throughout and focus mainly on damages, but we also comment on and do robustness analysis with respect to discounting. For the four values of γ, the associated optimal tax rates are given in **Table 1**. In addition to expressing the tax per ton of carbon, we also express the tax in US cents per gallon of gasoline using a carbon content of 2.4 kg/gallon.

4.1.1. Less stern discounting. We can also show the optimal tax rates assuming a lower subjective discount rate. Specifically, we select an alternative discount rate to be that suggested in the Stern (2007) review, namely, 0.1% per year. The optimal tax rates for this discount rate are presented in **Table 2**.

Table 1 Optimal taxes with base-line discounting

Sensitivities	Tax in US dollars/ton of carbon	Tax in US cents/gallon of gasoline
Low climate, low economic	6.9	1.6
Low climate, high economic	45.5	10.9
High climate, low economic	36.6	8.8
High climate, high economic	264.4	63.4

Table 2 Optimal taxes with a low discount rate

Sensitivities	Tax in US dollars/ton of carbon	Tax in US cents/gallon of gasoline
Low climate, low economic	60.3	14.5
Low climate, high economic	399.5	95.9
High climate, low economic	321.4	77.1
High climate, high economic	2319	556

Clearly, the tax values are much higher in this case. In the high–high sensitivity case, the tax per gallon of gasoline would exceed $5 and thus be nearly 10 times the tax with higher discounting.

4.1.2. Quasigeometric discounting. Iverson & Karp (2017) show that, if discounting is quasi-geometric, then we can find a Markov-perfect Nash equilibrium in a tax-setting game using the current model setting. In particular, we can extend the closed-form solutions studied in this section to such cases. Applying their formula to a case when the discount rate is 1.5% per year during the first decade and thereafter 0.1%, we obtain the optimal taxes listed in **Table 3**. We see that the implied numbers are similar to those resulting from Stern-like discounting.

4.2. Scenarios

Let us now use the model to compare the different scenarios. We solve the model for the four different combinations of parameters, representing the four combinations of high and low climate sensitivity and high and low economic sensitivity. Moreover, for each of the four cases, we solve the model without taxes and with taxes. We set the tax to the optimal level in the first period and then let it increase by 2% per year (22% per decade), which is approximately equal to the balanced-growth path for GDP.[3] Throughout, we use the high discount rate, i.e., a level of 1.5% per year.

Note that the model's prediction for T_{2015} depends on the climate sensitivity and, to a lesser extent, on first-period emissions (the two extreme values are 0.8°C and 2.4°C). The current global mean temperature is approximately 1°C above the average over the period 1951–1960. Using this as a calibration target would yield a moderate climate sensitivity of approximately two, interior to our range of uncertainty. There is no scientific consensus about whether the fairly low temperature

Table 3 Optimal taxes with falling discount rates

Sensitivities	Tax in US dollars/ton of carbon	Tax in US cents/gallon of gasoline
Low climate, low economic	55.8	13.4
Low climate, high economic	369.6	88.7
High climate, low economic	297.4	71.4
High climate, high economic	2146	515

[3] Recall that the optimal tax should be indexed to GDP, as shown in Equation 10. Thus, solving for a fully optimal equilibrium path implemented by taxes involves a fixed-point problem: At all points in time, the tax level depends on optimal GDP, but optimal GDP depends on the tax. The simplification we adopt in this section circumvents this fixed-point problem by having slightly suboptimal taxes.

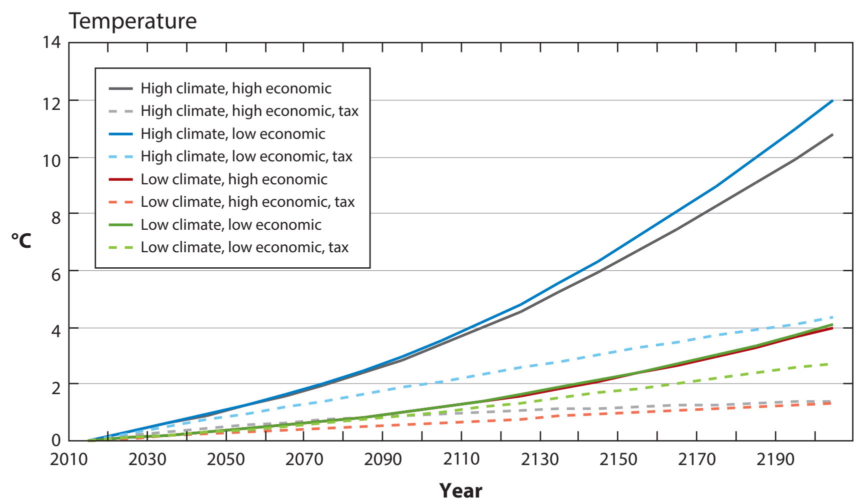

Figure 2

Increase in global mean temperature for all combinations of high and low climate and economic sensitivities with and without carbon taxes.

increase is a sign of a low climate sensitivity or is due to other temporary factors, such as inertia or dimming due to airborne particles.

In **Figure 2**, we show the path of global mean temperature. We graph increases in the temperature over the initial period, which varies between the scenarios, as discussed above.

For all four combinations of parameters, solid curves represent the laissez-faire allocation. **Figure 2** shows that, in laissez faire, the level of economic sensitivity is not important for the climate. Instead, the speed of climate change is largely determined by the climate sensitivity. In the case of high climate sensitivity, the temperature increases very fast: It will have risen by 3.4°C by the end of the century and will continue to accelerate thereafter. In the opposite case, with low climate sensitivity, the increase in the global mean temperature relative to today is 1°C by the end of the current century.

Figure 2 also shows that taxes are highly effective in bringing down global warming. When both the climate sensitivity and the economic sensitivity are high, the introduction of the optimal tax implies that global warming is slowed down sharply. Until 2100, the temperature increase over the current level will be less than 1°C, and 100 years later, it will have increased by only an additional 0.4°C. This is substantially smaller than in the case of low climate sensitivity and no taxes.

Another important point shown in **Figure 2** is that, with optimal taxes, there is a strong link between climate change and the economic sensitivity. In the case of a high climate sensitivity, climate change is, as noted above, almost halted. However, if the economic sensitivity is low, then substantially more climate change should be allowed—2.1°C relative to the initial level by 2105 and 4.3°C toward the end of the simulation period.

Finally, we see that, if the climate sensitivity is low, then climate change is obviously slower, but it is still affected rather substantially by the tax. This is particularly so in the case of high economic sensitivity, in which case no more than a 1.3°C increase should be allowed over the two-century horizon. In fact, this number is close to the corresponding number when the climate sensitivity is high. Thus, although the optimal tax rates are very different in the cases with low and high climate sensitivity, the targets for the temperature increase are similar in the cases with

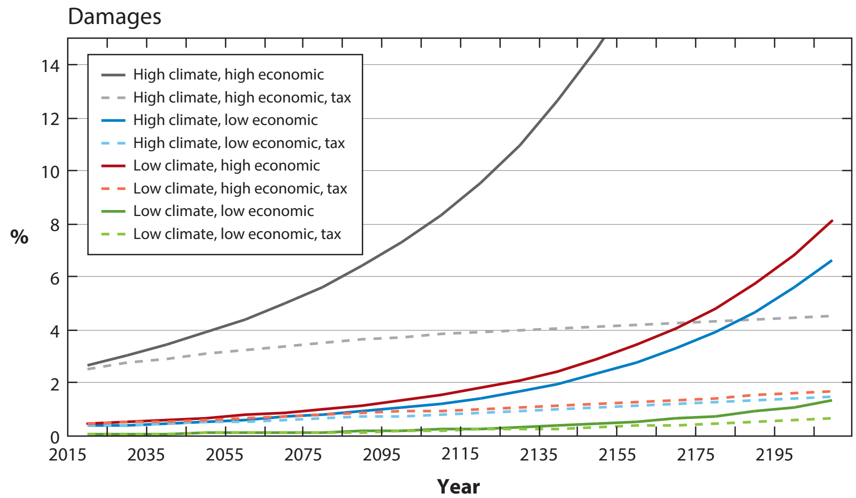

Figure 3

Climate damages in percent of GDP for all combinations of high and low climate and economic sensitivities with and without carbon taxes.

low and high economic sensitivity. Of course, the lower tax in the case of low climate sensitivity would imply more carbon emissions than in the high-climate-sensitivity case, but the resulting temperature increase would be almost the same.

For the case of economic effects, **Figure 3** shows the damages caused by climate change. Reflecting the finding for climate change, we see that taxes are effective in mitigating climate damages in all cases, thus keeping them on a fairly flat trajectory. Of course, the damage estimates for very high levels of climate change are especially uncertain in this case, but the purpose in the present review is not to speculate on costs beyond what are reported in the meta-study by Nordhaus & Moffat (2017).

Figure 4 shows global consumption, measured relative to the most benign scenario: that with low climate and economic sensitivities (with optimal taxes imposed). Consumption can be viewed as a flow measure of welfare.

Figure 4 reveals that the stakes are very high when climate and economic sensitivities are high. Without a climate policy, consumption is significantly lower. A climate policy cannot remove all negative consequences of climate change in this case, but it can remove a very significant part. In all the other scenarios, the stakes are substantially smaller. **Figure 5** depicts coal use.

We see that, in all the scenarios without taxes, coal use grows approximately exponentially.[4] In the case of high climate and high economic sensitivities, coal use is approximately flat under the optimal tax, while it does increase, albeit not exponentially, as long as either of the sensitivities is low.

Let us finally consider the consequences of policy mistakes. Specifically, suppose the true state of the world is such that both the climate sensitivity and the economic sensitivity are high while an overly passive climate policy is pursued, as represented by a tax that is optimal in the state

[4]Whether this implies that we will run out of coal within the simulation period is an unsettled issue. On the one hand, standard references like the report by BP (2017) estimate global proved coal reserves to be 816 Gt, which would not allow a trajectory like the higher ones in **Figure 5**. On the other hand, other estimates of the stock of all hydrocarbon sources that could potentially be used could actually allow such trajectories (Rogner 1997).

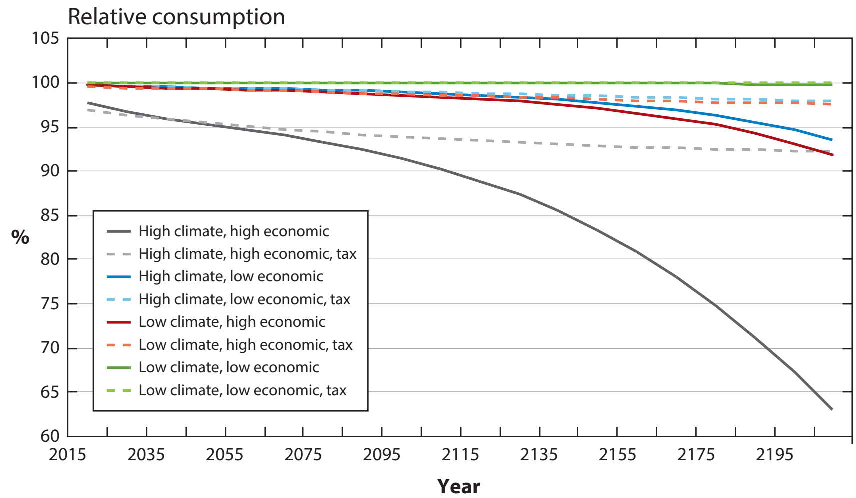

Figure 4

Consumption relative to the case with low climate and low economic sensitivities, with optimal taxes for all other combinations of climate and economic sensitivities with and without carbon taxes.

of low sensitivities. Conversely, also consider the situation where the true state of the world is benign, with both sensitivities at their low values, but where the highest tax (which is optimal in the high-sensitivities world) is adopted: overly zealous climate policy. The results in terms of global consumption of these two kinds of policy errors are presented in **Figure 6**. In both cases, we let the wrong tax be in place for all of the simulation period. Obviously, if we interpret this as only a mistake, such a persistent error is unlikely given that we would likely learn the true state and introduce the correspondingly appropriate tax. However, the use of a too-low tax could be due to

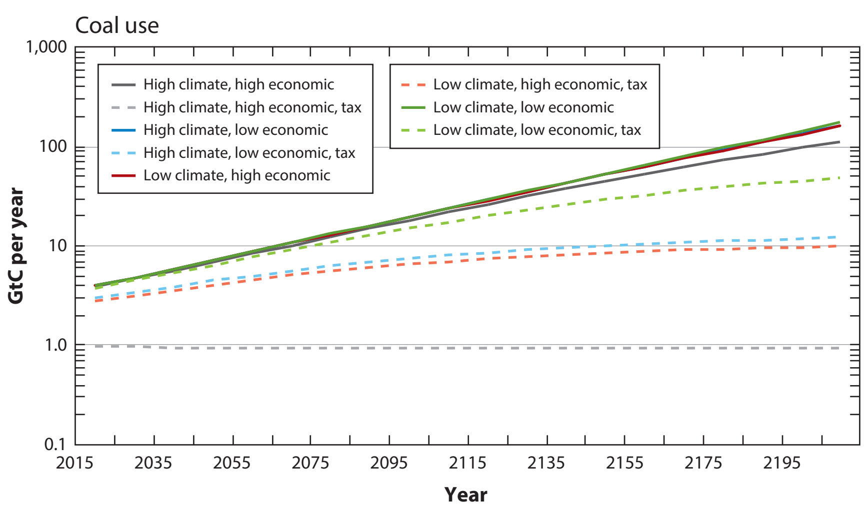

Figure 5

Coal use for all combinations of high and low climate and economic sensitivities with and without carbon taxes.

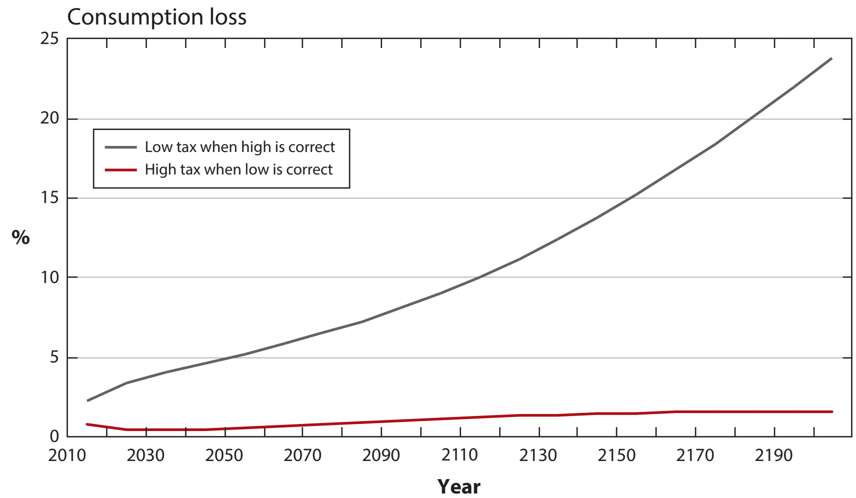

Figure 6

Global consumption loss due to policy mistakes for too cases: a low tax when the optimal tax is high and a high tax when the optimal tax is high.

an international coordination failure not related to a lack of information. Thus, such a scenario is also of interest.

As we see from **Figure 6**, there is a stark difference between the two types of errors. Failing to introduce a high tax when it is necessary has dramatic consequences for consumption and welfare, while unnecessarily imposing a (much-)too-high tax has very moderate consequences. The intuition for this result is that it is relatively cheap to replace coal-based energy production with greener sources. Thus, doing this in vain is not a great loss. However, not having replaced coal-based production with green energy if both the climate and economic sensitivities are high will inflict serious damage to welfare.

5. CONCLUDING REMARKS

We examine two kinds of uncertainty in this review. There are other kinds. For example, one could straightforwardly extend the present analysis to cover uncertainty about the carbon cycle. It would also be interesting to analyze uncertainty about mitigation costs, for example, by considering a range of elasticities of substitution between green and fossil fuels in energy provision. One could also discuss uncertainty about the assumptions we entertain in this review about technological change, both in its general form and in how technologies for energy production may develop. Yet another line of inquiry regards the possible irreversibilities that would arise if lower emissions required the scrapping of fossil-based capital, thus influencing the discussion of the two kinds of policy errors. There are also basic model parameters that could be altered. We assume, for example, logarithmic utility curvature, which allows for greater tractability but somewhat limits the range of welfare consequences. Similarly, more curvature could be introduced on the damage side. We leave all of these extensions for future work.

DISCLOSURE STATEMENT

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