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CLIMATE CHANGE AND GROWTH RISKS

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ABSTRACT

To study the welfare implications of rising temperature we propose a temperature-augmented long-run risks model that accounts for the interaction between temperature, economic growth and risk. The model simultaneously matches the projected temperature path, the observed consumption growth dynamics, discount rates provided by the risk-free rate and equity market returns, and the negative elasticity of equity prices to temperature risks documented in the data. We use the calibrated model to quantify the social cost of carbon (SCC) and to frame the optimal climate policy. We show that a preference for early resolution of uncertainty and long-run impact of temperature on growth imply a significant SCC and motivate early actions to abate global warming.

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Introduction

Using data from global and US capital markets, Bansal, Kiku, and Ochoa (2016) show that temperature fluctuations, particularly low-frequency temperature risks, have a significantly negative effect on equity valuations that suggests that global warming is an important source of economic risk. This article makes a contribution towards a better understanding of the welfare implications of rising temperature and, consequently, the optimal policy response to global warming. To study the potential impact of climate change on the macro-economy, we present a temperature-augmented long-run risks (LRR-T) model that accounts for the interaction between economic growth and temperature risks. We show that a preference for early resolution of uncertainty and long-run impact of temperature on growth imply a significant social cost of carbon emissions and motivate early actions to abate global warming.

Our model builds on the long-run risks framework of Bansal and Yaron (2004) that features recursive preferences of Kreps and Porteus (1978), Epstein and Zin (1989), and Weil (1990) with a preference for early resolution of uncertainty and a persistent expected growth component in consumption. To account for the potentially severe consequences of global warming we introduce temperature-induced natural disasters that affect current and future economic growth, similar in spirit to Rietz (1988) and Barro (2009). Disasters are triggered when temperature breaches a threshold level and capture the idea of tail risk related to global warming as discussed in Pindyck (2012). Our LRR-T model provides a framework, in which temperature rises economic risk and affects aggregate wealth and valuations of long-lived assets. We show that with a preference for early resolution of uncertainty, a rise in temperature, even in the distant future, lowers the current wealth to consumption ratio and that temperature variations carry a positive risk premium. These implications are consistent with the evidence of the negative elasticity of equity prices to long-run temperature risks documented in the data. In contrast, under power utility, which is the standard assumption in the integrated assessment models, aggregate wealth increases in states of high temperature and high likelihood of disasters. Consequently, as we show, the incentive to abate global warming, and the timing and the scale of abatement efforts depend critically on the attitude towards long-run (climate) risks.

We calibrate our LRR-T model to match the projected climate change and consumption dynamics, the estimates of temperature elasticity of equity valuations and the observed discount rates from capital markets.[1] The latter is important, as willingness to abate climate change and the social cost of carbon are highly sensitive to discount rates as highlighted in Nordhaus (2008) and Gollier (2012). We use the calibrated model to quantify the social cost of carbon (SCC) and to frame the socially optimal response to climate change. The social cost of carbon is an important concept in the economic analysis of global warming. Intuitively, it measures the present value of damages due to a marginal increase in carbon emissions and as such, it allows us to quantify and assess the incentive to curb industrial emissions. We find that with a preference for early resolution of uncertainty, the social cost of carbon is quite significant. In our baseline LRR-T model, SCC is measured at about 100 dollars of world consumption per metric ton of carbon. It declines to a still sizable $40 when temperature is assumed to affect the level of output but not the long-term growth. Thus, when distant risks matter, carbon emissions and rising temperature carry a significant price. In sharp contrast, in a power-utility setting, climate change is not perceived as sufficiently risky because its impact is deferred to the distant future. Consequently, SCC under power-utility preferences is very small, of merely 1 cent.

To evaluate the optimal policy response to temperature risks, we consider a social planner who may choose to abate a prospective increase in temperature and thus limit future disasters by investing in the development of carbon-free technologies. Abatement policies are costly investments that require resources that otherwise could be consumed. The optimal abatement effort, therefore, is chosen by trading off costs of lower current consumption versus benefits of lower climate-change risks in the future. We show that with a preference for early resolution of uncertainty, the social planner opts for an immediate and a relatively stringent abatement policy that allows to avert large disasters in the future. When the planner is indifferent towards the timing of resolution of uncertainty, as in the case of power utility, there is very little willingness to abate climate change. The power-utility planner postpones abatement for nearly 50 years until after the effects of global warming start unfolding, and lets the economy to be exposed to sizable losses. In essence, preferences for early resolution of uncertainty (which are supported by capital market data) are important to

[1] We focus on the exchange economy to maintain tractability and ensure that the model is able to match the asset market data. This is quantitatively difficult to achieve in a production-based setting.

motivate early and significant abatement.

The rest of the paper is organized as follows. In the next section, we set up the LRR-T model. Section 2 provides specifics of our calibration. In Section 3, we present the quantitative solution to the model and discuss its implications. Section 4 concludes.

1 LRR–T Model

In this section, we set up a unified general equilibrium model of the world economy and global climate. Our LRR-T model accounts for the interaction between current and future economic growth and climate change in a framework that features elements of Epstein and Zin (1989), Bansal and Yaron (2004), and Hansen and Sargent (2006) models. A unique dimension of our model is that it incorporates temperature-induced natural disasters that are expected to have a long-run effect on future well-being. This feature is consistent with by now the consensus view that global warming will have a long-lasting negative effect on ecological systems and human society (IPCC (2007, 2013)).[2]

1.1 Climate-Change Dynamics

We assume that industrial carbon emissions are driven by technologies that are used to produce consumption or output. Let Y_t denote the total (gross) amount of consumption goods, then the level of CO_2 emissions is given by:

$$E_t = Y_t^{\lambda_t} \,, \tag{1}$$

where $\lambda_t \geq 0$ is carbon intensity of consumption. The (log) growth rate of emissions is, therefore,

$$\Delta e_{t+1} = \lambda_{t+1} \Delta y_{t+1} + \Delta \lambda_{t+1} y_t \,, \tag{2}$$

where $e_t \equiv \log E_t$, $y_t \equiv \log Y_t$, and Δ is the first difference operator.

[2]While climate change has a broader meaning, we use it to refer to anthropogenic global warming due to the continuing buildup of carbon dioxide in the atmosphere caused by the combustion of fossil fuels, manufacturing of cement and land use change.

With no abatement efforts, carbon intensity is assumed to be exogenous and we calibrate it to match the projected path of CO_2 emissions under the business-as-usual (BAU) scenario of Nordhaus (2010). We assume that in the long-run limit, both intensity and emissions decline to zero to capture the eventual replacement of current technologies with carbon-free ones as fossil fuel resources become depleted. We will discuss our calibration in more details below.

The accumulation of greenhouse gasses, of which carbon dioxide is the most significant anthropogenic source, leads to global warming due to an increase in radiative forcing. The geophysical equation linking CO_2 emissions and global temperature is a modified version of that in Nordhaus (2008)'s DICE model.[3] In particular, we assume that global temperature relative to its pre-industrial level follows:

$$T_t = \nu_t T_{t-1} + \chi e_t \,, \tag{3}$$

where T_t is temperature anomaly (i.e., temperature above the pre-industrial level), e_t is the log of CO_2 emissions, $\nu_t \in (0, 1)$ is the rate of carbon retention in the atmosphere and, hence, the degree of persistence of temperature variations, and $\chi > 0$ is temperature sensitivity to CO_2 emissions.[4] Note that, effectively, Equation (3) describes a stock of man-made emissions in the atmosphere (i.e., CO_2 concentration), and temperature anomaly is assumed to be proportional to the level of carbon concentration. These dynamics are also consistent with the conclusions of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) that establishes an unequivocal link between the increase in the atmospheric concentration of greenhouse gasses and the rise in global temperature (IPCC (2013)).

We assume that climate change due to global warming has a damaging effect on the economy. Once temperature crosses a tipping point, $T_t \geq T^*$, the economy becomes subject to natural disasters that result in a significant reduction of economic growth. The probability of natural disasters and the loss function are described next.

[3] Nordhaus (2008) models carbon-cycle dynamics using a three-reservoir system that accounts for interactions between the atmosphere, the upper and the lower levels of the ocean. The dynamics of temperature that we use is qualitatively consistent with the implications of his structural specification. Also, quantitatively, our calibration is designed to match temperature dynamics under the BAU policy as predicted by Nordhaus (2010).

[4] We assume that ν_t is increasing in carbon intensity. This feature implies a more persistent effect of emissions at high levels of CO_2 concentration and temperature and is designed to capture re-inforcing feedbacks of global warming due to melting ice and show that increases absorbtion of sunlight, an increase in water vapor that causes temperature to climb further, a more intensive release of carbon dioxide and other greenhouse gases from soils as temperature rises, a reduced absorbtion of carbon by warmer oceans, etc.

1.2 Consumption Growth Dynamics

Consumption growth follows the dynamics as in Bansal and Yaron (2004) augmented by the impact of natural disasters caused by global warming. The growth rate of gross consumption ($y_t \equiv \log Y_t$) is given by:

$$\Delta y_{t+1} = \mu + x_t + \sigma\eta_{t+1} - D_{t+1}\,, \quad (4)$$

$$x_{t+1} = \rho_x x_t + \varphi_x \sigma \epsilon_{t+1} - \phi_x D_{t+1}\,, \quad (5)$$

where μ is the unconditional mean of gross consumption growth; x_t is the expected growth component; η_{t+1} and ϵ_{t+1} are standard Gaussian innovations that capture short-run and long-run risks, respectively; and $-D_{t+1}$ is a decline in consumption growth due to temperature-induced disasters. Effectively, D_{t+1} measures an economic cost of global warming.[5]

Note that in our specification climate-change disasters affect current and future expected consumption growth and, therefore, have a permanent effect on the economy. We focus on potentially catastrophic consequences of climate change that might not be possible to reverse or easily adapt to, and as such they are expected to have a permanent effect on human well-being. These include but not limited to rising sea levels and drowning of currently populated coastlines and islands, intensified heat waves, severe droughts, storms and floods, destruction of ecosystems and wildlife, spreading of contagious tropical diseases, shortages of food and fresh water supply, significant destruction of property and human losses. To incorporate these types of large-scale and permanent effects we assume that disasters affect the growth rate of the economy instead of just the current level of output as is typically assumed in the integrated assessment models.[6] A permanent impact of climate change and its implications for policy decisions are also analyzed in Pindyck (2012). We consider a more general specification in which global warming may affect not only current but also future consumption growth. While uncertainty over adaptation to global warming is well recognized, the assumption that rising temperature will have a negative effect on human welfare and global economy

[5] Our specification of climate-change driven disasters as rare tail events is reminiscent of rare disasters models of Rietz (1988), Barro (2009), Barro and Ursua (2012), Gabaix (2012) and Wachter (2013). As we discuss below, different from the standard disaster specifications, disaster risks in our model account for a relatively modest fraction of the overall risk premia.

[6] For example, the DICE/RICE models of Nordhaus (2008, 2010), the FUND model of Tol (2002a, 2002b) and Anthoff and Tol (2013), and the PAGE model of Hope (2011).

is standard in the climate-change literature (eg., Nordhaus (2010), Weitzman (2010), Anthoff and Tol (2012), Pindyck (2012)).[7]

We assume that natural disasters are triggered when temperature reaches a tipping point T^* and model their impact using a compensated compound Poisson process,

$$D_{t+1} = \sum_{i=1}^{N_{t+1}} \zeta_{i,t+1} - d_t \pi_t \,, \tag{6}$$

where N_{t+1} is a Poisson random variable with time-varying intensity π_t, and $\zeta_{i,t+1} \sim \Gamma(1, d_t)$ are gamma distributed jumps with a time-varying mean of d_t. We assume that both occurrence of natural disasters and their damages are increasing in temperature. In particular, the expected size of disasters is given by:

$$d_t = \begin{cases} q_1 T_t + q_2 T_t^2 \,, & \text{if} \quad T_t \geq T^* \\ 0\,, & \text{otherwise} \end{cases} \tag{7}$$

and disaster intensity follows:

$$\pi_t \equiv E_t[N_{t+1}] = \begin{cases} l_0 + l_1 T_t \,, & \text{if} \quad T_t \geq T^* \\ 0\,, & \text{otherwise,} \end{cases} \tag{8}$$

where parameters q_1, q_2, l_0 and l_1 are greater than zero. Quadratic loss functions are commonly used in the climate-change literature, e.g., Nordhaus (2008), Weitzman (2010), Lemoine and Traeger (2012), Golosov, Hassler, Krusell, and Tsyvinski (2014), and Heutel (2012).

1.3 CO_2 Abatement Policies

The social planner may decide to lower the likelihood of natural disasters and the amount of damages incurred by implementing a policy that limits carbon emissions and, consequently, slows down global warming. The decision of which, if any, abatement action to take depends on its benefits and costs.

We model the benefits of policy intervention as an acceleration in the development and adoption of carbon-free technologies. That is, we focus on abatement actions that reduce carbon emissions

[7] The implications of tail risks in the presence of uncertainty about climate-change impact are analyzed in Weitzman (2009).

not only in the short but also in the long run. Specifically, we assume that:

$$E_t^* = Y_t^{\lambda_t^*}, \tag{9}$$

$$\Delta\lambda_t^* = \Delta\lambda_t - \theta_t, \tag{10}$$

where E_t^* and λ_t^* are CO_2 emissions and carbon intensity under a chosen abatement policy, respectively; λ_t is intensity under the business-as-usual scenario; and $\theta_t \geq 0$ is the emission reduction function. Effectively, we assume that the matter-of-course long-run decline in carbon intensity under the BAU policy can be speeded up by θ_t if the social planner decides to act. Higher values of θ_t represent more stringent policies, and $\theta_t = 0$ corresponds to the BAU scenario.

Abatement policies are costly investments — they require resources that otherwise could be consumed. We assume that emission reductions cost $\Lambda_t Y_t$ units of consumption goods, and the abatement cost at time t depends on the targeted reduction level (θ_t):

$$\Lambda_t = \xi_t \theta_t^k, \tag{11}$$

where $\xi_t > 0$ and $k > 0$ (i.e., at any point in time, more stringent abatement policies cost more), and $\xi_t = \xi_0 e^{-gt}$ is assumed to decline over time at a rate of $g > 0$. A deterministic decline in the cost function represents an improvement in cost-efficiency of abatement technologies over time.

1.4 Cost-Benefit Tradeoff

Under the BAU scenario, agents in the economy consume all available goods. Thus, their consumption is given by: $C_t = Y_t$. If an abatement policy is adopted, agents have to give up a fraction of consumption goods to finance the policy in place. Consequently, their consumption is reduced by the policy implementation costs:

$$C_t = Y_t(1 - \Lambda_t), \tag{12}$$

and the actual consumption growth (in logs) is given by $\Delta c_t \approx \Delta y_t - \Delta\Lambda_t$. The net-of-costs consumption growth, therefore, follows:

$$\Delta c_{t+1} \;=\; \mu - \Delta\Lambda_{t+1} + x_t + \sigma\eta_{t+1} - \phi_c D_{t+1}\,. \tag{13}$$

In essence, by adopting an abatement policy, the social planner trades off costs of lower current consumption versus benefits of lower risk of natural disasters and lower damages in the future.

1.5 Preferences

Following the long-run risk literature, we define preferences recursively as in Kreps and Porteus (1978), Epstein and Zin (1989), and Weil (1990). We use U_t to denote the continuation utility at time t, which is given by:

$$U_t = \left\{(1-\delta)C_t^{1-\frac{1}{\psi}} + \delta\Big(E_t\Big[U_{t+1}^{1-\gamma}\Big]\Big)^{\frac{1-\frac{1}{\psi}}{1-\gamma}}\right\}^{\frac{1}{1-\frac{1}{\psi}}}, \tag{14}$$

where δ is the time-discount rate, γ is the coefficient of risk aversion, and ψ is the intertemporal elasticity of substitution (IES). When $\gamma = \frac{1}{\psi}$, than preferences collapse to the power utility specification, in which the timing of the resolution of uncertainty is irrelevant. When risk aversion exceeds the reciprocal of IES, $\gamma \geq \frac{1}{\psi}$, early resolution of uncertainty about future consumption path is preferred. Power utility is the standard assumption in the integrated assessment models of climate change. Preferences for early resolution of uncertainty are the benchmark in the long-run risks literature and, as emphasized in Bansal and Yaron (2004), are critical for explaining the dynamics of financial markets. We consider both specifications and highlight the importance of preferences to risks and to temporal resolution of risks for the analysis of global warming and policy decisions.

Note that the maximized life-time utility is proportional to the wealth to consumption ratio, $Z_t \equiv \frac{W_t}{C_t}$, and as such is determined by the present value of expected consumption growth from now to infinity. In particular,

$$U_t = \big[(1-\delta)Z_t\big]^{\frac{\psi}{\psi-1}}C_t\,, \tag{15}$$

and

$$Z_t = E_t \left[\sum_{j=0}^{\infty} \frac{C_{t+j}/C_t}{R_{j,t+j}} \right], \tag{16}$$

where $R_{j,t+j}$ is the discount rate of the consumption strip with j-time to maturity. Because prices are forward-looking, the current price of the consumption claim (and that of market equity) carries information about the impact of climate change on future economic growth and risk.

1.6 Dynamic Optimization Problem

Each period, the social planner makes a decision of which abatement policy θ_t is optimal to implement by solving utility-maximization problem. Let $\mathbb{S}_t$ summarize the state of the economy and climate at time t: $\mathbb{S}_t = \{T_t, Y_t, \lambda_t, \Lambda_t, x_t\}$. The dynamic optimization problem can be described recursively as:

$$U_t(\mathbb{S}_t) = \max_{\theta_t, C_t} \left\{ (1-\delta) C_t^{1-\frac{1}{\psi}} + \delta \left(E_t \left[U_{t+1}(\mathbb{S}_{t+1})^{1-\gamma} \right] \right)^{\frac{1-\frac{1}{\psi}}{1-\gamma}} \right\}^{\frac{1}{1-\frac{1}{\psi}}}, \tag{17}$$

$$\text{s.t.} \quad C_{t+1} = Y_{t+1}(1 - \Lambda_{t+1}), \tag{18}$$

$$\mathbb{S}_{t+1} = F(\mathbb{S}_t, \theta_t). \tag{19}$$

Utility maximization is subject to two constraints: the resource allocation constraint in Equation (18), and the state dynamics in Equation (19), where $F(\cdot, \cdot)$ summarizes the transitional dynamics of the state vector under the chosen policy.

We solve the dynamic programming problem numerically using value function iterations. We start at the "terminal" date at which temperature anomaly disappears and the solution becomes stationary, and work backwards in time. We discretize the state space and use Chebyshev polynomial approximation of the value and abatement policy functions. Expectations at the maximization stage (see Equation (17)) are computed via simulations. Notice that the optimal abatement policy that we derive is dynamically consistent, thus, future abatement decisions will comply with the policies chosen today.

1.7 Social Cost of Carbon

The social cost of carbon (SCC) has become an important concept in the cost-benefit analysis of global warming. SCC measures the present value of damages due to a marginal increase in carbon emissions. Formally, it is defined as marginal utility of carbon emissions:

$$SCC_t = \frac{\partial U_t}{\partial E_t} \Big/ \frac{\partial U_t}{\partial C_t} \tag{20}$$

The scaling by marginal utility of consumption allows us to express the cost in units of consumption goods (time-t dollars), which makes SCC easy to interpret. Using Equation (15), we can express the social cost of carbon at time 0 as:

$$SCC_0 = \frac{\psi}{\psi - 1} \frac{\partial Z_0 / \partial E_0}{Z_0} C_0 \,. \tag{21}$$

That is, SCC is equal to the (appropriately scaled) monetized value of a percentage change in wealth due to an additional unit of emissions. Intuitively, the social cost of carbon measures an increase in current consumption that is required to compensate for damages caused by a marginal increase in date-0 emissions.

2 Calibration of the BAU Scenario

We calibrate the path of carbon intensity (λ_t) and temperature (T_t) in the absence of any abatement efforts to match the business-as-usual forecasts of CO_2 emissions and global warming in Nordhaus (2010) and IPCC (2007, 2013). Time in the model is measured in decades and we assume that the steady state in the BAU case will be reached in 60 periods or 600 years from now. The steady state corresponds to the state in which anthropogenic emissions decline to zero and the temperature anomaly disappears due to the ultimate de-carbonization of the economy. The first two panels of Figure 1 show the calibrated path of carbon intensity and the amount of emissions along the transitional path. Under the BAU policy, carbon intensity is expected to remain relatively high over the next two centuries and carbon emissions accelerate since the economy is growing.

As more and more CO_2 emissions are released, the concentration of carbon in the atmosphere increases and temperature anomaly escalates. The projected BAU path of temperature is shown in Panel (c) of Figure 1. Calibration of global warming dynamics and the impact of climate change on consumption growth are presented in Table I.[8] To capture re-enforcing feedback effects of emissions, we allow the retention of carbon in the atmosphere, ν_t, to increase in carbon intensity. We assume that about 80% of current CO_2 emissions will remain in the atmosphere for another century, their decay will increase as the rate of emissions slows down. The average value of the retention rate under the BAU scenario is equal to 0.962, which implies that about 70% of CO_2 molecules emitted along the transitional path are removed from the atmosphere within a century. The precise atmospheric life of carbon dioxide is yet unknown but our calibration is designed to roughly match the available estimates in the geophysical literature (Jacobson (2005), and Archer (eg., 2005, 2009)).

We set the tipping point of global warming disasters to 2°C that according to the Copenhagen accord is internationally recognized as a likely trigger of dangerous changes in the climate system. If the current trend in emissions continues, temperature is expected to cross the disaster threshold in about 30-35 years from now (see Figure 1). This assumption is fairly consistent with the most recent forecast of the IPCC. As reported in the Fifth Assessment Report, the global mean surface temperature anomaly is expected to exceed 2°C in three to four decades from now (IPCC (2013)).

Once the 2°C tipping point is crossed, the global economy faces the risk of natural cataclysms. Both intensity and size of climate-induced disasters are increasing with temperature and their expected paths are presented in Figure 2. Time-varying intensity dynamics are motivated by the evidence in Raddatz (2009) that, worldwide, the number of climatic disasters (such as droughts, floods, and extreme temperature) has increased over the last four decades — the period that has experienced a steep increase in temperature. The initial impact of global warming is assumed to be relatively moderate but it is intensified as temperature keeps rising. In particular, we assume that upon the crossing of the 2°C threshold, the annual probability of disasters is about 1.2% and their average size is -0.7%. As temperature reaches its peak, the disaster probability rises to 2.8% per annum and average losses increase to -6.0%.

Table II summarizes our calibration of preferences and consumption dynamics. Our LRR-T

[8] To facilitate interpretation of the calibrated parameters, we report and discuss them in annualized terms.

model features preferences for early resolution of uncertainty and incorporates a negative effect of global warming on current and future consumption growth. We choose preference parameters so that the model is able to match key moments of financial data. In particular, we set risk aversion at 5, the intertemporal elasticity of substitution at 1.5, and the subjective time-discount factor at 0.99. We set the unconditional mean of consumption growth at 1.8% and assume that the standard deviation of i.i.d. gaussian shocks is 1.6% per annum. We calibrate the dynamics of the long-run risk component to match persistence of consumption growth in normal times. Consistent with the US consumption data, in our specification the first-order autocorrelation of consumption growth absent climate disasters is equal to 0.44. Exposure of the expected consumption growth to disaster risks is set at 0.05. Note that while the average size of climate disasters in the expected growth component is assumed to be quite modest, their effect on consumption is propagated due to persistence of long-run risks. That is, upon a disaster, consumption growth does not immediately bounce back to its normal level but is expected to remain low for a relatively long while.

Note that in contrast to the standard integrated assessment models, in which climate change is assumed to cause a deterministic loss in future output or consumption, in our model, global warming affects the economy entirely through a risk channel. Figures 3 and 4 illustrate the implications of global warming for the distribution of consumption growth in our baseline specification. Notice that because temperature-induced disasters are compensated, they have no effect on the ex-ante mean of log consumption growth (see Panel (a) of Figure 3). Thus, similar to gaussian i.i.d. and long-run risks, ex-ante, global warming does not affect the log level of future consumption path but does affect its variation. As Panel (b) of Figure 3 shows, climate-change driven disasters increase the annualized ex-ante volatility of cumulative consumption growth by up to 0.18% (which is more than ten percent increase in volatility relative to a no-disaster case). Also, because global-warming disasters represent tail risks, the distribution of future consumption growth is both negatively skewed and fat-tailed. A side-by-side comparison of the distribution of the normalized consumption growth at the peak of climate-driven disasters and the corresponding distribution absent disasters is presented in Figure 4. To summarize, while ex-ante, global-warming does not alter the future path of consumption, it introduces an additional source of risk in the economy. Thus, ex-post, global warming consequences for consumption can be substantial.

In addition to our LRR-T model, we discuss three alternatives. In all alternative specifications, we shut down the long-run risk channel and assume that global warming affects only realized consumption growth. That is, if a disaster is realized, the level of consumption declines on impact but future consumption growth remains unaffected. We use these simplified dynamics to analyze the implications of risk preferences for policy decisions on climate change. To this end, we consider three preference specifications: (1) preference for early resolution of uncertainty, which we refer to as "KPEZW-Preferences", (2) power utility with high degree of risk aversion — "CRRA-highRA", and (3) power utility with low risk aversion — "CRRA-lowRA". In the KPEZW-case, we maintain the same preference configuration as in our LRR-T model. In the case of power utility, we set either risk aversion or IES at their corresponding baseline values. That is, under CRRA-highRA preferences, risk aversion is set at 5, and in the CRRA-lowRA case, risk aversion is set at 0.67 (the reciprocal of our baseline IES value of 1.5).

In our set-up, abatement policies are specified as an effort to stimulate the development and adoption of carbon-free technologies and, as such, they lead to a permanent reduction in emissions. Anthoff and Tol (2013) also allow abatement efforts to have a permanent effect, at least in part. Given the similarities in our modeling approaches, we calibrate the abatement cost function to be consistent with mitigation costs implied by their FUND model. More ambitious abatement efforts cost more and we assume that the cost function is convex by setting k at 1.5, the scale parameter ξ_0 is set at 5 (see Equation (11)). Abatement costs decline over time at a rate of 1.5% per annum that is chosen to match the average TFP growth in the post-war US economy.

The dynamics of future climate changes and their economic consequences are highly uncertain and not yet well-understood. While some empirical evidence on the impact of rising temperature and climatic disasters does exist, it is based on human experiences that have not yet been subjected to catastrophic climate changes that we consider. Therefore, we can use it only as a guidance rather than a target. Whenever possible, we calibrate the model parameters to be broadly consistent with assumptions of the standard integrated assessment models and consensus forecasts outlined by the IPCC. With this in mind, we do not intend to claim that our calibrated dynamics represent the future better than others. We consider plausible dynamics and focus on highlighting the channels through which beliefs about climate-change risks and risk preferences affect policy decisions. To discriminate across the LRR-T model and alternative specifications, we confront them with empirical evidence on the impact of rising temperature on equity prices.

3 Policy Decisions and Welfare Implications

We begin our analysis with the LRR-T model, in which agents have preferences for early resolution of uncertainty and global warming has a permanent effect on the economy through climate-induced disasters in realized and expected consumption growth. Afterwards we consider simplified dynamics for consumption growth and explore the implications of risk preferences for the optimal cost-benefit tradeoff and welfare.

3.1 LRR-T Model

In our model, detailed in Table II, temperature risks have a negative effect on consumption level and future growth and agents care about long-run risks through preferences for early resolution of uncertainty. Solving the maximization problem, we find that the social planner in this environment opts for a stringent mitigation policy from the very beginning despite the fact that earlier efforts are relatively costly. The optimal level of abatement effort (θ_t) and its cost (Λ_t) are presented in Figure 5. Figure 6 illustrates the policy implications for carbon emissions and temperature. Recall that earlier abatement efforts are valuable as they yield long-term benefits, i.e., an earlier development and adoption of carbon-free technologies implies a progressive increase in emission reductions over time. Panel (a) of Figure 6 shows that industrial carbon emissions under the optimal policy are expected to decline by about 80% in 100 years from now and essentially disappear by 2200. It is optimal to give up about 0.03% of the current output and up to 0.95% later on to mitigate climate risks. And while it is too costly to contain temperature anomaly under the tipping point, the achieved reduction in carbon emissions guarantees that it does not exceed 2.8°C and does not stay above the disaster threshold for too long.

Note that in the BAU scenario, even at the peak of temperature anomaly, climate-induced catastrophes are low-probability events. On average, the highest likelihood of disasters is short of 3% per year. However, if realized, their economic consequences can be highly significant. Panel (a) of

Figure 7 shows that the 90%-confidence interval of disaster size under the business-as-usual scenario includes quite substantial losses of as large as 15%–18% of consumption. In our specification, these damages are non-recoverable — they lead to a permanent decline in consumption level and a long-term reduction in growth. Under preferences for early resolution of uncertainty, such low-probability yet sizable and persistent events represent a significant concern that makes the social planner act today to prevent them in the future. Panel (b) of Figure 7 shows that the optimal abatement policy effectively eliminates catastrophic outcomes. The average size of disasters is reduced to under 1% and the 95-percentile of the disaster-size distribution is kept well under 4%. Notice also a significant reduction in duration of global warming disasters under the optimal policy — disaster period starts later and is expected to last for only few decades.

By trading off a fraction of current consumption for limiting the likelihood and size of disasters in the future, agents are able to achieve a significantly higher level of utility relative to the business-as-usual scenario. The utility gain of the optimal abatement policy is around 11%. The immediate call for action is also reflected in the social cost of carbon, which is quite sizable under the LRR-T specification. As shown in Table III, under the business-as-usual scenario, SCC is estimated at about \$104 per ton of carbon. The social cost of carbon is measured in 2012 dollars of world household final consumption expenditure per metric ton of carbon. In the presence of risks that affect long-term growth, agents' utility is highly sensitive to emissions due to both high potential damages and late resolution of climate risks. The two channels combined lead to the high price of carbon emissions.

Temperature risks aside, our LRR-T specification corresponds to the long-run risks model of Bansal and Yaron (2004). As they show, with preferences for early resolution of uncertainty, risks that matter for the long run carry high risk premia and are able to account for the dynamics of equity prices and asset returns. Our calibration of the gaussian part of consumption dynamics is similar to theirs and, therefore, is consistent with financial market data. As Table IV shows, the average risk-free rate in the LRR-T specification is 0.9%, and the risk premium on consumption claim is about 1.7%. Hence, assuming leverage of 3, the implied equity premium is about 5% per annum. It is important to emphasize that most of the risk premium is the compensation for long-run gaussian risks, and only a relatively modest fraction of it is due to temperature risks.

3.2 Welfare Implications of Risk Preferences

To examine the effect of preferences for welfare implications and policy decisions, we consider three alternative specifications. In all of them, we simplify consumption dynamics by shutting off the long-run risk component and assume that the only effect of global warming is through its negative impact on realized consumption growth. Under these dynamics, climate risks continue to have a permanent negative impact on consumption level but are assumed to have no effect on future economic growth. We compute and compare optimal climate policy decisions of three social planners under different risk preferences: preferences for early resolution of uncertainty, power utility with high degree of risk aversion (and low IES) and power utility with low risk aversion (and high IES) as summarized in Table II.

Figure 8 plots the optimal level of abatement cost and the implied path of temperature for each alternative specification. Consider first the economy with KPEZW-preferences. As Panel (a) shows, the optimal response of the social planner under preferences for early resolution of uncertainty is to promptly set up an abatement policy to slow down global warming and to avert large disasters. Because the amount of temperature risks in the alternative set-up is smaller, the initial scale of abatement is somewhat lower relative to that in the LRR-T model, yet similarly, an abatement policy is set in motion right away and abatement efforts are accelerated at a high rate in the future.

The optimal response to climate risks in a power-utility setting is quite different. A power-utility planner (under the two risk-aversion configurations) chooses to postpone abatement into the future and even then implements a relatively modest level of effort. In fact, as Figure 8 shows, both high- and low-RA power-utility planners find it optimal to do nothing until temperature crosses over the tipping point and the likelihood of economic disasters becomes nontrivial. From their perspective, current abatement costs outweigh future benefits and they do not act until climate-change risks become real. In other words, the optimal response to global warming of power-utility planners is to mitigate it as it unfolds rather than to prevent it. Even at the peak of climate-driven disasters, power-utility planners are willing to spend only a small amount on abatement efforts, letting temperature stay well above the disaster threshold for a very long while. As Panel (b) shows, under the KPEZW-based optimal policy, temperature anomaly is kept under 3.3°C and the disaster period lasts for approximately one hundred years; whereas under the CRRA-based optimal policies, temperature anomaly reaches 5°C and climate-induced disasters stretch out over more than 200 years.

The reluctance to mitigate global warming in the power-utility settings is reflected in the social cost of carbon, which under power utility is quite trivial. As Table III shows, SCC is merely 1 cents per metric ton of carbon in the high risk-aversion configuration and virtually zero in the case of low risk aversion. This suggests that in the power-utility settings, climate-change risks are essentially discounted out as they are expected to realize in a relatively distant future. In contrast, with preferences for early resolution of uncertainty, distant climate risks carry a significant weight and their importance is reflected in a sizable $42 social cost of carbon. Also, while optimal abatement efforts are welfare improving in all three cases, their quantitative benefits are quite different. The utility gain of the chosen optimal policy under KPEZW-preferences is a significant 4.0%, whereas it is only 0.02% and essentially zero in the power-utility setting with high and low risk aversion, respectively.

The magnitude of the social discount rate has become a subject of controversy and disagreement in the climate-change literature. The level of the discount rate is certainly important for translating future damages into their present-value terms, particularly in the context of global warming which impact is expected to unfold over the course of centuries and, therefore, entails long-term discounting. However, the magnitude of the discount rate that has attracted so much attention, by itself, is not sufficient for understanding welfare implications of climate-change risks. To illustrate the point, we refer to Table IV that presents asset pricing implications of the alternative specifications. First, compare the implications of KPEZW-preferences and power utility with the low degree of risk aversion. Because the intertemporal elasticity of substitution is the same, the risk-free rates and therefore discount rates in the two specifications are very similar of about 2.2–2.3%. To be precise, the level of discount rates of consumption strips across all maturities is slightly higher in the KPEZW-case compared with CRRA-lowRA preferences. Given that the damage function is identical, the present value of expected global warming damages in the power-utility case is higher than that in the case of KPEZW-preferences. Yet, among the two, it is the planner with KPEZW-preferences who is concerned with climate-change risks and attaches a high price tag to carbon emissions. Further, if we now compare the two power-utility specifications, we find that despite big differences in discount rates (10.3% v.s. 2.2% under high and low risk aversion, respectively), both social planners care equally little about temperature risks and do not consider early or significant abatement efforts worthwhile. That is, in a power-utility economy, whether it is characterized by high or low discount rates, distant temperature risks are not considered a pressing issue and, consequently, current carbon emissions carry an almost zero marginal price. This evidence demonstrates that the optimal response to climate-change risks is not simply a matter of discounting but rather of temporal characteristics of climate risks and risk preferences.

What accounts for differences in optimal climate policies and welfare implications is the elasticity of discount rates and utility to carbon emissions. Hansen and Scheinkman (2012), and Borovička and Hansen (2014) provide a rigorous analysis of cash-flow and price elasticities. We illustrate them graphically in Figure 9. Consider a one-percent increase in carbon emissions at time 0. The additional amount of emissions leads to marginally higher temperature and, hence, a higher probability and a larger size of disasters in the future. Panel (a) of Figure 9 shows the percentage increase in annual expected damages due to the increase in current emissions. This is the negative cash-flow effect of the additional unit of emissions, which is invariant to preferences. The discount-rate effect and therefore wealth implications are preference-dependent. As shown in Panel (b), under KPEZW-preferences, an increase in current emissions leads to an increase in risk premia and a fall in asset prices. In particular, the current wealth to consumption ratio of KPEZW-agents declines by 0.003% and their utility decreases by 0.009%. In contrast, in the CRRA-highRA economy, discount rates fall significantly in response to higher emissions due to a fall in the risk-free rates. The negative discount-rate effect dominates the negative cash-flow effect resulting in an increase in current prices. That is, under power utility, the wealth to consumption ratio is actually higher if disaster losses are expected to be bigger. The power-utility agents are still worse off since their utility is inversely related to wealth, but because both the elasticity of wealth to emissions and the elasticity of utility to wealth are quite low, the decline in utility is very tiny, more than three orders of magnitude smaller than the corresponding decline under recursive preferences. As the figure also shows, the elasticity of discount rates and, consequently, utility in the case of power utility with low risk aversion is virtually zero. To summarize, with preferences for early resolution of uncertainty, the planner is wary of risks that are going to be realized in the distant future and does not disregard them as easily as the power-utility planners. Consequently, the life-time utility of KPEZW-agents is more sensitive to emissions compared with power-utility preferences, which is reflected in the higher social cost of carbon.

3.3 Temperature Risks and Equity Prices

Using data from global and US capital markets, Bansal, Kiku, and Ochoa (2016) show that temperature risks, particularly, low-frequency temperature risks have a significantly negative impact on equity valuations. Quantitatively, in the data, a one degree Celsius increase in temperature leads to about -5% decline in equity valuations. They also show that the negative impact of temperature on equity valuations has been rising over time. In Table V we report the model-implied response of the price to consumption ratio to temperature risks under various specifications of preferences and time-series dynamics. For each specification that we discussed above, we simulate 50,000 paths of emissions, temperature and consumption and solve for the price of the consumption claim. Then, using the regression specification of Bansal, Kiku, and Ochoa (2016), we regress the log of the price-consumption ratio (valuation ratio) on temperature controlling for the relevant state variables. Note that in our model, all temperature fluctuations reflect long-run temperature risks because our model abstracts from any short-run weather-type variations. Hence, our model-based estimates measure elasticities of consumption claim prices to long-run temperature risks.

As the table shows, under recursive preferences, valuations fall in response to an increase in temperature. In particular, in out baseline LRR-T model, a one degree Celsius increase in temperature lowers the price of the consumption claim by about 1.74%. While this magnitude seems lower than the empirical estimates, it is important to recognize that inside the model we consider the consumption-paying asset whereas the data estimates are based on market equity. If we account for market leverage of about 3, the response of equity prices to temperature shocks implied by our LRR-T specification would be around -5.2%, which is fairly similar to the empirical estimates. Also, consistent with the empirical evidence in Bansal, Kiku, and Ochoa (2016), the model-implied sensitivity of asset prices to temperature risks increases as the economy approaches the disaster threshold. In particular, ten and twenty years from now, the price response rises in magnitude from the current -0.0174 to -0.019 and -0.021, respectively.

The power-utility implied response of prices to permanent temperature risks is very different compared with recursive preferences. As Table V shows, in the power-utility case, asset prices rise with temperature. This is the discount-rate or, more precisely, the risk-free rate effect that we discussed above. In the power-utility setting, an increase in temperature leads to a decline in discount rates due to a significant decline in risk-free rates and this effect dominates the negative cash-flow effect of temperature. Consequently, the wealth of the agent and the price of the consumption claim increase. For example, under CRRA-highRA utility, the valuation of a levered claim on consumption increases by about 0.045% in response to a one degree Celsius increase in temperature. This evidence speaks strongly against power utility specification as it fails to match a robustly negative elasticity of asset prices to temperature risks documented in the data.

4 Conclusion

To study the potential impact of climate change, we propose a long-run risks model with temperature-induced natural disasters that are expected to affect future economic growth and risk. Our model simultaneously matches the projected temperature path, consumption growth dynamics, discount rates provided by risk-free and equity market returns, and the negative temperature elasticity of equity prices documented in the data. We use the calibrated model to compute the social cost of carbon and to solve for the optimal policy response to risks imposed by global warming. We find that concerns for the long run represented by preferences for early resolution of uncertainty and long-run impact of temperature on economic growth yield a significant SCC and a considerable utility loss and, therefore, call for an immediate and sustained reduction in carbon emissions.

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Table I

Calibration of Global Warming

Parameter	Description	Value
Climate Dynamics		
$\bar{\nu}$	Atmospheric retention of carbon	0.962
χ	Temperature sensitivity to emissions	0.0045
Natural Disasters		
T^*	Tipping point	2.0°C
ℓ_0	Disaster intensity parameters	0.0050
ℓ_1	Disaster intensity parameters	0.0033
q_1	Damage function parameter	0.0011
q_2	Damage function parameter	0.0011

Table I presents calibration of global warming under the business-as-usual scenario. The parameter values are annualized.

Table II

Calibration of Preferences and Consumption Dynamics

	LRR-T Model	**Alternative Specifications**		
		KPEZW-Preferences	CRRA-highRA	CRRA-lowRA
Preferences				
β	0.99	0.99	0.99	0.99
γ	5	5	5	0.67
ψ	1.5	1.5	0.2	1.5
Consumption				
μ	0.018	0.018	0.018	0.018
σ	0.016	0.016	0.016	0.016
ρ_x	0.96			
φ_x	0.25			
ϕ_x	0.05			

Table II presents calibration of preferences and consumption dynamics under the business-as-usual scenario. Our LRR-T model features preference for early resolution of uncertainty and incorporates a negative impact of global warming on consumption level and expected consumption growth. Under Alternative Specifications, the conditional mean of consumption growth is constant and climate change is assumed to only affect the level of consumption. We consider three specifications of preferences under the alternative dynamics: preferences for early resolution of uncertainty (KPEZW-Preferences), power utility with high degree of risk aversion (CRRA-highRA) and power utility with low level of risk aversion (CRRA-lowRA). Empty entries in the table correspond to zeros. The parameter values are annualized.

Table III
Social Cost of Carbon

	BAU	Optimal
LRR-T Model	103.6	4.32
Alternatives:		
KPEZW-Preferences	39.01	1.18
CRRA-highRA	0.01	0.01
CRRA-lowRA	0.00	0.00

Table III reports the social cost of carbon in the business-as-usual (BAU) scenario and under the optimal abatement policy (Optimal) in the LRR-T Model that features the long-run risk component and preferences for early resolution of uncertainty, and alternative specifications with constant expected growth and three types of risk preferences: preferences for early resolution of uncertainty (KPEZW-Preferences), power utility with high degree of risk aversion (CRRA-highRA) and power utility with low level of risk aversion (CRRA-lowRA). The social cost of carbon is measured in 2012 dollars of world consumption per metric ton of carbon.

Table IV

Asset Pricing Implications under BAU scenario

	LRR-T	**Alternative Specifications**		
	Model	KPEZW-Preferences	CRRA-highRA	CRRA-lowRA
Risk-Free Rate	0.91	2.11	10.08	2.22
Risk Premia	1.70	0.16	0.17	0.02
Discount Rates:				
10yr Strip	1.51	2.28	10.33	2.24
100yr Strip	2.41	2.29	10.31	2.24

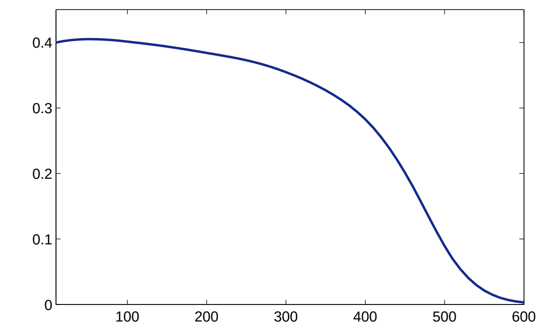
Table IV presents asset pricing implications of the LRR-T Model that features the long-run risk component and preferences for early resolution of uncertainty, and alternative specifications with constant expected growth and three types of risk preferences: preferences for early resolution of uncertainty (KPEZW-Preferences), power utility with high degree of risk aversion (CRRA-highRA) and power utility with low level of risk aversion (CRRA-lowRA). The moments are computed under the business-as-usual scenario. The table reports the risk-free rate and risk premia on consumption claim averaged over the transitional path, and discount rates on consumption strips with 10- and 100-year maturities. Returns and premia are expressed in annualized percentage terms.

Table V

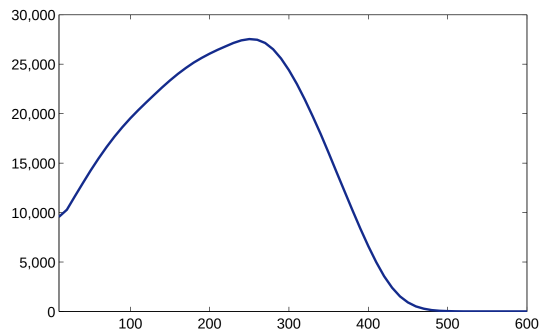
Model-Implied Price Response to Temperature Risks

	Response
LRR-T Model	-0.0174
Alternatives:	
KPEZW-Preferences	-0.0063
CRRA-highRA	0.0002
CRRA-lowRA	0.0000

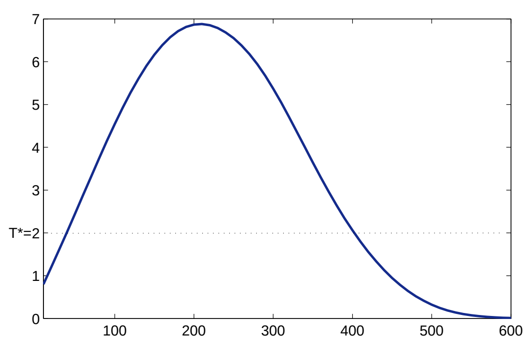
Table V reports the response of the price-consumption ratio to temperature risks for the LRR-T model that features the long-run risk component and preferences for early resolution of uncertainty, and alternative specifications with constant expected growth and three types of risk preferences: preferences for early resolution of uncertainty (KPEZW-Preferences), power utility with high degree of risk aversion (CRRA-highRA) and power utility with low level of risk aversion (CRRA-lowRA). For each specification, we simulate the data and compute the model-implied response by regressing the price-consumption ratio on temperature controlling for the relevant state variables. The simulated data consist of 50,000 draws.



(a) Carbon Intensity



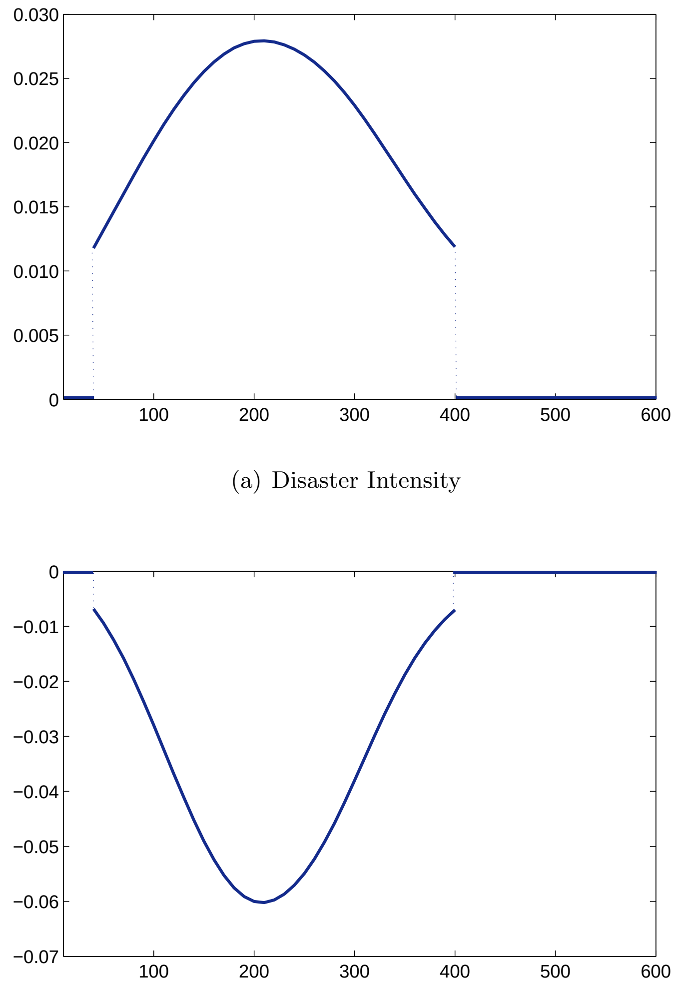
(b) Expected Path of Carbon Emissions



(c) Expected Path of Temperature Anomaly

Figure 1. Dynamics under the BAU Scenario

Figure 1 illustrates the business-as-usual scenario. Panel (a) shows the evolution of carbon intensity; Panel (b) presents the projected path of carbon emissions; Panel (c) shows the projected path of temperature anomaly (temperature relative to its pre-industrial level). Emissions are measured in millions of metric ton of carbon per annum, and temperature is in degrees Celsius. The dotted line in Panel (c) represents the tipping point of global warming. The horizontal axis is the time-line measured in years from today.

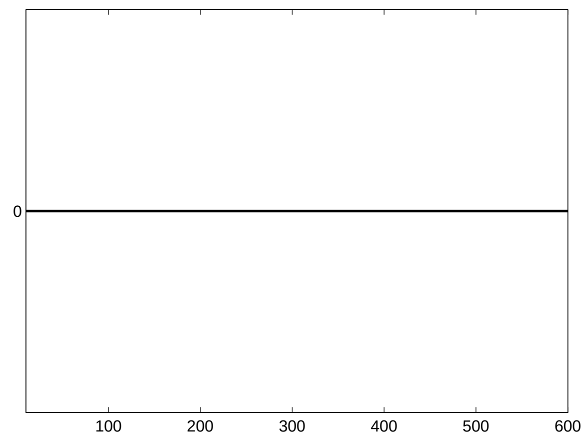


(a) Disaster Intensity

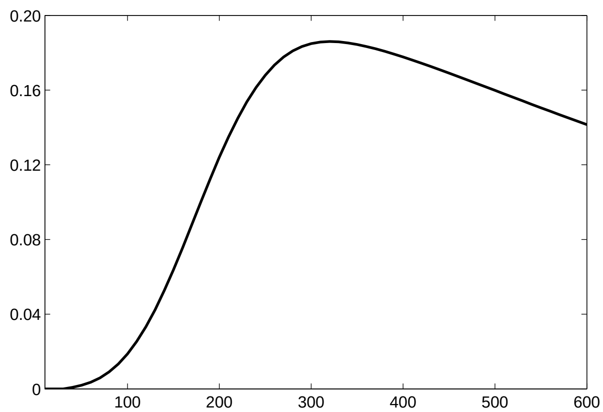
(b) Disaster Size

Figure 2. Global Warming Disasters under the BAU policy

Figure 2 shows the consequences of global warming in the business-as-usual case. Panel (a) plots the expected intensity of climate change disasters per annum; Panel (b) shows the average annual size of disasters ($-d_t$). The horizontal axis is the time-line measured in years from today.



(a) Change in Mean



(b) Change in Volatility

Figure 3. Change in Ex-Ante Consumption Moments due to Disasters

Figure 3 shows the change in the conditional mean and volatility of future consumption due to global-warming disasters. Panel (a) plots the difference between ex-ante mean of cumulative log consumption growth under the business-as-usual scenario and the conditional mean absent temperature disasters. Panel (b) presents the corresponding difference in volatility of cumulative consumption growth. Volatility is annualized and expressed in percentage terms. The horizontal axis is the time-line measured in years from today.

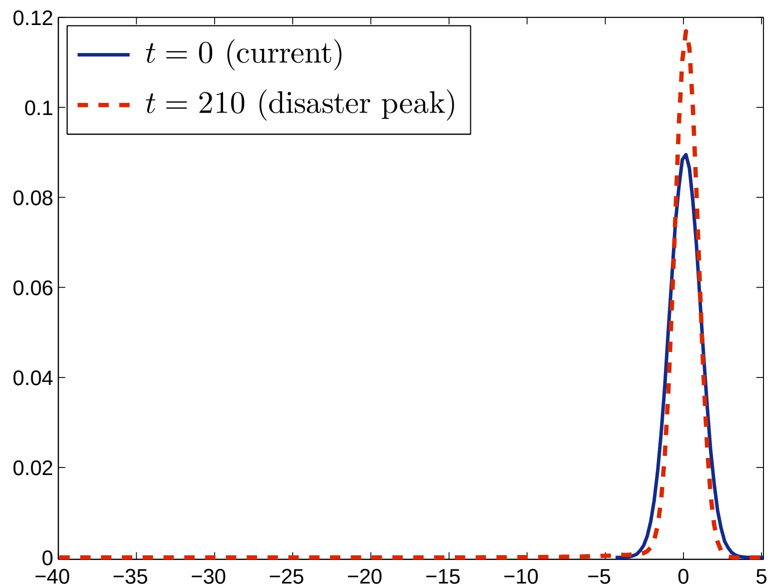
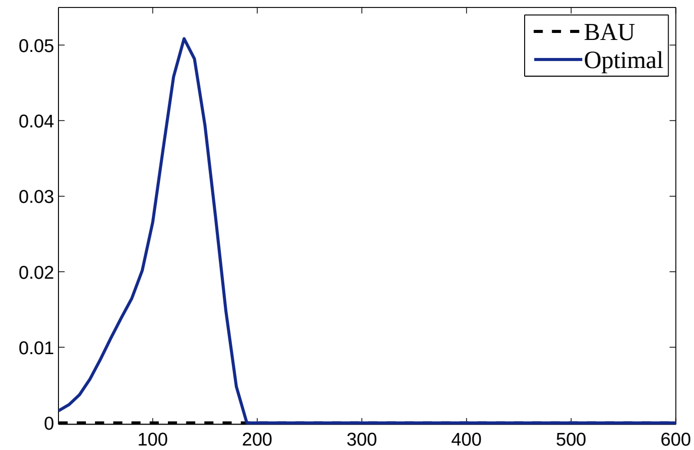
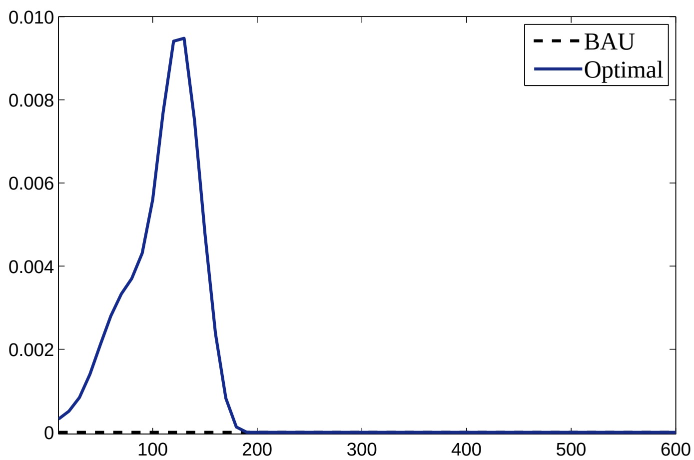


Figure 4. Distribution of Consumption Growth

Figure 4 shows the implications of global-warming disasters for consumption growth. The plot presents the distribution of normalized consumption growth at time-0 (when disasters are absent) and 210 years from now (at the peak of global-warming disasters).



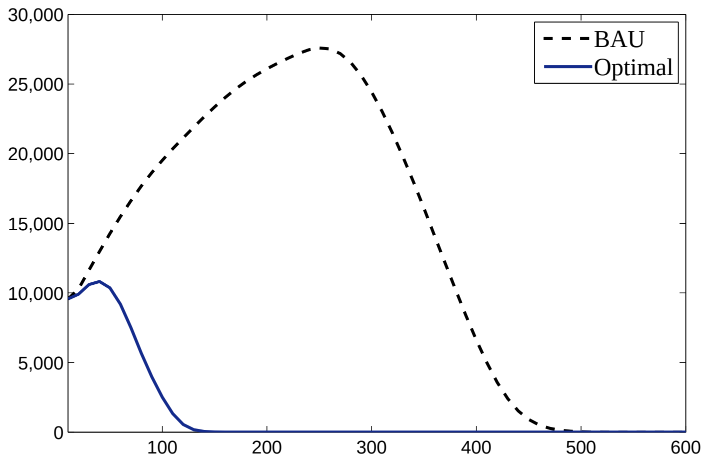
(a) Abatement Effort



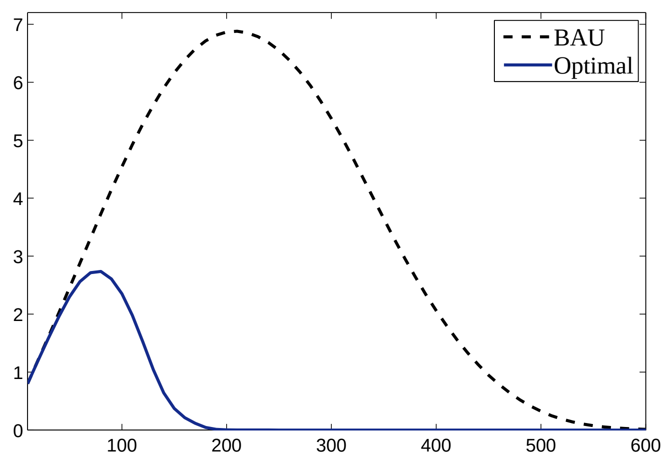
(b) Abatement Cost

Figure 5. Optimal Abatement Policy

Figure 5 shows the optimal abatement policy in the LRR-T model that features long-run risks and preferences for early resolution of uncertainty. Panel (a) presents the optimal abatement effort, Panel (b) shows the cost of optimal policy. Abatement effort represents the reduction in carbon intensity, cost is expressed as a fraction of consumption goods. The horizontal axis is the time-line measured in years from today.



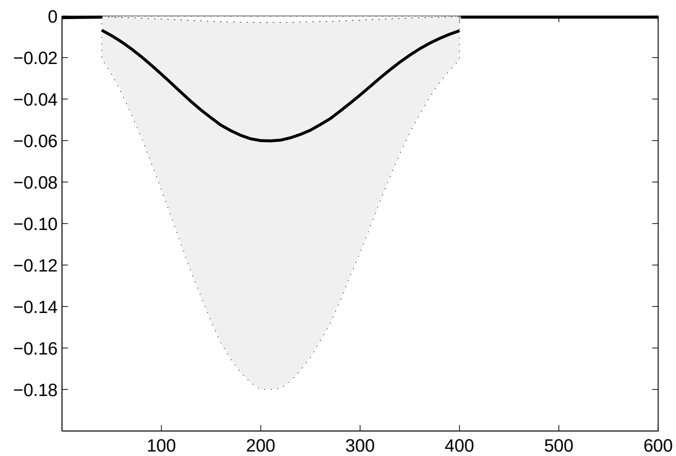
(a) Emissions



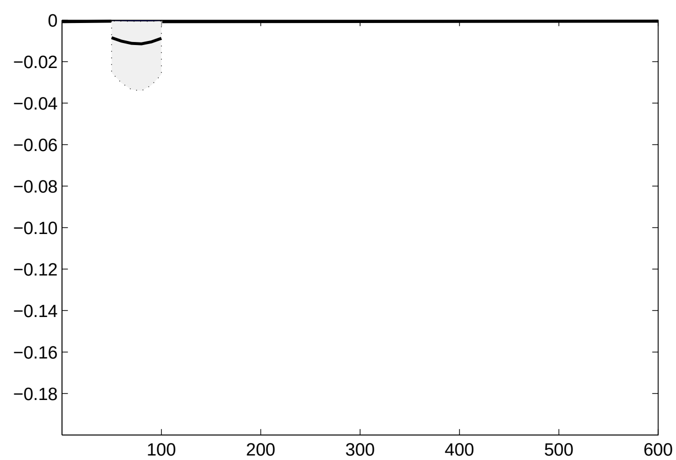
(b) Temperature

Figure 6. Implications of Optimal Abatement Policies

Figure 6 shows the implications of the optimal abatement policy in the LRR-T model that features long-run risks and preferences for early resolution of uncertainty. Panel (a) presents the optimal level of carbon emissions, Panel (b) shows the implied evolution of temperature. Emissions are measured in millions of metric ton of carbon per annum, and temperature is in degrees Celsius. The horizontal axis is the time-line measured in years from today.



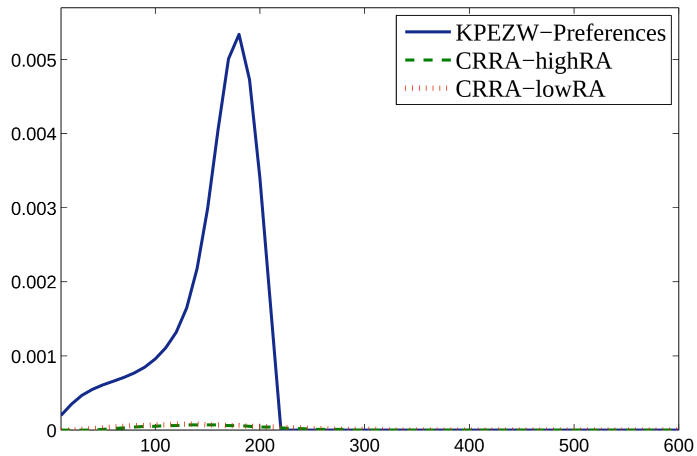
(a) BAU Scenario



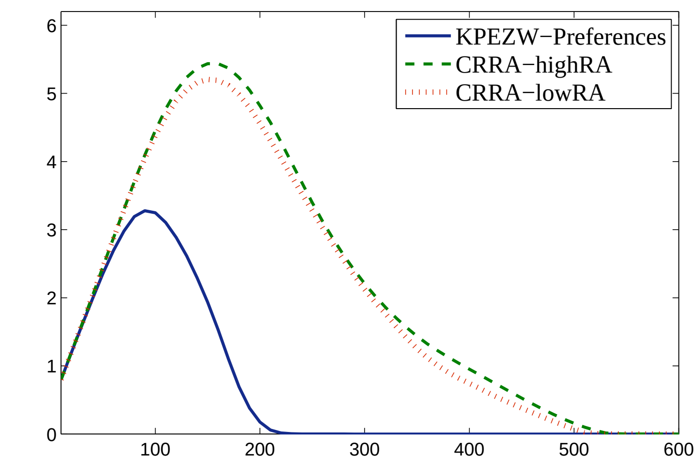
(b) Optimal Policy

Figure 7. Distribution of Disaster Size

Figure 7 shows the benefits of the optimal abatement policy in the LRR-T model that features long-run risks and preferences for early resolution of uncertainty. Panel (a) shows the distribution of disaster size in the business-as-usual scenario; Panel (b) present the corresponding distribution under the optimal climate policy. The thick line is the average disaster size and the shaded area represents the 5–95 percentile band. The horizontal axis is the time-line measured in years from today.



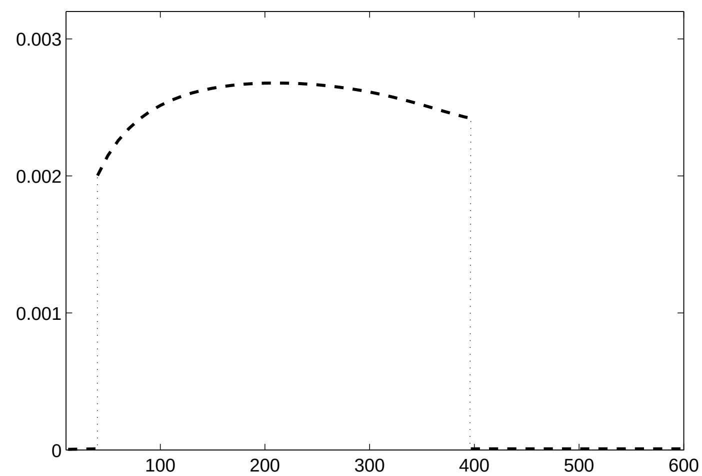
(a) Abatement Cost



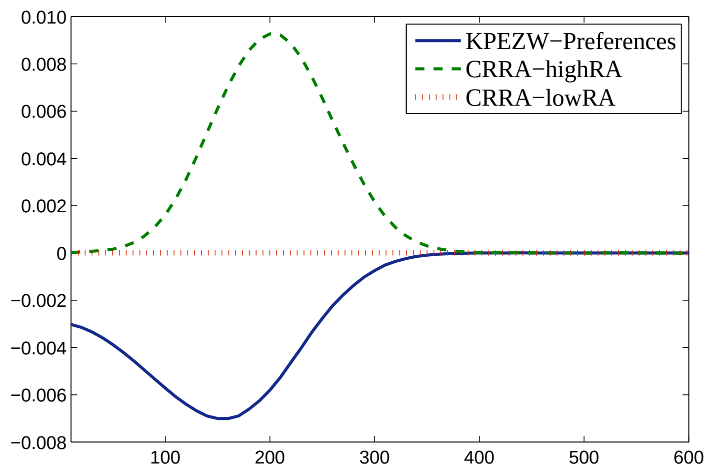
(b) Temperature

Figure 8. Policy Decisions under Alternative Specifications

Figure 8 shows the cost of the optimal abatement policy (Panel (a)) and the implied temperature path (Panel (b)) under three alternative specifications of risk preferences. Time-series dynamics of consumption and climate impact across the three specifications are kept the same: consumption is assumed to follow a random walk subject to climate-induced disasters. The cost is expressed as a fraction of consumption and temperature is in degrees Celsius. The horizontal axis is the time-line measured in years from today.



(a) Sensitivity of Damages



(b) Sensitivity of Wealth-Consumption Ratio

Figure 9. Sensitivity to Emissions

Figure 9 shows the impact of an increase in current emissions on future damages and the wealth-consumption ratio. Panel (a) shows the percentage increase in annual expected damages if time-0 emissions are raised by 1%, Panel (b) presents the corresponding elasticity of the wealth-consumption ratio. Both panels are constructed under the business-as-usual scenario for three alternative specifications of preferences. The horizontal axis is the time-line measured in years from today.