Climate Change and Growth Risks

Ravi Bansal, Dana Kiku and Marcelo Ochoa*

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Abstract

We use the forward looking information from global equity markets to estimate the elasticity of equity prices to temperature fluctuations and find that global warming has a significant negative effect on asset valuations. We also find that the negative elasticity of prices is increasing with time/sample span, suggesting that the impact of climate change has been rising over time. We use our empirical work to calibrate a long-run risks model with temperature-induced disasters that affect future output. The model simultaneously matches the observed temperature and consumption growth dynamics, discount rates provided by risk-free and equity market returns, and the estimated temperature elasticity of asset prices. We use the calibrated model to compute the social cost of carbon (SSC). We find that a preference for early resolution of uncertainty and long-run impact of temperature on growth rates are important to justify action to abate climate change and a sizable SSC.

*Ravi Bansal is affiliated with the Fuqua School of Business at Duke University and NBER, Dana Kiku is at the University of Illinois at Urbana-Champaign, and Marcelo Ochoa is at the Federal Reserve Board. The analysis and conclusions set forth are those of the authors and do not indicate concurrence by other members of the research staff or the Board of Governors.
Introduction

Global warming and its potential impact on the macro-economy is a matter of considerable importance. This article makes a contribution towards understanding the interactions between rising temperature, growth and risk. To study the potential impact of climate change on the macro-economy, we present a long-run risks (LRR) model that jointly models the path of temperature, consumption, and temperature induced damages to output. We use our model to quantify the social cost of carbon and the willingness-to-pay to abate climate change. To measure the impact of global warming on the economy and to provide guidance in calibrating our model we use data from global capital markets to estimate the temperature elasticity of forward-looking equity prices. We find that this elasticity is negative and statistically significant. Our evidence underscores the important interaction between temperature, economic growth and risk that determines equity prices.

Key ingredients in the LRR model of Bansal and Yaron (2004) are 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. Our temperature augmented LRR model, which we refer to as LRR-T model, incorporates temperature-induced disasters that affect income and expected growth. These catastrophic disasters are triggered only when temperature breaches a trigger point and capture the idea of tail risk related to global warming as discussed in Pindyck (2012). The planner chooses the amount of resources to spend to abate a prospective increase in temperature and thus limit future disasters – this is the dynamic trade-off the planner faces. Our setup allows for both the level and growth of income to be damaged by increases in temperature.\(^1\) Our LRR-T model provides a framework, in which temperature impacts the aggregate wealth-to-consumption ratio (and valuations of long-lived assets) through both expected growth and discount rate channels. In terms of specific implications of our model, we show that even a rise in temperature in the distant future lowers current wealth-to-consumption ratio, and temperature variation carries a positive risk premium in the economy. In contrast, in the case of power utility with risk-aversion larger than one, the risk premium for temperature risk is negative, as in states in which temperature raises the aggregate wealth also rises while consumption falls. This underscores the importance of the LRR-T model setup to evaluate temperature related

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\(^1\)These effects are also featured in Pindyck (2012), where temperature is assumed to negatively impact the growth rate of GDP, and Nordhaus (2008), where temperature negatively affects TFP.
risks.\footnote{We focus on the exchange economy to maintain tractability regarding the consumption dynamics and ensure that we match assets markets data. This is quantitatively difficult to manage in a production-based setting.} The LRR-T model implications for long-lived assets such as equities motivate the empirical work we conduct in the paper.

A significant issue in the literature on economics of climate change is the uncertainty related to the magnitudes of key inputs (e.g., disaster size and its intensity) — see Pindyck (2007) for a detailed discussion of this issue. Micro evidence by Tol (2002a, 2002b) provides some guidance regarding temperature-induced damages, but there is no clear historical evidence pertaining to the tail risks of climate change and the induced catastrophic losses. The negative effects of rising temperature on growth and risk are likely to be more pronounced in the future and are therefore difficult to measure in historical output data. Capital markets provide us with forward-looking equity prices which discount future economic growth – if temperature does have measurable growth or risk related discount-rate effects it should also have measurable impact on current equity valuations. We pursue this idea and use equity and temperature data from 39 countries to measure the temperature elasticity of current equity valuation. We find that after controlling for global growth and discount-rate effects local temperature has a significant negative impact on equity valuations – that is, higher temperature lowers valuation ratios. The estimated semi-elasticity is -3.6\%, that is, a 1 Celsius rise in temperature leads to a 3.6\% decline in valuations. Interestingly, we find that this elasticity is becoming more negative over time – it begins with -2.2\% for the 1970-1990 period and rises to -3.6\% over the entire sample till now. This is important as this indicates that in the period over which global temperature has risen its impact on growth and/or risk has also increased. We also document that low-frequency movements in temperature are mostly responsible for these negative effects. Earlier work by Dell, Jones, and Olken (2012) reports weak and mixed evidence of temperature effects on GDP growth rates. In contrast we focus on forward-looking equity valuations that capture both long-term expected growth and risk effects, which the annual GDP growth rate measure does not provide. Our estimate of the temperature elasticity of equity valuation and data on discount rates from capital markets provide important guidance to calibrate our model.

Our LRR-T model calibration matches the climate and consumption dynamics, measures of temperature elasticity of equity valuations and historical discount rates from capital markets. This is important, as the magnitude of willingness-to-pay and the social cost of carbon (SSC) as highlighted in Nordhaus (2008) and Gollier (2012) are quite sensitive to discount rates. We find that that the
incentive to abate global warming and the timing of abatement efforts critically depend on the attitude towards risk. With preferences for early resolution of uncertainty (as in Kreps and Porteus (1978), and Epstein and Zin (1989)), the social planner opts for an immediate and a relatively stringent abatement policy that allows to avert large disasters in the future. When the social planner is indifferent towards the timing of resolution of uncertainty, as in the case of power utility, in both high and low discount-rate settings, there is very little willingness to currently abate climate change. The planner postpones abatement for nearly 50 years and lets the economy to be exposed to sizable losses. In essence, a preference for early resolution of uncertainty is important to motivate early and significant abatement.

A key output of our model calibration is the 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. Our estimates of the social cost of carbon are sizable when the planner has a preference for early resolution of uncertainty. In our LRR-T model, we find that SCC is about 100 dollars; it falls to 42 dollars when temperature affects the level of output but not the long-term growth. In the case of power utility, SCC is very small, under 2 cents, since long-term climate change is not viewed as sufficiently risky.

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 for asset markets. In Section 4, we examine the impact of long-run temperature fluctuations on equity prices in the data. Section 5 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 impact on ecological systems and human society (IPCC (2007, 2013)).

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:

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

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

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

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

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. In particular, we assume that global temperature relative to its pre-industrial level follows:

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

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

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3While 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.

4Nordhaus (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).
of persistence of temperature variations, and \( \chi > 0 \) is temperature sensitivity to CO\(_2\) emissions.\(^5\) 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 the concentration. These dynamics are also consistent with the conclusions of the Fifth Assessment Report of the IPCC that establishes an unequivocal link between the increase in the atmospheric concentration of greenhouse gases 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 catastrophic natural disasters that result in a significant reduction of economic growth. The probability of natural disasters and the loss function are described next.

### 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 \( \Delta y_t \equiv \log Y_t \) is given by:

\[
\begin{align*}
\Delta y_{t+1} &= \mu + x_t + \sigma \eta_{t+1} - D_{t+1}, \\
x_{t+1} &= \rho x_t + \varphi x_t \sigma \epsilon_{t+1} - \phi_x D_{t+1},
\end{align*}
\]

where \( \mu \) is the unconditional mean of gross consumption growth; \( x_t \) is the expected growth component; \( \eta_{t+1} \) and \( \epsilon_{t+1} \) 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. Note that in our specification climate-change disasters affect current and future expected consumption growth and, therefore, have a permanent effect on the economy.

Note that we focus on catastrophic consequences of climate change that might not be possible

\(^5\) We assume that \( \nu_t \) 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 absorption 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 absorption of carbon by warmer oceans, etc.
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 level of output as is typically assumed in 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 is the standard in the climate-change literature (eg., Nordhaus (2010), Weitzman (2010), Anthoff and Tol (2012), Pindyck (2012)).

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

\[
D_{t+1} = \sum_{i=1}^{N_{t+1}} \zeta_{i,t+1} - d_t \pi_t, \quad (6)
\]

where \(N_{t+1}\) is a Poisson random variable with time-varying intensity \(\pi_t\), 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:

\[
d_t = \begin{cases} 
q_1 T_t + q_2 T_t^2, & \text{if } T_t \geq T^*
\end{cases}
\]

\[
l_0 + l_1 T_t, & \text{if } T_t \geq T^* 
\end{cases}
\]

and disaster intensity follows:

\[
\pi_t \equiv \mathbb{E}_t[N_{t+1}] = \begin{cases} 
l_0 + l_1 T_t, & \text{if } T_t \geq T^*
0, & \text{otherwise}
\end{cases}
\]

(8)

Quadratic loss functions are commonly used in the climate-change literature, e.g., Nordhaus (2008),

\(^6\)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).

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

$$E_t^* = Y_t^{\lambda_t^*}, \quad (9)$$
$$\Delta \lambda_t^* = \Delta \lambda_t - \theta_t, \quad (10)$$

where $E_t^*$ and $\lambda_t^*$ are CO$_2$ emissions and carbon intensity under a chosen abatement policy, respectively; $\lambda_t$ 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 $\theta_t$ if the social planner decides to act. Higher values of $\theta_t$ 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 ($\theta_t$):

$$\Lambda_t = \xi_t \theta_t^k, \quad (11)$$

where $k > 0$ (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:

\[
C_t = Y_t(1 - \Lambda_t),
\]

(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:

\[
\Delta c_{t+1} = \mu - \Delta \Lambda_{t+1} + x_t + \sigma \eta_{t+1} - \phi c D_{t+1}.
\]

(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 Epstein and Zin (1989), and Weil (1990). We use \( U_t \) to denote the continuation utility at time \( t \), which is given by:

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

(14)

where \( \delta \) is the time-discount rate, \( \gamma \) is the coefficient of risk aversion, and \( \psi \) is the intertemporal elasticity of substitution (IES). When \( \gamma = \frac{1}{\psi} \), then 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.

1.6 Dynamic Optimization Problem

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

$$U_t(S_t) = \max_{\theta_t, C_t} \left\{ \left(1 - \delta\right)C_t^{1 - \frac{1}{\gamma}} + \delta \left( E_t \left[ U_{t+1}(S_{t+1}) \right] \right)^{1 - \frac{1}{\gamma}} \right\}^{\frac{1}{1 - \frac{1}{\gamma}}}, \quad (15)$$

subject to

$$C_{t+1} = Y_{t+1}(1 - \Lambda_{t+1}), \quad (16)$$

and

$$S_{t+1} = F(S_t, \theta_t). \quad (17)$$

Utility maximization is subject to two constraints: the resource allocation constraint in equation (16), and the state dynamics in equation (17), where $F(\cdot, \cdot)$ summarizes the transitional dynamics of the state vector under the chosen policy.

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 the infinite future. In particular,

$$U_t = \left[ (1 - \delta)Z_t \right]^{\frac{\gamma}{1 - \gamma}} C_t, \quad (18)$$

and

$$Z_t = E_t \left[ \sum_{j=0}^{\infty} \frac{C_{t+j}/C_t}{R_{j,t+j}} \right], \quad (19)$$

where $R_{j,t+j}$ is the discount rate of the consumption strip with $j$-time to maturity. As prices are forward-looking, the current price of a consumption claim (and that of market equity) carries information about climate risks that are expected to unfold in the future and agents’ preferences towards such long-run risks. Note that any current and future expected abatement costs are also reflected in the current level of wealth and prices.
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 (15)) are computed via simulations. Notice that the optimal abatement policy that we derive is dynamically consistent, thus, future abatement decisions will comply with the rule 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:

$$\text{SCC}_t = \frac{\partial U_t}{\partial E_t} / \frac{\partial U_t}{\partial C_t}$$  \quad (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 (18), we can express the social cost of carbon at time 0 as:

$$\text{SCC}_0 = \frac{\psi}{\psi - 1} \frac{\partial Z_0}{\partial E_0} C_0.$$  \quad (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 Calibrating the BAU Scenario

We calibrate the path of carbon intensity ($\lambda_t$) 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
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 CO₂ 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. To capture re-enforcing feedback effects of emissions, we allow the retention of carbon in the atmosphere, νt, to increase in carbon intensity. We assume that about 80% of current CO₂ 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 CO₂ 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 (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

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7To facilitate interpretation of the calibrated parameters, we report and discuss them in annualized terms.

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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 $2^\circ$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 model features preferences for early resolution of uncertainty and incorporates a negative effect of global warming on current and future consumption growth. We chose 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.

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 current 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 “EZ-Preferences”, (2) power utility with high degree of risk aversion – “CRRA-highRA”, and (3) power utility with low risk aversion – “CRRA-lowRA”. In the EZ-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 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 $\xi_0$ 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 focus on. 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 each with empirical evidence on the effect of temperature on equity prices and financial market data.

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 ($\theta_t$) and its cost ($\Lambda_t$) are presented in Figure 3. Figure 4 illustrates the policy implications for carbon emissions and temperature. Recall that earlier abatement efforts are valuable as they yield long-term benefits, i.e., earlier development and adoption of carbon-free technologies implies a progressive increase in emission reductions over time.

Panel (a) of Figure 4 shows that industrial carbon emissions under the optimal policy are expected to decline by about 11% and 53% in 50 and 100 years from now, respectively, and essentially disappear by 2200. It is optimal to give up about 0.05% of the current output and up to 0.9% 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 2.5°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 5 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 and 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 5 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 the 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 10%. 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 IV, under the business-as-usual scenario, SCC is estimated at about $100 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 their model and, therefore, is consistent with financial market data. As Table III shows, the average risk-free rate in the LRR-T specification is 1.2%, and the risk premium on consumption claim is about 1.4%. Hence, the implied equity premium, assuming leverage of around 2–3, is about 3–4.5% 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 driven by temperature risks. In particular, only about 0.3% of risk premia comes as a compensation for disaster 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 6 plots the optimal level of abatement effort and the implied path of temperature for each alternative specification. Consider first the economy with EZ-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 case, 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 6 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. That is, 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 EZ-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 4.8°C and 5.5°C in the low- and high-RA cases, respectively, 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 IV 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 EZ-preferences is a significant 4.4%, whereas it is
only 0.3% and 0.1% 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 most of the attention by itself is not sufficient for understanding welfare implications of climate-change risks. To illustrate the point, we refer to Table III that presents asset pricing implications of the alternative specifications. First, compare the implications of EZ-preferences and power utility with the low degree of risk aversion. Because the intertemporal elasticity of substitution is the same, the level of 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 EZ-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 EZ-preferences. Yet, among the two, it is the planner with EZ-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 will 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 (2013) provide a rigorous analysis of cash-flow and price elasticities. We illustrate them graphically in Figure 7. 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 7 shows the percentage
change in annual expected damages due to the increase in current emissions. This is the cash-flow
effect of the additional unit of emissions, which is invariant to preferences. The discount rate effect,
presented in Panel (b), does depend on risk preferences. As the figure shows, due to an increase
in risk premia, discount rates under EZ-preferences respond positively to the increase in current
emissions. Both effects lead to a fall in asset prices and a decline in utility. In particular, the
wealth to consumption ratio and utility of EZ-agents in this case decline by 0.006% and 0.017%
respectively. In contrast, in the case of power-utility with high risk aversion, discount rates fall in
response to higher emissions and this decline dominates the negative cash-flow effect resulting in
an increase in current prices. That is, in the CRRA-highRA economy, the wealth to consumption
ratio is higher the larger the expected losses are. 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
EZ-agents is more sensitive to emissions compared with power-utility preferences, which is reflected
in the higher social cost of carbon.

4 Temperature Risks and Asset Prices

Our model captures the idea that increasing temperature has negative consequences for the macro-
economy; it lowers growth and raises macro-economic risk. Further, with a preference for early
resolution of uncertainty, higher temperature lowers wealth-to-consumption ratio and raises risk
premia. Empirical research on the effects of rising temperature on the macroeconomy have primarily
focused on the effects of temperature on growth and found weak evidence in support of this channel
— see for example, Dell, Jones, and Olken (2012). The temperature effect on risk channel is
not much explored in earlier work. In contrast to the earlier approaches which focus on the growth
channel, we use forward-looking asset prices, which reflect both expected growth and risk fluctuations
to measure the impact of temperature on the macro-economy. The long-horizon forward looking nature of equity prices could provide sharper information about the effects of temperature on the macro-economy either through the risk or through the growth channel. To preview our findings, our empirical evidence suggests that temperature risks are likely to have a permanent negative effect on the global economy and points towards preferences for early resolution of uncertainty.

4.1 Data and Factor Structure

For the equity market data, our panel consists of 39 countries and spans the time period from 1970 and 2006. Country-level temperature data are taken from Dell, Jones, and Olken (2012), the price-dividend data come from the Global Financial Data and provide a market proxy for the wealth-to-consumption ratio for each country. Country-specific macro data (such as per-capita GDP growth, inflation, unemployment, interest rates) are taken from the World Bank database. To control for income-heterogeneity, we also consider dividing countries into three income groups (lower middle, upper middle and high income) according to the World Bank income classification, and nine geographical regions. The list of 39 countries is provided in Table X and is the most exhaustive list of reliable cross country equity market data we could find. By its very nature this data is tilted towards developed economies as they are more likely to have a history of equity markets. In our sample, 35 out of 39 countries have experienced a significant increase in temperature over the sample period. Figure 8 shows the histogram of the trend in local temperature defined by the difference in average temperature over the 2002-2006 period and the five-year average at the beginning of the sample (1970-1974). The median long-run change in temperature across countries is 0.65°C, and as the figure shows only three countries of this set of 39 counties experienced a decline in temperature over the sample period.

In terms of the factor structure for equity price-dividend ratios, we find a strong low dimensional factor structure. The first principal component explains 69% of the variation across the 39 countries and the second 9.95%. This indicates that most of the cross-country variation in the equity valuation is dominated by common global macro-economic factors. We use these two dominant factors to control for global macro-factors that influence equity prices beyond any local climate-related factors.

8Due to the unavailability of asset price data, our sample does not include countries in the low income category. The nine regions represent East Asia and Pacific, East Europe and Central Asia, Latin America and Caribbean, Middle East and North Africa, South Asia, Sub-Saharan Africa, North America, Western Europe, and Australasia.
4.2 Impact of Temperature on Equity Valuations

To estimate the effect of temperature risks on asset prices, we run the following panel regression:

\[ v_{i,t} = \bar{b}_i + \phi T_{i,t} + b_0 v_{i,t-1} + b_1 PC_{1,t} + b_2 PC_{2,t} + \varepsilon_{i,t} \]  

(22)

where \( v_{i,t} \) is the log of the equity price to dividend ratio of country \( i \) at date \( t \), \( \bar{b}_i \) is the country-specific fixed effect, \( T_{i,t} \) is local temperature, and \( PC_{1,t} \) and \( PC_{2,t} \) are the first two principal components extracted from the cross-section of price-dividend ratios. Our focus is on parameter \( \phi \) that measures sensitivity of asset prices to temperature variations. The set of controls is chosen to capture the effect of global risks on asset prices. As asset prices are affected by channels that are distinct from temperature, we estimate the common global components affecting equity valuations by using the first two principal components extracted from the cross-section of price-dividend ratios. To allow these global macro risks to have differential effect across countries, we also include the interaction of the two principal components with country-income dummies. The remaining persistence in asset prices is absorbed by the lagged country-specific price-dividend ratio. The estimated response of asset prices to temperature risks, \( \hat{\phi} \), is reported in Table V. For brevity, we present and discuss the generalized least-squares estimates only; point estimates and inference based on the ordinary least-squares are very similar. Using the whole sample, we find that temperature risks have a significant negative effect on asset prices. To interpret its magnitude, note that \( \phi \) measures semi-elasticity of asset prices to temperature fluctuations. Hence, a one standard deviation increase in temperature of around 0.55°C leads to about 2% decline in price-dividend ratios. This evidence is robust to several additional controls, such as country specific inflation, real interest rate, GDP growth and unemployment, as well as global macro indicators such as the default spread, the global interest rate (nominal minus inflation) and growth. For brevity we don’t report all these details as we find none of these controls alter significantly our point point estimates on temperature.\(^9\)

One issue of interest is to explore if the effect of temperature on the economy has changed across time. This is hard to measure given the short historical samples that we observe. We use an early sample and then progressively use all the data to measure the temperature effects on

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\(^9\) In addition, we allowed for the interaction of temperature with the share of the agricultural sector as well as the distance to the equator but find them insignificant. We find that the temperature impact is stronger in lower income countries, however, because our sample contains only few lower income countries, we focus on the average effect.
equity valuations. Table VI report our findings and shows that the effect of temperature on equity valuations has risen over time. The point estimate almost doubles from −0.020 for the early 1970-1990 sample to −0.038 in the sample that also includes more recent years. This evidence suggest that as temperature rises, global warming imposes higher risks on the economy and, hence, leads to a bigger decline in wealth. Our model also captures this feature, as temperature rises the size and probability of disasters rises, leading to greater losses. Further, this evidence also underscores a measurement issue that the signals regarding the impact of temperature on macro-economy will rise with temperature, one should expect measured impacts to be smaller now and rise subsequently.

One could argue that the regression specification in equation (22) does not sharply differentiate between long run movements in temperature relative to short-term annual fluctuations. Year-to-year changes in temperature can be volatile, and only a small fraction of these annual fluctuations affects the long run temperature movements associated with global warming. To identify the effect of trend shocks, we replace the level of temperature in specification (22) with movements in temperature trend. We construct the trend by taking either a three-, five- or eight-year moving-average of temperature and identify trend shocks using an AR(1) filter. The estimates of price elasticity to low-frequency risks are reported in Table VII. In each specification, we find a negative and statistically significant response of asset prices to long-run temperature shocks. Our point estimates based on the three-, five- and eight-year moving-averages suggest that a one standard deviation increase in temperature trend lowers the price-dividend ratio by 1.2%, 1.4% and 1.9% respectively. Our results remain robust if instead of using trend shocks we measure the response of prices to three, five and eight-year changes in temperature. Similar evidence is found if we identify the temperature trend using a HP filter.

To further investigate the effect of temperature risks on prices, we estimate their joint dynamics using a first-order vector-autoregression (VAR). We continue to use the first two principal components of price-dividend ratios and their interactions with income dummies to control for global risks and incorporate regional fixed effects. Specifically, we exploit the following panel VAR specification:

$$X_{i,t} = a_{i,t} + AX_{i,t-1} + BX_t + u_{i,t}$$  \hspace{1cm} (23)

where $X_{i,t} = (T_{i,t}, v_{i,t})'$ is a vector of local temperature and price-dividend ratios, $a_{i,t}$ are regional fixed effects, and $X_t$ is the vector of global controls. Table VIII reports the VAR regression output
and Figure 9 plots the impulse response function of asset prices to a one-standard deviation shock in temperature implied by our VAR estimates. The shaded area around the estimated response represents the two standard-error band. Consistent with the evidence presented above, the VAR-based reaction of asset prices to temperature shocks is negative. While the short-run response is not statistically strong, the medium- and long-run effects of temperature are all significantly negative. Thus, an increase in the current level of temperature seems to have a permanent effect on growth and, therefore, wealth.

4.3 Evidence and Our Model

In Table IX 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 10,000 paths of emissions, temperature and future consumption and solve for the price of the consumption claim. Then, similarly to the data, we regress the log of the current price-consumption ratio (valuation ratio) on realized temperature controlling for the relevant state variables. That is, we compute the model-implied analog of \( \hat{\phi} \) that we estimated in the data using the regression specification in equation (22). As the table shows, under recursive preferences valuations fall in response to an increase in temperature, which reflects the key LRR model channel for climate change. For the the LRR-T model the magnitude of the valuations decline to a rise in temperature is similar to the data at about -1.7%.

The power-utility implied response of prices to permanent temperature risks is very different compared with recursive preferences. As Table IX shows, in the power-utility case, asset prices actually 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 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. The price-consumption ratio increases by 0.03% in response to a 0.55°C rise in temperature. This evidence speaks strongly against power utility specification as it fails to match a robustly negative elasticity of asset prices to temperature variation observed in the data.
5 Conclusion

We use the forward looking information from global equity markets to estimate the elasticity of equity prices to temperature movements and find that climate change has significant negative effect on asset valuations. We also find that this negative elasticity is increasing with time/sample size, suggesting that climate effects are increasing over time. We use our empirical work to calibrate a long-run risks model with temperature-induced natural disasters which affect output in the economy. The model simultaneously matches observed temperature and consumption growth dynamics, discount rates provided by risk-free and equity market returns, and our estimated temperature elasticity of asset prices. We use this calibrated model to compute the social cost of carbon (SSC) of insuring against distant temperature induced disasters. We find that concerns for the long run (preference for early resolution), and long run temperature-induced growth effects yield significant utility losses.
References


### Table I
Calibration of Global Warming

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
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</thead>
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<tr>
<td>( \bar{\nu} )</td>
<td>Atmospheric retention of carbon</td>
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</tr>
<tr>
<td>( \chi )</td>
<td>Temperature sensitivity to emissions</td>
<td>0.0045</td>
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#### Climate Dynamics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T^* )</td>
<td>Tipping point</td>
<td>2.0°C</td>
</tr>
<tr>
<td>( \ell_0 )</td>
<td>Disaster intensity parameters</td>
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<tr>
<td>( \ell_1 )</td>
<td>Disaster intensity parameters</td>
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<td>( q_1 )</td>
<td>Damage function parameter</td>
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<tr>
<td>( q_2 )</td>
<td>Damage function parameter</td>
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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

<table>
<thead>
<tr>
<th>LRR-T Model</th>
<th>Alternative Specifications</th>
<th>EZ-Preferences</th>
<th>CRRA-highRA</th>
<th>CRRA-lowRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preferences</td>
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<td>0.99</td>
<td>0.99</td>
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<tr>
<td>β</td>
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<td>0.99</td>
<td>0.99</td>
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<tr>
<td>γ</td>
<td></td>
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<td>5</td>
<td>5</td>
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<tr>
<td>ψ</td>
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<td>1.5</td>
<td>0.2</td>
</tr>
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<td>ψ</td>
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<tr>
<td>Consumption</td>
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<td>μ</td>
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<td>σ</td>
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<td>ρ_x</td>
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<td>0.96</td>
<td>0.016</td>
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<td>φ_x</td>
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<td>φ_x</td>
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<td>0.05</td>
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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 (EZ-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
Asset Pricing Implications under BAU scenario

<table>
<thead>
<tr>
<th></th>
<th>LRR-T Model</th>
<th>EZ-Preferences</th>
<th>CRRA-highRA</th>
<th>CRRA-lowRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk-Free Rate</td>
<td>1.22</td>
<td>2.14</td>
<td>10.07</td>
<td>2.22</td>
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<tr>
<td>Risk Premia</td>
<td>1.41</td>
<td>0.13</td>
<td>0.14</td>
<td>0.02</td>
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<tr>
<td>Discount Rates:</td>
<td></td>
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<tr>
<td>10yr Strip</td>
<td>1.68</td>
<td>2.30</td>
<td>10.29</td>
<td>2.24</td>
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<tr>
<td>100yr Strip</td>
<td>2.50</td>
<td>2.33</td>
<td>10.29</td>
<td>2.24</td>
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</table>

Table III 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. 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 IV
Social Cost of Carbon

<table>
<thead>
<tr>
<th></th>
<th>BAU</th>
<th>Optimal</th>
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<tr>
<td>LRR-T Model</td>
<td>99.10</td>
<td>3.70</td>
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<tr>
<td>Alternatives:</td>
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<tr>
<td>EZ-Preferences</td>
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<td>CRRA-highRA</td>
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<td>0.01</td>
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<tr>
<td>CRRA-lowRA</td>
<td>0.00</td>
<td>0.00</td>
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Table IV 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. The social cost of carbon is measured in 2012 dollars of world consumption per metric ton of carbon.
Table V
Equity Valuations and Temperature

<table>
<thead>
<tr>
<th>Regressor</th>
<th>Estimate</th>
<th>t-stat</th>
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</thead>
<tbody>
<tr>
<td>$T_{i,t}$</td>
<td>-0.036</td>
<td>-2.84</td>
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<tr>
<td>$v_{i,t-1}$</td>
<td>0.517</td>
<td>12.20</td>
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<tr>
<td>$PC_{1,t}$</td>
<td>0.109</td>
<td>11.87</td>
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<tr>
<td>$PC_{2,t}$</td>
<td>-0.018</td>
<td>-0.91</td>
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</table>

Table V reports the response of equity prices to temperature risks estimated in the following panel regression:

$$v_{i,t} = \bar{b}_i + \phi T_{i,t} + b_0 v_{i,t-1} + b_1 PC_{1,t} + b_2 PC_{2,t} + \varepsilon_{i,t}$$

where $v_{i,t}$ is the log of the price-dividend ratio of country $i$, $\bar{b}_i$ is the country-specific fixed effect, $T_{i,t}$ is local temperature, and $PC_{1,t}$ and $PC_{2,t}$ are the first two principal components extracted from the cross-section of price-dividend ratios. The table present the generalized least-squares estimates of the slope coefficients and the corresponding robust t-statistics. The panel consists of 39 countries and spans the 1970-2006 period.
Table VI
Equity Valuations and Temperature: Sub-Sample Evidence

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\hat{\phi}$</th>
<th>t-stat</th>
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<tr>
<td>1970-2006</td>
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<td>1970-1990</td>
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<td>1970-2000</td>
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<td>1970-2003</td>
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<td>-2.99</td>
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</tbody>
</table>

Table VI reports the response of equity prices to temperature risks estimated in the following panel regression:

$$v_{i,t} = \bar{b}_i + \phi T_{i,t} + b_0 v_{i,t-1} + b_1 PC_{1,t} + b_2 PC_{2,t} + \varepsilon_{i,t}$$

where $v_{i,t}$ is the log of the price-dividend ratio of country $i$, $\bar{b}_i$ is the country-specific fixed effect, $T_{i,t}$ is local temperature, and $PC_{1,t}$ and $PC_{2,t}$ are the first two principal components extracted from the cross-section of price-dividend ratios. The first row of the table presents the generalized least-squares estimate of $\phi$ along with the robust t-statistic based on the full sample, the rest shows the subsample evidence. The panel consists of 39 countries and spans the 1970-2006 period.
Table VII
Price Response to Low-Frequency Temperature Risks

<table>
<thead>
<tr>
<th>Trend Specification</th>
<th>$\hat{\phi}$</th>
<th>t-stat</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-year MA</td>
<td>-0.053</td>
<td>-2.18</td>
</tr>
<tr>
<td>5-year MA</td>
<td>-0.087</td>
<td>-2.67</td>
</tr>
<tr>
<td>8-year MA</td>
<td>-0.239</td>
<td>-3.07</td>
</tr>
</tbody>
</table>

Table VII shows the response of equity prices to low-frequency temperature risks estimated in the following panel regression:

$$v_{i,t} = \bar{b}_i + \phi T_{\text{shock}}_{i,t} + b_0 v_{i,t-1} + b_1 PC_{1,t} + b_2 PC_{2,t} + \varepsilon_{i,t}$$

where $v_{i,t}$ is the log of the price-dividend ratio of country $i$, $\bar{b}_i$ is the country-specific fixed effect, $T_{\text{shock}}_{i,t}$ is an innovation in the trend of local temperature, and $PC_{1,t}$ and $PC_{2,t}$ are the first two principal components extracted from the cross-section of price-dividend ratios. Temperature trends are proxied for by a three-, five or eight-year moving-average (MA) and low-frequency shocks are identified using an AR(1) filter. The table presents the generalized least-squares estimates of $\phi$ along with the robust t-statistics. The panel consists of 39 countries and covers the 1970-2006 period.
Table VIII
VAR Dynamics of Equity Prices and Temperature

<table>
<thead>
<tr>
<th></th>
<th>$T_{i,t}$</th>
<th>$v_{i,t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{i,t-1}$</td>
<td>0.99</td>
<td>−0.007</td>
</tr>
<tr>
<td></td>
<td>[200.8]</td>
<td>[−2.30]</td>
</tr>
<tr>
<td>$v_{i,t-1}$</td>
<td>0.03</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>[0.80]</td>
<td>[32.49]</td>
</tr>
<tr>
<td>$\bar{R}^2$</td>
<td>0.99</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Table VIII shows the estimates of the first-order panel vector-autoregression (VAR) for equity prices and temperature. $T_{i,t}$ denotes local temperature, $v_{i,t}$ is the log of the price-dividend ratio of country $i$. The exogenous variables included in the VAR comprise the first two principal components extracted from the cross-section of price-dividend ratios and regional dummies. T-statistics are reported in brackets. The panel consists of 39 countries and covers the 1970-2006 period.
Table IX
Model-Implied Price Response to Temperature Risks

<table>
<thead>
<tr>
<th></th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>LRR-T Model</td>
<td>-0.0170</td>
</tr>
<tr>
<td>Alternatives:</td>
<td></td>
</tr>
<tr>
<td>EZ-Preferences</td>
<td>-0.0072</td>
</tr>
<tr>
<td>CRRA-highRA</td>
<td>0.0005</td>
</tr>
<tr>
<td>CRRA-lowRA</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Table IX 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. 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 10,000 draws.
Table X
List of Countries

<table>
<thead>
<tr>
<th>Argentina</th>
<th>Spain</th>
<th>Netherlands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>Finland</td>
<td>Norway</td>
</tr>
<tr>
<td>Austria</td>
<td>France</td>
<td>New Zealand</td>
</tr>
<tr>
<td>Belgium</td>
<td>U.K.</td>
<td>Peru</td>
</tr>
<tr>
<td>Brazil</td>
<td>Greece</td>
<td>Philippines</td>
</tr>
<tr>
<td>Canada</td>
<td>Indonesia</td>
<td>Portugal</td>
</tr>
<tr>
<td>Switzerland</td>
<td>India</td>
<td>Russia</td>
</tr>
<tr>
<td>Chile</td>
<td>Italy</td>
<td>Sweden</td>
</tr>
<tr>
<td>China</td>
<td>Japan</td>
<td>Turkey</td>
</tr>
<tr>
<td>Colombia</td>
<td>Korea, rep.</td>
<td>Taiwan</td>
</tr>
<tr>
<td>Germany</td>
<td>Sri Lanka</td>
<td>U.S.A.</td>
</tr>
<tr>
<td>Denmark</td>
<td>Mexico</td>
<td>Venezuela</td>
</tr>
<tr>
<td>Egypt</td>
<td>Malaysia</td>
<td>South Africa</td>
</tr>
</tbody>
</table>

Table X provides a list of countries in our data set.
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. Dotted line in Panel (c) represents the tipping point of global warming. The horizontal axis is the time-line measured in years from today.
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.
Figure 3. Optimal Abatement Policy

Figure 3 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.
Figure 4. Implications of Optimal Abatement Policies

Figure 4 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.
Figure 5 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.
Figure 6. Policy Decisions under Alternative Specifications

Figure 6 shows the optimal abatement effort (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. Temperature is in degrees Celsius. The horizontal axis is the time-line measured in years from today.
Figure 7. Sensitivity to Emissions

Figure 7 shows the impact of an increase in current emissions on future damages and discount rates of consumption strips. 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 discount rates. 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.
Figure 8. Histogram of the Trend in Local Temperature

Figure 8 shows the histogram of the long-run change in local temperature measured by the difference between average temperature over 2002-2006 and that over 1970-1974. The cross-sectional data comprise 39 countries; temperature is measured in degrees Celsius.
Figure 9. Impulse Response of Prices to Temperature Shocks

Figure 9 presents the impulse response function of the price-dividend ratio to a one standard-deviation innovation in temperature implied by a first-order VAR specification for temperature and prices. The estimated response is represented by the solid line, the shaded area shows the two standard-error band. Time-horizon on the horizontal axes is measured in years.