What Do Capital Markets Tell Us About Climate Change?

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Abstract

We use the forward-looking information from the US and global capital markets to estimate the economic impact of long-run temperature fluctuations. We find that global warming has a significant negative effect on asset valuations and that temperature risks carry a negative price. We also find that the negative elasticity of equity prices to temperature risks have been increasing over time, which suggests that the impact of climate change on the macro-economy has been rising. We use our empirical evidence to calibrate a long-run risks model with temperature-induced disasters in future output and growth and quantify the social cost of carbon emissions. 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 estimated temperature elasticity of equity prices. 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.

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Introduction

Global warming and its potential impact on the macro-economy is a matter of considerable importance. There is by now a substantial amount of evidence that weather or short-run climatic fluctuations have a significant effect on various aspects of economic activity, human health, mortality, social and political conflicts.[1] However, little is yet known about the significance of long-run temperature risks that lead to global warming. This article makes a contribution towards understanding the economic impact of persistent temperature variations. Using data from global and US capital markets, we show that temperature fluctuations, in particular, low-frequency temperature risks have a significant negative effect on aggregate wealth. The empirical evidence that we present suggests that global warming is an important source of economic risk and that the social cost of industrial carbon emissions is substantial.

To understand the implications of long-run temperature risks and to provide a theoretical foundation for our empirical analysis, we present a temperature-augmented long-run risks (LRR-T) model that accounts for the interaction between climate change, economic growth and risk. Our model builds on the long-run risks framework of Bansal and Yaron (2004) that features a preference for early resolution of uncertainty and time-varying expected growth. 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). Different from the standard integrated assessment (IAM) models, in which climate change is assumed to cause a deterministic loss in output, in our model, temperature is a source of economic risk. A persistent increase in temperature rises economic risk and affects aggregate wealth and asset valuations through the discount-rate channel. We show that with a preference for early resolution of uncertainty, a rise in temperature lowers the current wealth to consumption ratio and that temperature variations carry a negative price.

Our model has several important predictions that we use as a guidance in our empirical work. First, consistent with the consensus view, in our model, the most significant effects of global warming are expected to unfold in a relatively distant future. It is, therefore, difficult if not impossible to

[1] Dell, Jones, and Olken (2015) provide a thorough review of the recent empirical research on the impact of weather risks.

assess them from past and current output data. Our theoretical analysis, however, suggests that it might be possible to learn about climate-change risks from forward-looking equity prices. Even if temperature has no impact on current growth or risk but is expected to affect them in the future, it should have a measurable impact on current equity valuations. We pursue this idea and use cross-country capital market and temperature data to estimate elasticity of equity valuations to temperature risks. Our panel consists of 39 countries and span the 1970-2012 time period. We find that after controlling for global and local risk factors, temperature has a significantly negative impact on equity valuations — that is, higher temperature lowers valuation ratios. Quantitatively, a one degree Celsius increase in temperature leads to about 5% decline in equity valuations. We also find that temperature elasticity has become more negative over time — its magnitude changes from about -3% in the early pre-2000 sample to -5% over the entire sample period. This evidence suggests that during the period over which global temperature has risen, its impact on the economy has amplified. Importantly, we show that the negative impact of temperature on equity valuations is mostly driven by its low-frequency (i.e., trend) fluctuations that correspond to global warming. Earlier empirical works by Dell, Jones, and Olken (2012), and Bansal and Ochoa (2012) examine the effect of temperature variations on income growth. In contrast, we focus on forward-looking equity valuations — this allows us to learn about both long-term growth and risk effects of temperature, which past income data do not provide.

Further, while for simplicity we consider the economy in aggregate without explicitly modeling its sectors or markets, the cross-sectional implications of our model are straightforward. Assets that are highly exposed to temperature risks should carry higher risk premia relative to assets with smaller sensitivity. We test this prediction using a cross-section of 25 book-to-market and size sorted portfolios from the US equity markets. We show that, controlling for market risk, with just few exceptions, equity portfolios have negative exposure to temperature fluctuations. We also find that firms that carry high premia (such as value) are more sensitive to temperature risks compared with low-premia firms (such as growth). The cross-sectional estimate of the market price of temperature risks is significantly negative — hence, temperature risks carry a positive risk premium in equity markets. Also, consistent with the evidence from global markets, we find that the negative response of equity returns to temperature risks is largely due to the negative impact of persistent changes in temperature that are associated with global warming.

We argue that the cross-sectional variation in exposure to temperature risks is likely due to the cross-sectional variation in the composition of firms' assets. In particular, value firms that are intensive in physical capital are likely to be less flexible in adapting to variations in climate and therefore feature higher exposure to temperature fluctuations compared with growth, intangible capital intensive firms. Also, growth firms whose labor capital consists mainly of high-skilled workers that work indoors, in an air conditioning environment are likely to be less exposed to extreme temperature variations compared with firms that employ low-skilled workers who work outdoors (those tend to be value firms).[2] We corroborate our argument by showing that, relative to growth firms, value companies feature a much higher degree of co-movement with high heat exposed industries — industries that operate in hot and humid environments. In fact, we find that, controlling for market risk, exposure of book-to-market and size sorted portfolios to high heat exposed sectors can explain a large fraction of variation in their temperature betas and their risk premia.

We use our empirical estimates and the LRR-T model to quantify the social cost of carbon (SCC) that has become an important concept in the economic analysis of global warming and policy decision making. Intuitively, SCC measures the present value of damages due to a marginal increase in carbon emissions and as such, it allows us to assess the incentive to curb industrial emissions. To provide the estimate of SCC, we calibrate our model to match the projected trend in global temperature, consumption dynamics, our estimates of temperature elasticity of equity valuations and the observed discount rates from capital markets.[3] The latter is important as the social cost of carbon can be highly sensitive to discount rates as highlighted in Nordhaus (2008), Gollier (2012) and Golosov, Hassler, Krusell, and Tsyvinski (2014). 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, which is equivalent to a tax of about 20 cent per gallon of gas. It declines to a still sizable $40 when temperature is assumed to affect only 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, we show that in a power-utility setting, climate change is not perceived as sufficiently

[2] Graff Zivin and Neidell (2014) find that in the right tail of the temperature distribution, time allocation to labor in outdoor industries is significantly affected by temperature fluctuations.

[3] 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.

risky because its impact is deferred to the future. Consequently, the social cost of carbon under power-utility preferences is very small, of merely 1 cent per metric ton of carbon. We also show that a power-utility specification, which is the standard assumption in the integrated assessment models, fails to account for the documented negative elasticity of asset prices to temperature risks — in contrast to the data, under power utility, aggregate wealth increases in states of high temperature and high likelihood of disasters. In all, this evidence shows that the social cost of carbon emissions and, hence, the incentive to abate global warming depend critically on the attitude towards long-run risks. The implications of risk preferences for the optimal policy response to climate change are explored in a companion paper (see Bansal, Kiku, and Ochoa (2015)).

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. In Section 4, we document the impact of long-run temperature fluctuations on equity prices using data from global capital markets. In Section 5 we provide empirical evidence of the impact of temperature risks using the US data. Section 6 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)).[4]

[4] 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.

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.

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 production technologies with carbon-free technologies 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.[5] 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.[6]

[5] 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).

[6] 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.

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 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.

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:

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

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

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.[7]

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

[7] 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), 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.

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.[8] 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 standard in the climate-change literature (eg., Nordhaus (2010), Weitzman (2010), Anthoff and Tol (2012), Pindyck (2012)).[9]

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:

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

and disaster intensity follows:

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

where parameters q_1, q_2, l_0 and l_1 are greater than zero. Quadratic loss functions are commonly

[8] 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).

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

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 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:

$$U_t = \left\{ (1-\delta) C_t^{1-\frac{1}{\psi}} + \delta \Big(E_t \Big[U_{t+1}^{1-\gamma} \Big] \Big)^{\frac{1-\frac{1}{\psi}}{1-\gamma}} \right\}^{\frac{1}{1-\frac{1}{\psi}}}, \tag{9}$$

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 welfare analysis of global warming.

Note that the maximized life-time utility is proportional to the wealth to consumption ratio and as such it is determined by the present value of expected consumption growth from now to infinity. Specifically, the value function normalized by current consumption is given by:

$$\frac{U_t}{C_t} = \big[(1-\delta) Z_t \big]^{\frac{\psi}{\psi-1}}, \tag{10}$$

where $Z_t \equiv \frac{W_t}{C_t}$ is the aggregate wealth-consumption ratio. Aggregate wealth can be represented by a portfolio of consumption strips that mature at time $\{t+j\}_{j=0}^{\infty}$; consequently, the wealth-consumption ratio can be expressed as

$$Z_t = E_t \left[\sum_{j=0}^{\infty} \frac{C_{t+j}/C_t}{R_{j,t+j}} \right], \tag{11}$$

where $R_{j,t+j}$ is the discount rate of the consumption strip with j-time to maturity (i.e., the discount rate of an asset that pays aggregate consumption at time $t+j$). Equation (11) highlights the forward-looking nature of aggregate wealth and asset prices — the current price of the consumption claim carries information about agents' expectations about future economic growth (C_{t+j}/C_t) and risk ($R_{j,t+j}$). If climate change is expected to have a significant impact of either future growth or risk, it will be reflected in current wealth and asset prices. Also, as Equation (10) shows, the agent's utility is affected by climate change only through the impact of climate risks on the wealth-consumption ratio. In other words, the elasticity of aggregate wealth and asset prices to temperature risks is a sufficient statistic for the economic impact of climate change.

1.4 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:

$$SCC_t = -\frac{\partial U_t}{\partial E_t} \Big/ \frac{\partial U_t}{\partial C_t} \tag{12}$$

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 (10), we can express the social cost of carbon at time 0 as:

$$SCC_0 = \frac{\psi}{\psi - 1} \frac{-\partial Z_0 / \partial E_0}{Z_0} C_0 \, . \tag{13}$$

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.

As Equation (13) shows, the social cost of carbon emissions is determined by the elasticity of the valuation ratio to carbon emissions. An increase in current emissions leads to higher temperature and affects asset prices through two channels — the cash-flow channel that carries the impact of temperature variations on future growth, and the discount-rate channel that carries the impact of temperature on future risk.[10] Note that while the cash-flow effect depends on the damage function and is invariant to agents' preferences, the discount rate effect is determined importantly by risk preferences. For example, in an economy, where agents do not care about distant risks including climate risks that are expected to unfold in the future, the discount rate effect and, therefore, the social cost of carbon will be trivial. In contrast, in an economy, where agents are concerned about future risks, the discount-rate effect of rising temperature on asset prices might be quite significant and carbon emissions might carry sizable risk premia. In all, Equation (13) implies that capital markets might provide very useful information about the importance of temperature risks and the magnitude of the social cost of carbon emissions.

2 Calibration

We calibrate the path of carbon intensity (λ_t) and temperature (T_t) 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 are expected to accelerate.

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.[11] 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

[10] Hansen and Scheinkman (2012), and Borovička and Hansen (2014) provide a rigorous analysis of price elasticities.
[11] To facilitate interpretation of the calibrated parameters, we report and discuss them in annualized terms.

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 1c). 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 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.

The dynamics of future climate changes and their economic consequences are highly uncertain and not yet well-understood. Pindyck (2007), and Heal and Millner (2014) provide a comprehensive discussion of various sources of uncertainty in environmental economics. While some empirical evidence on the impact of rising temperature and climatic disasters does exist (for example, Tol (2002a, 2002b)), 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 each with financial market data and empirical evidence on the impact of rising temperature on equity prices.

We solve the model 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 policy function.

3 Asset Pricing Implications of Temperature Risks

Different from 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 through a risk channel. That is, climate change is a source of economic risk. Figure 3 displays the implications of global warming for the distribution of consumption growth. Notice that because temperature-induced disasters are compensated, they have no effect on the ex-ante mean of log consumption growth. This is 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, i.e., risk. As Panel (a) shows, climate-change driven disasters increase the ex-ante variation of future growth. In our calibration, at the peak of temperature anomaly, the ex-ante annualized volatility of cumulative consumption growth is about 0.18% higher compared with a no-disaster economy (in relative terms this corresponds to more than ten percent increase in volatility). Also, because global-warming disasters represent tail risks, the distribution of future consumption growth is both negatively skewed and fat-tailed. Panel (b) of Figure 3 presents a side-by-side comparison of the distribution of the normalized consumption growth at the peak of climate-driven disasters and the corresponding distribution in the economy with no disasters.

To understand the pricing implications of temperature risks, consider a marginal increase in current emissions. The additional amount of emissions leads to higher temperature and, hence, a higher likelihood of disasters in the future. The price of these temperature risks is displayed in Panel (a) of Figure 4, which shows the elasticity of the stochastic discount factor (SDF) to a one-percent increase in time-0 emissions. As the figure shows, higher temperature leads to an increase in marginal utility. That is, temperature risks carry a negative price. Note also that because both the frequency and the size of future damages depend on the level of temperature, so does the magnitude of the price of temperature risks. The elasticity of aggregate wealth to the corresponding increase in current emissions is presented in Panel (b). As the figure shows, the wealth-consumption ratio falls in response to an increase in temperature. Higher emissions and temperature raise risk premia and future discount rates and, therefore, lead to a decline in asset valuations.

To explore the implications of risk preferences for the joint dynamics of asset prices and temperature, we consider two alternative specifications: (1) preferences for early resolution of uncertainty, which we refer to as “Pref for ERU”, and (2) constant relative risk aversion preferences that we refer to as “Power Utility”. To facilitate the comparison, we simplify consumption dynamics by shutting off the long-run risk component and assuming that global warming affects only 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. The calibration of the two alternative specifications is summarized in Table II.

Figure 5 shows the response of aggregate wealth-to-consumption ratio to a one-percent increase in current emissions under the two preference specifications. Similar to our baseline LRR-T model, under preferences for early resolution of uncertainty, higher emissions lead to an increase in discount rates and a fall in asset valuations. In contrast, in the power-utility economy, discount rates decline in response to higher emissions and higher temperature (due to a significant decline in risk-free rates) and asset prices feature a positive elasticity to temperature risks. That is, under power utility, the wealth-to-consumption ratio is higher when disasters are expected to be more frequent and economic losses are expected to be larger. The power-utility agents are still worse off since their utility is inversely related to wealth, but because the elasticity of utility to wealth is quite low, the decline in utility is very tiny, more than three orders of magnitude smaller than the corresponding decline under recursive preferences.

The response of asset prices to temperature fluctuations in our baseline LRR-T model and under the two alternative specifications is summarized in Table III. For each specification, we simulate 50,000 paths of emissions, temperature and consumption and solve for the price of the consumption claim. Temperature elasticities of asset prices are estimated by regressing the log of the price-consumption ratio on temperature controlling for the relevant state variables. As the table shows, under recursive preferences, asset valuations fall in response to an increase in temperature. In particular, in the LRR-T model, a 0.53°C increase in temperature (which corresponds to one standard deviation of the empirical distribution) lowers the price of the consumption claim by about 0.92%. If we account for market leverage of around three, the response of equity prices to temperature shocks implied by our LRR-T model is about −2.8%, which as we show below is quantitatively similar to our empirical estimates. As also shown in Figure 4, the sensitivity of asset prices to temperature risks increases with temperature (as the economy gets closer to the disaster threshold). For example, ten and twenty years from now, the price response rises in magnitude from the current −0.0174 to −0.019 and −0.021, respectively.

As Table III further shows, the power-utility implied response of prices to temperature risks is very different compared with recursive preferences. In the power-utility case, asset prices rise with temperature. Quantitatively, the price-consumption ratio increases by about 0.024% in response to a 0.53°C increase in 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 and, consequently, an increase in asset prices.

Risk preferences have also important implications for the marginal cost of carbon emissions, which we present in Table IV. In our LRR-T model, SCC is estimated at about $104 per ton of carbon.[12] 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. Further, even when the long-run risk channel is shut off, under preferences for early resolution of uncertainty, distant climate risks continue to carry a significant weight and the social cost of carbon remains significant, of about $40. In contrast, in the power-utility setting, SCC is quite trivial, of merely 1 cents per metric ton of carbon. In essence, climate-change risks under power utility are effectively discounted out as they are expected to realize in a relatively distant future. That is, with preferences for early resolution of uncertainty, agents are concerned about temperature risks that are going to be realized in the distant future and do not disregard them as easily as the power-utility agents. Consequently, the life-time utility under preferences for early resolution of uncertainty is more sensitive to emissions compared with power-utility preferences, which is reflected in the high social cost of carbon.[13]

Temperature risks aside, our LRR-T model 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, the implied equity premium, assuming leverage of 3, 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 the overall premium is due to temperature risks.

[12]The social cost of carbon is measured in 2012 dollars of world household final consumption expenditure per metric ton of carbon.

[13]Nordhaus (2014), and Golosov, Hassler, Krusell, and Tsyvinski (2014) report significant estimates of the social cost of carbon under power utility preferences because they assume that climate change causes a sizable reduction in the current and near-future output. Differently, we assume that significant consequences of temperature risks will be realized in the future rather than today and, therefore, find that the power-utility agent assigns a trivial price to carbon emissions. Whether the impact of climate change is realized now or in the future, under power utility preferences asset prices feature a positive elasticity to temperature risks, which is inconsistent with the robustly negative response of asset prices to temperature fluctuations in the data that we document and discuss below.

4 Temperature and Asset Prices: Evidence from Global Markets

In our model, rising temperature increases economic risk and thus has a negative effect on the macro-economy. Further, with a preference for early resolution of uncertainty, higher temperature leads to a decline in aggregate wealth and asset prices. The empirical research on the impact of global warming on the macro-economy has primarily focused on the effect of temperature on growth. For example, Dell, Jones, and Olken (2012) analyze the impact of rising temperature on output and find evidence that current output and short-term future growth tend to decrease with temperature, although the negative effect seems to be entirely concentrated in low-income countries. Motivated by the model, we take a different approach and measure the impact of temperature on the macro-economy using forward-looking equity prices rather than past growth rates. Long-horizon equity prices reflect information about future expected growth rates and future risks. Hence, if temperature is expected to affect future growth and/or risk, these expectations ought to be reflected in capital markets provided that agents care about the future. This is the idea that we pursue in our empirical analysis of equity prices and temperature fluctuations. Below, we estimate and evaluate the impact of temperature risks on equity valuations using panel data from global financial markets. To preview our findings, our empirical evidence suggests that climate change measured by a long-term increase in temperature is expected to have a significant negative effect on the global economy.

4.1 Data

To measure the economic impact of temperature, we use country-level panel data that cover 39 countries and span the time period from 1970 and 2012. Country-level and global temperature that correspond to land-surface temperature anomaly are taken from the Berkeley Earth open database. Temperature anomaly is measured in degrees Celsius and is defined relative to the 1951-1980 average. The price-dividend data come from the Global Financial Data and provide a market proxy for the wealth-to-consumption ratio. We also collect market equity returns for each country in our sample. Country-specific macro data (such as gross domestic product, inflation, unemployment, real interest rates) are taken from the World Bank database. The list of 39 countries is provided in Table V. This is the most exhaustive set with reliable capital market data that we could find, as such, it is tilted towards developed economies as they are more likely to have a history of equity markets.

In our sample, 38 out of 39 countries have experienced a significant increase in temperature over the sample period. The median temperature anomaly across countries is about 0.38°C and over the last decade, between 2003 and 2012, the anomaly averages 0.73°C . Figure 6 shows the histogram of the temperature anomaly in the most recent decade in our sample. We find that local temperature series have a strong common component that is highly correlated with variation in global temperature. The first principal component of annual temperature series accounts for about 53% of the total variation in temperature across countries and has a 71% correlation with global temperature anomaly. At low frequencies, the co-movement in local temperature becomes much stronger — about 81% of the overall variation in the five-year averages of local temperature is captured by the first principal component. This evidence suggests that systematic climate risk is mostly driven by low-frequency temperature risks (i.e., risks associated with global warming) rather than by weather or short-run temperature fluctuations. As illustrated in Figure 7, the low-frequency component of local temperature essentially corresponds to the trend in global warming.

Our analysis of equity prices reveals a strong low dimensional factor structure also in price-dividend ratios. We find that the first principal component extracted from the cross-section of price-dividend ratios accounts for about 69% of the total variation in prices across countries and the second component explains an additional 10%. This suggests that the cross-country variation in equity valuations is dominated by few common macro-economic factors. Jagannathan and Marakani (2015) show that the first two price-dividend ratio factors provide robust proxies for future economic growth and variation in macro-economic uncertainty. Guided by their evidence, we use the first two principal components to control for global macro-economic risks in our regression analysis.

4.2 Impact of Temperature on Equity Valuations and Returns

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

$$v_{i,t} = \bar{v}_i + \phi_K \overline{T}^K_{i,t} + \alpha_c' C_{i,t} + \alpha_v v_{i,t-1} + \varepsilon_{i,t} \tag{14}$$

where $v_{i,t}$ is the log of the equity price-dividend ratio of country i at date t, $\bar{v}_i$ is the country-specific fixed effect, $\overline{T}^K_{i,t}$ is a K-year moving-average of local temperature, and $C_{i,t}$ is a set of controls that captures the effect of global (and local) risks on asset prices, i.e., macro-economic risks that are distinct from temperature. To analyze the impact of temperature fluctuations at different frequencies, short and long, we consider different K's ranging from one to five years (note that when $K = 1$, $\overline{T}_{i,t}^{K}$ corresponds to annual temperature anomaly). In our baseline specification that we refer to as Specification I, we control for common global macro-economic variations using two price-dividend ratio factors.[14] To confirm the robustness of our evidence, in Specification II we consider a richer set of controls that in addition to global factors includes country-specific variables. The set of local controls comprises inflation, unemployment, real interest rate, and growth in gross domestic product (gdp). The remaining persistence in asset prices is absorbed by the lagged country-specific price-dividend ratio. We estimate both specifications using the Arellano and Bond (1991)'s GMM estimator applied to the first-differenced data and use the White (1980)'s robust estimator of the variance-covariance matrix.

Our focus is on parameter ϕ_K that measures sensitivity of equity prices to local temperature variations. The estimates of temperature elasticities are reported in Table VI. We find that at both short and long horizons, temperature risks have a significant negative effect on equity valuations. In Specification I, the estimated elasticities vary between -0.075 (t-stat $= -4.65$) at the short horizon and -0.120 (t-stat $= -10.99$) at the long horizon. To interpret the magnitude of the estimates, note that ϕ_K measures semi-elasticity of asset prices to temperature fluctuations. Hence, controlling for country fixed effects and global macro-economic risks, a one standard-deviation increase in annual temperature anomaly of around 0.53°C leads to about 3.9% decline in equity valuations. The impact of low-frequency temperature risks is similar; for example, a one standard-deviation increase in the five-year temperature trend lowers equity valuations by about 4.4%. The evidence is robust to the inclusion of local controls. In Specification II, the estimated elasticities are all significantly negative and the magnitude of temperature risks on equity valuations across different horizons averages 4%.[15]

In Table VII we explore if the effect of temperature on the economy has changed across time. Ideally, to uncover such changes, we would want to compare temperature elasticities measured over

[14] To allow global macro risks have differential effect across countries, we also include the interaction of the two principal components with country-income dummies. While the estimates on the interaction terms are mostly significant, their inclusion has virtually no effect on the estimated elasticity of equity prices to temperature risks and its significance. Therefore, for parsimony, we report evidence based on the specification with no interaction terms.

[15] The magnitude of t-statistics in Specification II is somewhat smaller compared with Specification I, which is partly due to a shorter panel of data. Note that in Specification I, the panel consists of 39 countries and spans the period from 1970 to 2012. In Specification II, the panel is reduced to 35 countries over the 1980-2009 period due to the lack of the country-level controls.

earlier and more recent sample periods. This, however, is not entirely feasible given the fairly short span of the available data. Therefore, to explore time-variation in elasticities we estimate them using overlapping samples. In our baseline specification, we start with the early 1970-2000 sample and then progressively increase the sample end to 2005 and 2012 by adding more recent data. In Specification II, the sample starts in 1980 and the sample end varies between 2000 and 2009. Our estimates reported in Table VII show that the effect of temperature on equity valuations has risen considerably over time. At the one-year horizon, the point estimates change from -0.034 and -0.016 in the early sample to -0.075 and -0.076 in the full sample in Specifications I and II, respectively. Similarly, the price impact of temperature risks measured at lower frequencies (i.e., for $K > 1$) almost doubles when more recent data are incorporated in estimation. This evidence suggests that as temperature rises, global warming imposes higher risks on the economy and, therefore, leads to a larger decline in wealth. As we discuss below, our model is consistent with this evidence — in the model, rising temperature increases the size and the probability of disasters over time, leading to a steeper decline in aggregate wealth.

To measure the economic impact of temperature risks we exploit both time-series and cross-sectional variation in temperature. As mentioned above, local temperature series, especially their low-frequency fluctuations, feature a strong common (global) component. In Table VIII we explore to what extend global temperature risks affect capital markets. The table shows the response of equity valuations to global temperature estimated by running a panel regression as in Equation (15) but using global temperature anomaly instead of local temperature series. We find that global temperature risks have a significant negative effect of equity prices. This evidence suggests that, to a large extent, common time-series variation in temperature across countries accounts for the negative elasticity of equity valuations to local temperature risks.

In Table IX, we show exposure of equity returns to temperature risks estimated using a similar panel regression, specifically:

$$r_{i,t} = \bar{r}_i + \phi_K \,\overline{T}^K_{i,t} + \alpha_c' C_{i,t} + \varepsilon_{i,t} \tag{15}$$

where $r_{i,t}$ is the log of the equity return of country i, $\bar{r}_i$ is the country-specific fixed effect, $\overline{T}^K_{i,t}$ is a K-year moving-average of local temperature, and $C_{i,t}$ is a set of controls. We control for common global risks using the first two principal components extracted from the cross-section of equity returns. Similar to the evidence based on valuation ratios, we find that equity returns tend to decline upon positive news about temperature, in particular, upon news about low-frequency temperature fluctuations. Equity exposure to the five-year trend in temperature is estimated at -0.055 (t-stat $= -3.53$) and -0.061 (t-stat $= -2.70$) under Specifications I and II, respectively.

4.3 Long-Run vs. Short-Run Temperature Risks

As shown above, long-run temperature risks represented by variations in three- and five-year moving-average trends as well as short-run annual temperature risks have a significant negative effect on equity valuations. Note that year-to-year changes in temperature capture two types of risks: short-run or weather-type risks and low-frequency temperature variations associated with global warming. To understand which risks matter more, we consider the following panel regression:

$$v_{i,t} = \bar{v}_i + \phi_{LR}\, LR^K_{i,t} + \phi_{SR}\, SR_{i,t} + \alpha_c' C_{i,t} + \alpha_v v_{i,t-1} + \varepsilon_{i,t} \ , \tag{16}$$

where $LR^K_{i,t}$ proxies for low-frequency temperature risks and is measured by the K-year moving-average of local temperature, for $K = \{3,\ 5\}$, and $SR_{i,t}$ is annual temperature orthogonalized with respect to long-run fluctuations. We orthogonalize short- and long-run temperature variations in order to identify their separate effects. The estimates of long- and short-run elasticities, $\hat{\phi}_{LR}$ and $\hat{\phi}_{SR}$, are presented in Table X.

Consistent with the evidence discussed above, we find a negative and statistically significant response of equity valuations to low-frequency variations in temperature. We also find that once we control for long-run fluctuations in temperature, short-run temperature risks tend to also have a negative effect on equity prices, however, its magnitude is generally small and its significance is not robust, in particular in specifications that include local controls. As Table X also shows, the negative response of equity valuations to low-frequency temperature risks remains strongly significant if alternatively we measure long-run temperature risks using the Hodrick and Prescott (1997) filter. In unreported results, we also estimate exposure of equity returns to long- and short-run temperature risks and similarly find statistically negative betas with respect to low-frequency risks and generally insignificant exposure to short-run variations in temperature. Our evidence thus suggests that the negative impact of temperature on the economy is mostly driven by its low-frequency (i.e., trend) risks that correspond to global warming.

To further examine the impact of long- and short-run temperature risks on equity prices, we estimate their joint dynamics using a first-order vector-autoregression (VAR). Specifically, we exploit the following panel VAR specification:

$$X_{i,t} = \bar{a}_i + A\, X_{i,t-1} + b\, C_t + u_{i,t} \tag{17}$$

where $X_{i,t} = (\overline{T}^8_{i,t},\ T_{i,t},\ v_{i,t})'$ is a vector of the eight-year moving-average of local temperature, the annual temperature series and the price-dividend ratio of country i. We include country fixed effects ($\bar{a}_i$) and use the two price-dividend ratio factors to control for global risks (C_t denotes the vector of global controls). The VAR-regression output is reported in Table XI, and in Figure 8 we plot the implied impulse responses of equity prices to a one-standard deviation shock in temperature trend ($\overline{T}^8_{i,t}$) and a one-standard deviation innovation in annual temperature ($T_{i,t}$). The shaded area around the estimated responses represents the two standard-error band. As Panel (a) shows, the VAR-based response of equity prices to low-frequency temperature risks is significantly negative. Notice also that the effect of trend shocks is quite persistent – an increase in temperature trend leads to a decline in equity prices on impact and in the long run. Similar to the evidence presented above, short-run temperature fluctuations do not seem to have any sizable effect. In all, our empirical suggests that a persistent increase in temperature that contributes to global warming has a significant negative impact on the world economies.

5 Temperature and Asset Prices: Evidence from the US Markets

In this section, using data from the US capital markets, we provide further evidence that temperature risks, particulary low-frequency temperature variations, have a significant negative effect on wealth and carry a negative price. We also show that value firms are more exposed to temperature fluctuations relative to growth firms. We argue that the cross-sectional variation in exposure to temperature risks is likely due to the cross-sectional variation in the composition of firms' assets. In particular, physical capital intensive firms such as value are less capable of adapting to climate risks and therefore feature high sensitivity to temperature fluctuations. Growth firms that tend to be intensive in intangible capital are likely to exhibit low exposure to temperature risks. Also, growth firms whose labor force consists mainly of high-skilled workers that work indoors, in an air conditioning environment are likely to be less exposed to extreme temperature variations compared with firms that employ low-skilled workers who work outdoors (those tend to be value firms). In our analysis, we use two data sets: the standard set of 25 portfolios sorted by market capitalization and book-to-market ratio, and a set of industry portfolios that span the 1934-2014 time period. We will describe our industry classification below.

We first present evidence on the elasticity of book-to-market and size sorted portfolios to temperature fluctuations, which we estimate by regressing equity returns on the US temperature controlling for variations in the aggregate market portfolio. Figure 9 shows a scatter plot of average portfolio returns and equity exposure to annual change in temperature (Panel (a)) and to variation in the five-year moving average in temperature (Panel (b)). Note that with only few exceptions, equity portfolios have negative elasticity to temperature fluctuations, which confirms our evidence from global financial markets that asset prices tend to decline in response to an increase in temperature. Further, note that portfolios that carry high premia, such as value and small, feature high sensitivity to temperature risks, which suggests that temperature risks carry a negative price.

We estimate the price of temperature risks in a cross-sectional regression of average excess returns of the 25 portfolios on temperature betas. We consider two specifications – Specification 1 that controls for market risk, and Specification 2 that controls for both market and economic growth risks. Following the long-run risk literature, we use an innovation in a smoothed aggregate consumption growth to proxy for variations in macro-economic growth. Table XII presents the cross-sectional estimates and their significance based on standard errors computed using the Fama and MacBeth (1973) regression procedure, and Shanken (1992)-corrected standard errors that account for estimation errors in betas. We find that the estimate of the market price of temperature risks is significantly negative, particularly when temperature risk is measured by low-frequency variations. For example, under Specifications 1 and 2, the market price of variations in five-year temperature trend is estimated at -0.22 and -0.19 with the corrected t-statistics of -2.44 and -2.08, respectively.

To ensure that our evidence is not simply due to a lucky draw, we run the following simulation experiment. We generate temperature series of the sample size that matches the data and replace the actual temperature series with the simulated draw. We then estimate equity exposure to simulated temperature and run a cross-sectional regression of average returns on the estimated betas. We repeat this simulation exercise 10,000 times and construct a Monte Carlo distribution of the t-statistics under the null that temperature variations have no effect on equity prices. The bottom row of Table XII reports the proportion of Monte Carlo samples that feature t-statistics below the corresponding statistics in the data. It shows that for low-frequency temperature risks, the sample t-statistics are below the 95-percentile cutoff of the Monte Carlo distribution. That is, if persistent temperature risks had no effect on equity prices, it would be extremely unlikely to find that they are significantly priced in capital markets.

Consistent with our evidence from global markets, we find that the negative response of the US equity to temperature risks is largely due to the negative impact of persistent variations in temperature, i.e., risks that correspond to global warming. We illustrate this evidence in Figure 10 that presents a scatter plot of average excess returns and portfolio exposure to long- and short-run temperature risks. We proxy for low-frequency risks by the change in the five-year moving average trend in temperature and to isolate transient (short-run) variations we orthogonalize variations in annual temperature with respect to trend risks. First notice that while exposure to long-run temperature risks is mostly negative, short-run temperature betas are distributed evenly around zero. As the figure further shows, exposure to trend risks accounts for a significant fraction of variation is risk premia and by itself explains about 42% variation in average returns. Exposure to short-run temperature risks that do not contribute to variations in the trend contains much less information about risk premia and accounts for only 11% of the cross-sectional dispersion in average returns.

To provide a micro-foundation of our cross-sectional evidence, we analyze the degree of co-movement between BM/Size sorted portfolios and industries that by the nature of their operations might feature deferent exposure to temperature fluctuations. To this end, we construct ten industry portfolios that represent different sectors of the US economy and, following the classification of the National Institute for Occupational Safety and Health (NIOSH) and Graff Zivin and Neidell (2014), we divide them into two groups: high- and low-heat exposed sectors. The first group comprises mining, oil and gas extraction, construction, transportation, and utilities — industries with a significant amount of outdoor operations. The remaining sectors: manufacturing, wholesale, retail trade, services, and communications, are classified as sectors with low exposure to heat.[16]

In Table XIII we verify that so-classified industries indeed feature quite different sensitivities to temperature risks. The table presents exposure of industry portfolios to temperature risks estimated by regressing market-adjusted industry returns on the change in one-, three- or five-year moving average of temperature.[17] Notice that with the exception of wholesale, industries in the low-heat exposure group have small positive sensitivity to temperature variation, whereas firms in high-heat exposure industries have negative elasticity to temperature risks, particularly to persistent temperature risks. In Table XIV we confirm that the differences between the two groups are significant. We estimate the following panel regression:

$$R_{i,t} = b_0 + \phi\, \Delta\overline{T}_t^K + \phi_H\, \Delta\overline{T}_t^K \cdot H_i + b_M\, R_{m,t} + \varepsilon_{i,t}$$

where $R_{i,t}$ is the return of industry i, $\Delta\overline{T}_t^K$ is a change in the K-year moving average of temperature, H_i is a dummy variable that equals one if industry i belongs to the set of high-heat exposed industries and zero otherwise, and $R_{m,t}$ is the return of the aggregate market portfolio. We find that the estimate of ϕ_H that reflects the difference in temperature betas of high- and low-heat exposure groups is negative and is strongly significant when temperature risks are measured at low frequencies.

In Figure 11 we analyze the co-movement of book-to-market and size sorted portfolios with high- and low-heat exposed industries. The figure presents scatter plots of average excess returns and average exposure of market-adjusted returns of 25 BM/Size sorted portfolios to the two industry groups. We find that high temperature-exposure and high risk-premia portfolios co-vary strongly with industries that operate in hot and humid environments. That is, value and small firms that are highly exposed to temperature risks feature high covariation with high-heat exposed industries. Low temperature exposure and low risk-premia portfolios (such as growth and large) tend to have low loadings on high-heat exposed industries. As Panel (a) shows the loading of BM/Size portfolios on industries with high-heat exposure is able to explain a significant portion of variation in their expected returns. The cross-sectional variation in the degree of co-movement with high-heat exposed

[16] We are unable to consider the agricultural sector because a portfolio of public agricultural firms is extremely thin — on average, it contains about 9 firms and in the first part of the sample it comprises of only 1-2 firms. Firms in the financial section are excluded.

[17] The evidence is virtually the same if in addition to market risk we also control for economic growth risk.

sectors is particularly pronounced across book-to-market characteristic. Value firms that tend to derive most of their value from installed physical capital are highly correlated with industries that feature high exposure to temperature risks. In contrast, growth firms that hold a significant amount of intangible assets are likely to be relatively immune to temperature variations and, therefore, exhibit much less co-movement with high-heat exposed industries.

6 Conclusion

To summarize, using cross- and within-country data we show that temperature risks have a significant negative effect on wealth. An increase in temperature, especially at low frequencies, lowers equity valuations around the globe and in the US markets. To understand the implications of persistent temperature risks and to guide our empirical analysis, we model the dynamic interaction between economic growth and climate change. We show that even if the real effect of rising temperature is deferred into the future, its wealth effect is realized today. That is, even if global warming increases uncertainty or lowers expectations about growth in a relatively distant future, under preferences for early resolution of uncertainty, it leads to an immediate decline in wealth and equity valuations. Hence, forward-looking capital markets might provide valuable information about the economic impact of temperature risks – information that might not be possible to learn from the past (backward-looking) income growth data. We explore this idea in our empirical work. Consistent with our model predications, we find that low-frequency temperature risks have a significant negative effect on equity valuations and carry a sizable premium in equity markets.

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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**	
		Pref for ERU	Power Utility
Preferences			
β	0.99	0.99	0.99
γ	5	5	5
ψ	1.5	1.5	0.2
Consumption			
μ	0.018	0.018	0.018
σ	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 two specifications of preferences under the alternative dynamics: preferences for early resolution of uncertainty (Pref for ERU) and CRRA preferences (Power Utility). Empty entries in the table correspond to zeros. The parameter values are annualized.

Table III

Model-Implied Response of Equity Prices to Temperature Risks

	Response
LRR-T Model	−0.0174
Alternatives:	
Pref for ERU	−0.0063
Power Utility	0.0002

Table III 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 two types of risk preferences: preferences for early resolution of uncertainty (Pref for ERU) and CRRA preferences (Power Utility). 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.

Table IV

Capital Market Implications

	LRR-T Model	**Alternative Specifications**	
		Pref for ERU	Power Utility
SCC	103.6	39.01	0.01
Risk-Free Rate	0.91	2.11	10.08
Risk Premia	1.70	0.16	0.17
Discount Rates:			
10yr Strip	1.51	2.28	10.33
100yr Strip	2.41	2.29	10.31

Table IV presents the social cost of carbon (SCC) and 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 two types of risk preferences: preferences for early resolution of uncertainty (Pref for ERU) and CRRA preferences (Power Utility). SCC is measured in 2012 dollars of world consumption per metric ton of carbon. The risk-free rate and risk premia on consumption claim are averaged over the transitional path, discount rates represent expected rates of returns on consumption strips with 10- and 100-year maturities. Returns and premia are expressed in annualized percentage terms.

Table V

List of Countries

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

Table V provides a list of countries in our data set.

Table VI

Elasticity of Equity Prices to Temperature Variations

	Specification I		Specification II	
K	$\hat{\phi}_K$	t-stat	$\hat{\phi}_K$	t-stat
1yr	−0.075	−4.65	−0.076	−4.41
3yr	−0.092	−13.29	−0.138	−5.59
5yr	−0.120	−10.99	−0.105	−3.33
Country FE	✓		✓	
Global Controls	✓		✓	
Local Controls			✓	

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

$$v_{i,t} = \bar{v}_i + \phi_K \overline{T}^K_{i,t} + \alpha'_c C_{i,t} + \alpha_v v_{i,t-1} + \varepsilon_{i,t} \ ,$$

where $v_{i,t}$ is the log of the price-dividend ratio of country i, $\bar{v}_i$ is the country-specific fixed effect, $\overline{T}^K_{i,t}$ is a K-year moving-average of local temperature, and $C_{i,t}$ is a set of controls. In Specification I, we control for common global variation using two price-dividend ratio factors. In Specification II, the set of controls also includes country-specific inflation, unemployment, real interest rate, and gdp growth. Both specifications are estimated using the Arellano and Bond (1991)'s GMM estimator applied to the first-differenced data. The table presents the estimates of the slope coefficient, ϕ_K, and the corresponding t-statistics based on the White (1980)'s robust estimator of the variance-covariance matrix. In Specification I, the panel consists of 39 countries and spans the 1970-2012 period; in Specification II, the panel comprises 35 countries over the 1980-2009 period.

Table VII

Equity Valuations and Temperature: Sub-Sample Evidence

Specification I			Specification II		
$K = 1$yr	$\hat{\phi}_1$	t-stat	$K = 1$yr	$\hat{\phi}_1$	t-stat
1970−2000	−0.034	−3.21	1980−2000	−0.016	−1.51
1970−2005	−0.040	−4.37	1980−2005	−0.043	−3.21
1970−2012	−0.075	−4.65	1980−2009	−0.076	−4.41
$K = 5$yr	$\hat{\phi}_5$	t-stat	$K = 5$yr	$\hat{\phi}_5$	t-stat
1970−2000	−0.071	−8.64	1980−2000	0.058	1.79
1970−2005	−0.080	−7.95	1980−2005	−0.023	−0.56
1970−2012	−0.120	−10.99	1980−2009	−0.105	−3.33
Country FE	✓		Country FE	✓	
Global Controls	✓		Global Controls	✓	
Local Controls			Local Controls	✓	

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

$$v_{i,t} = \bar{v}_i + \phi_K \overline{T}^K_{i,t} + \alpha_c' C_{i,t} + \alpha_v v_{i,t-1} + \varepsilon_{i,t} \ ,$$

where $v_{i,t}$ is the log of the price-dividend ratio of country i, $\bar{v}_i$ is the country-specific fixed effect, $\overline{T}^K_{i,t}$ is a K-year moving-average of local temperature, and $C_{i,t}$ is a set of controls. In Specification I, we control for common global variation using two price-dividend ratio factors. In Specification II, the set of controls also includes country-specific inflation, unemployment, real interest rate, and gdp growth. Both specifications are estimated using the Arellano and Bond (1991)'s GMM estimator applied to the first-differenced data. The table presents the estimates of the slope coefficient, ϕ_K, and the corresponding t-statistics based on the White (1980)'s robust estimator of the variance-covariance matrix. In Specification I, the panel consists of 39 countries; in Specification II, the panel comprises 35 countries.

Table VIII

Elasticity of Equity Prices to Global Temperature

	Specification I		Specification II	
K	$\hat{\phi}_K$	t-stat	$\hat{\phi}_K$	t-stat
1yr	−0.146	−17.42	−0.164	−9.87
3yr	−0.158	−5.08	−0.095	−2.08
5yr	−0.223	−3.29	−0.215	−3.14
Country FE	✓		✓	
Global Controls	✓		✓	
Local Controls			✓	

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

$$v_{i,t} = \bar{v}_i + \phi_K \,\overline{T}^K_{G,t} + \alpha_c' C_{i,t} + \alpha_v v_{i,t-1} + \varepsilon_{i,t} \ ,$$

where $v_{i,t}$ is the log of the price-dividend ratio of country i, $\bar{v}_i$ is the country-specific fixed effect, $\overline{T}^K_{G,t}$ is a K-year moving-average of global temperature, and $C_{i,t}$ is a set of controls. In Specification I, we control for common global variation using two price-dividend ratio factors. In Specification II, the set of controls also includes country-specific inflation, unemployment, real interest rate, and gdp growth. Both specifications are estimated using the Arellano and Bond (1991)'s GMM estimator applied to the first-differenced data. The table presents the estimates of the slope coefficient, ϕ_K, and the corresponding t-statistics based on the White (1980)'s robust estimator of the variance-covariance matrix. In Specification I, the panel consists of 39 countries and spans the 1970-2012 period; in Specification II, the panel comprises 35 countries over the 1980-2009 period.

Table IX

Exposure of Equity Returns to Temperature Risks

	Specification I		Specification II	
K	$\hat{\phi}_K$	t-stat	$\hat{\phi}_K$	t-stat
1yr	-0.016	-1.65	-0.021	-1.18
3yr	-0.055	-3.65	-0.068	-2.75
5yr	-0.055	-3.53	-0.061	-2.70
Country FE	✓		✓	
Global Controls	✓		✓	
Local Controls			✓	

Table IX reports exposure of equity returns to temperature risks estimated in the following panel regression:

$$r_{i,t} = \bar{r}_i + \phi_K \, \overline{T}_{i,t}^{K} + \alpha_c' C_{i,t} + \varepsilon_{i,t} \ ,$$

where $r_{i,t}$ is the log of the equity return of country i, $\bar{r}_i$ is the country-specific fixed effect, $\overline{T}_{i,t}^{K}$ is a K-year moving-average of local temperature, and $C_{i,t}$ is a set of controls. In Specification I, we control for common global variation using two equity return factors. In Specification II, the set of controls also includes country-specific inflation, unemployment, real interest rate, and gdp growth. The table presents the estimates of the slope coefficient, ϕ_K, and the corresponding t-statistics based on the White (1980)'s robust estimator of the variance-covariance matrix. In Specification I, the panel consists of 39 countries and spans the 1970-2012 period; in Specification II, the panel comprises 35 countries over the 1980-2009 period.

Table X

Equity Response to Long- and Short-Run Temperature Risks

	Specification I		Specification II	
	Estimate	t-stat	Estimate	t-stat
$K = 3\text{yr}$				
ϕ_{LR}	-0.096	-7.75	-0.138	-4.78
ϕ_{SR}	-0.041	-4.50	-0.026	-1.00
$K = 5\text{yr}$				
ϕ_{LR}	-0.118	-8.85	-0.135	-3.37
ϕ_{SR}	-0.041	-4.06	-0.028	-1.05
HP-trend				
ϕ_{LR}	-0.135	-11.51	-0.136	-3.27
ϕ_{SR}	-0.027	-3.95	-0.066	-2.97
Country FE	✓		✓	
Global Controls	✓		✓	
Local Controls			✓	

Table X reports the response of equity valuations to long- and short-run temperature risks estimated in the following panel regression:

$$v_{i,t} = \bar{v}_i + \phi_{LR}\, LR^K_{i,t} + \phi_{SR}\, SR_{i,t} + \alpha_c' C_{i,t} + \alpha_v v_{i,t-1} + \varepsilon_{i,t} \ ,$$

where $v_{i,t}$ is the log of the price-dividend ratio of country i, $\bar{v}_i$ is the country-specific fixed effect, $LR^K_{i,t}$ proxies for low-frequency temperature risks and is measured by the three- or five-year moving-average of local temperature, $SR_{i,t}$ is annual temperature orthogonalized with respect to long-run fluctuations, and $C_{i,t}$ is a set of controls. In the lower panel, $LR^K_{i,t}$ is replaced with the Hodrick-Prescott trend. In Specification I, we control for common global variation using two price-dividend ratio factors. In Specification II, the set of controls also includes country-specific inflation, unemployment, real interest rate, and gdp growth. Both specifications are estimated using the Arellano and Bond (1991)'s GMM estimator applied to the first-differenced data. The table presents the estimates of the slope coefficients, ϕ_{LR} and ϕ_{SR}, and the corresponding t-statistics based on the White (1980)'s robust estimator of the variance-covariance matrix. In Specification I, the panel consists of 39 countries and spans the 1970-2012 period; in Specification II, the panel comprises 35 countries over the 1980-2009 period.

Table XI
VAR Dynamics of Equity Prices and Temperature

	$\overline{T}^{8}_{i,t}$	$T_{i,t}$	$v_{i,t}$
$\overline{T}^{8}_{i,t-1}$	0.921	0.385	-0.093
	[107.1]	[7.06]	[-2.29]
$T_{i,t-1}$	0.026	0.158	-0.017
	[5.44]	[5.19]	[-0.73]
$v_{i,t-1}$	0.014	0.076	0.520
	[3.15]	[2.65]	[24.41]
$\bar{R}^2$	0.96	0.31	0.67

Table XI shows the estimates of the first-order panel VAR for equity prices and temperature. $\overline{T}^{8}_{i,t}$ denotes the eight-year moving-average of local temperature, $T_{i,t}$ is annual temperature series, and $v_{i,t}$ is the log of the price-dividend ratio of country i. The exogenous variables included in the VAR comprise two price-dividend ratio factors that control for common macro-economic risks and country-specific fixed effects. T-statistics are reported in brackets. The panel consists of 39 countries over the 1970-2012 period.

Table XII

Market Price of Temperature Risks

	Specification 1		**Specification 2**	
	1-year	5-year	1-year	5-year
$\hat{\lambda}_T$	-1.64	-0.22	-1.53	-0.19
(t-stat)	(-4.42)	(-3.56)	(-4.00)	(-3.14)
[t-stat*]	$[-1.97]$	$[-2.44]$	$[-1.87]$	$[-2.08]$
p-value*	0.07	0.02	0.09	0.04

Table XII presents the estimates of the cross-sectional regression of average excess returns of 25 size and book-to-market sorted portfolios on their exposure to temperature risks. Temperature exposure is estimated by regressing portfolio excess returns on the change in one- or five-year moving average of temperature controlling for market risk (Specification 1) plus macro-economic growth risk (Specification 2). The table shows the estimates of the price of temperature risk ($\hat{\lambda}_T$), the Fama and MacBeth (1973)-based t-statistics (t-stat in parentheses), and the Shanken (1992)-corrected t-statistics (t-stat* in brackets). The bottom line reports the proportion of Monte Carlo samples generated under the null that temperature risks have no effect on equity prices with a corrected t-statistic below the sample statistics. The data are annual and cover the 1934-2014 period.

Table XIII

Industry Exposure to Temperature Risks

	Horizon		
	1-year	3-year	5-year
High Heat-Exposed			
MINE	0.005	−0.111	−0.080
OILG	−0.022	−0.116	−0.112
CNST	−0.001	−0.108	−0.183
TRAN	−0.030	−0.053	−0.124
UTIL	−0.016	−0.003	−0.122
Average	−0.013	−0.078	−0.124
Low Heat-Exposed			
MANU	0.000	0.017	0.027
WHOS	0.011	−0.059	−0.050
RETS	0.006	0.062	0.014
SERV	0.004	0.013	0.069
COMM	0.004	0.045	0.061
Average	0.005	0.016	0.024

Table XIII shows exposure of industry portfolios to temperature risks estimated by regressing portfolio returns on the change in one-, three- or five-year moving average of temperature controlling for market risk. The data are annual and cover the 1934-2014 period.

Table XIV

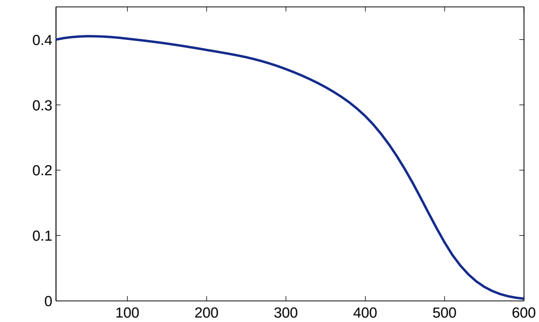
Industry Exposure to Temperature Risks: Panel Regression

	Horizon		
	1-year	3-year	5-year
$\hat{\phi}$	0.005	0.016	0.018
(t-stat)	(0.53)	(0.64)	(0.43)
p-value	0.73	0.76	0.68
$\hat{\phi}_H$	-0.017	-0.095	-0.136
(t-stat)	(-1.36)	(-2.65)	(-2.36)
p-value	0.15	0.02	0.03

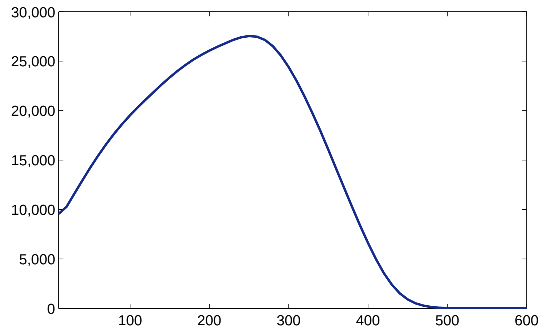
Table XIV presents the estimates of the following panel regression:

$$R_{i,t} = b_0 + \phi\, \Delta\overline{T}_t^K + \phi_H\, \Delta\overline{T}_t^K \cdot H_i + b_M\, R_{m,t} + \varepsilon_{i,t}$$

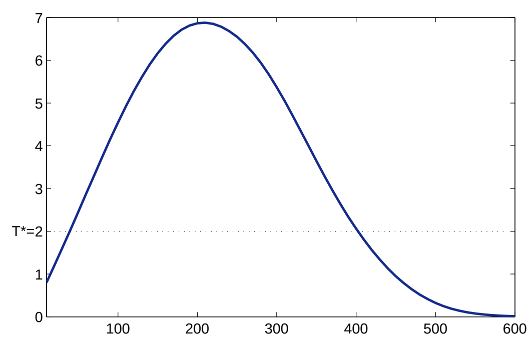
where $R_{i,t}$ is the time-t return of industry i, $\Delta\overline{T}_t^K$ is a change in the K-year moving average of temperature, H_i is a dummy variable that equals one if industry i belongs to a set of high heat-exposed industries, and $R_{m,t}$ is the return of the aggregate market portfolio. T-statistics are reported in parentheses; p-value is the proportion of Monte Carlo samples generated under the null that temperature risks have no effect on equity prices with a t-statistic below the corresponding sample statistics. The data are annual and cover the 1934-2014 period.



(a) Carbon Intensity



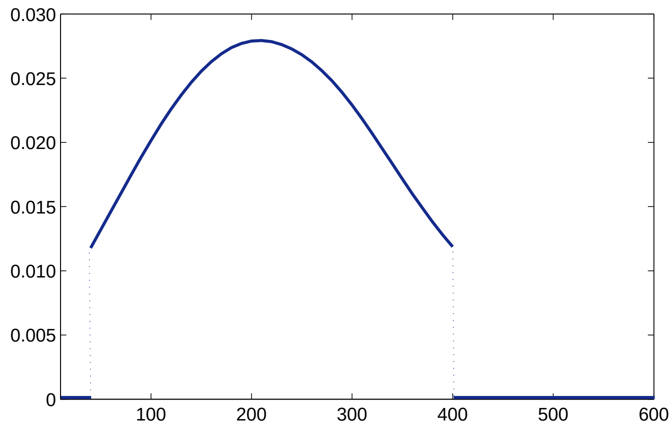
(b) Expected Path of Carbon Emissions



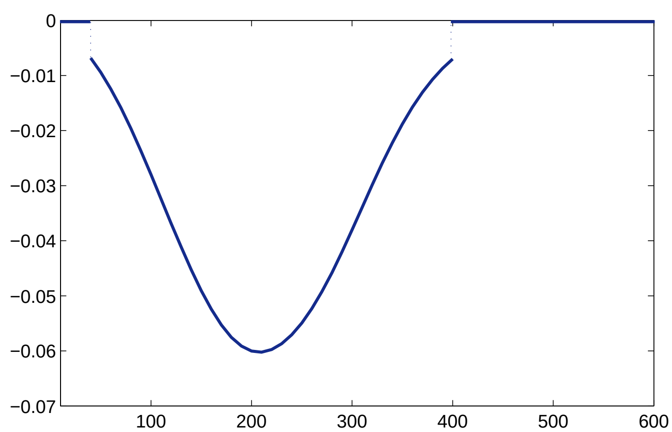
(c) Expected Path of Temperature Anomaly

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.



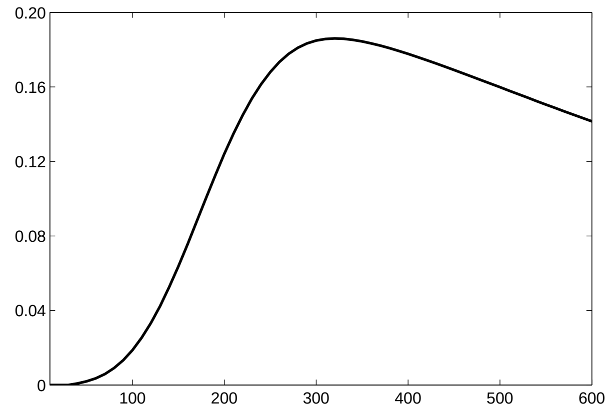
(a) Disaster Intensity



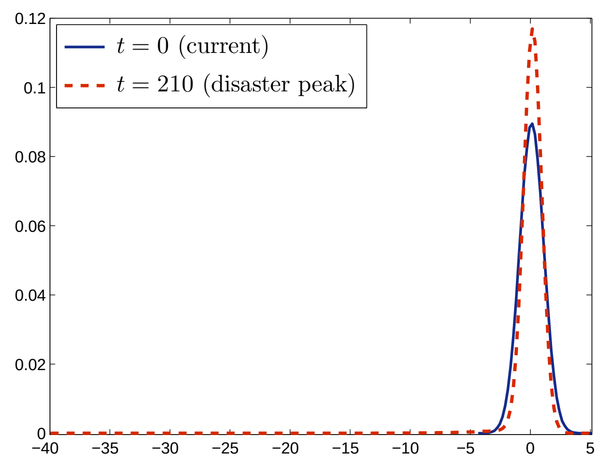
(b) Disaster Size

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.



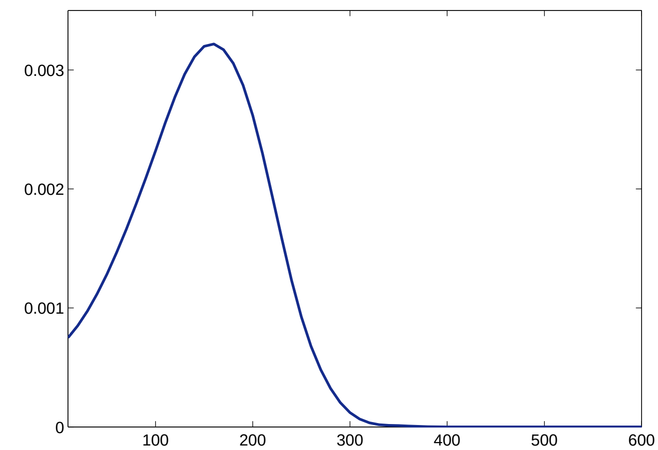
(a) Change in Ex-Ante Volatility



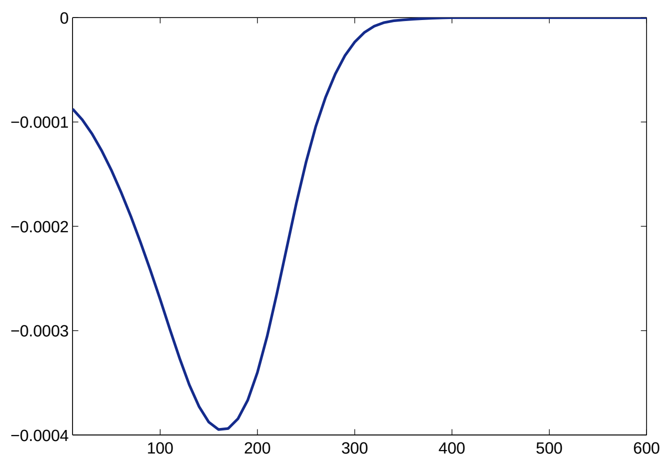
(b) Distribution of Consumption Growth

Figure 3. Implications of Global Warming for Consumption Growth

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



(b) Elasticity of W/C

Figure 4. Elasticity of the SDF and Wealth-Consumption Ratio to Emissions

Panel (a) of Figure 4 presents the elasticity of the stochastic discount factor (SDF) to a one-percent increase in time-0 emissions implied by the LRR-T model. Panel (b) presents the corresponding elasticity of the wealth-consumption ratio (W/C). The horizontal axis is the time-line measured in years from today.

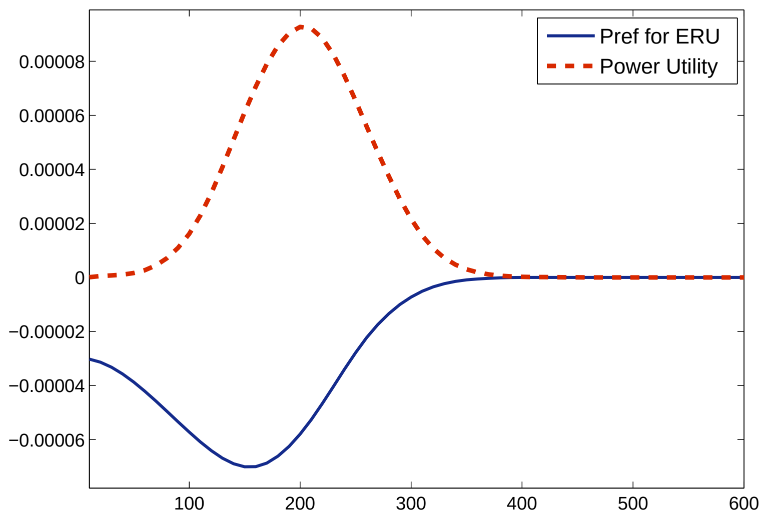


Figure 5. Sensitivity to Emissions

Figure 5 shows the elasticity of the wealth-consumption ratio to a one-percent increase in time-0 emissions for two alternative specifications of preferences: preferences for early resolution of uncertainty (Pref for ERU) and CRRA preferences (Power Utility). The horizontal axis is the time-line measured in years from today.

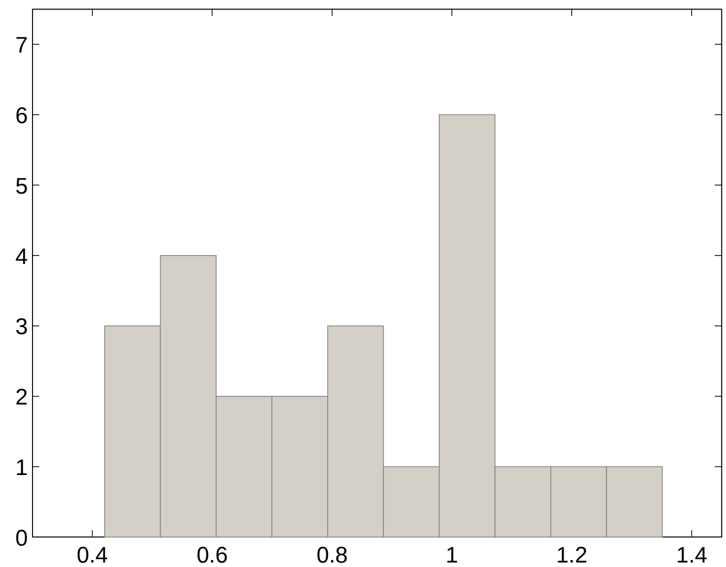


Figure 6. Histogram of the Trend in Local Temperature

Figure 6 shows the histogram of the trend in local temperature measured by the change in average temperature over the 2003-2012 period relative to the 1951-1980 average. The cross-sectional data comprise 39 countries; temperature is measured in degrees Celsius.

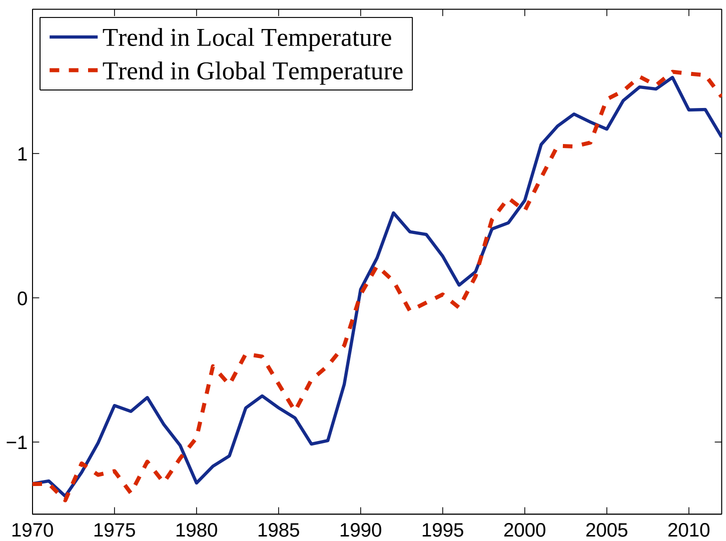
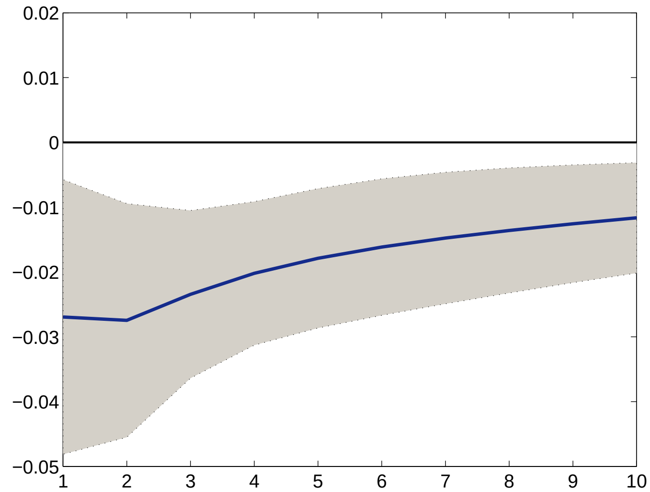
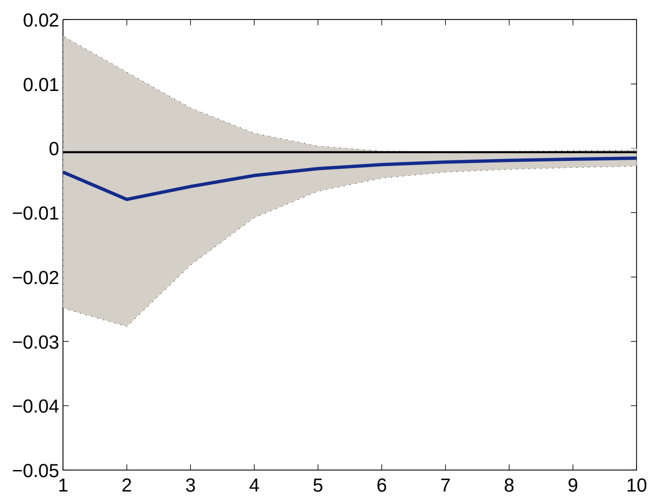


Figure 7. Trend in Local and Global Temperature

Figure 7 shows the first principal component of the five-year moving-average of local temperature series (solid line) and the five-year moving-average of global temperature (dashed line). The two time-series are normalized. The panel data comprise 39 countries over the 1970-2012 period.



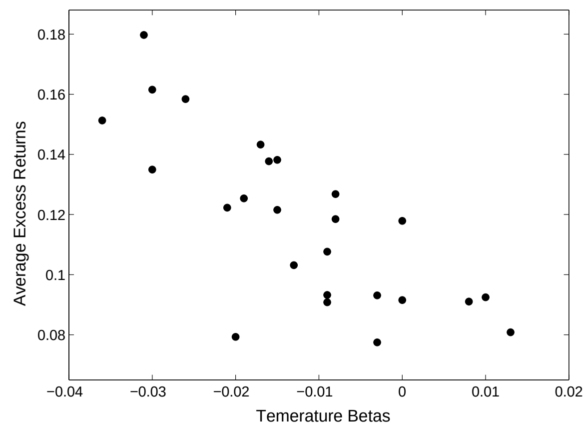
(a) Response to Long-Run Shock



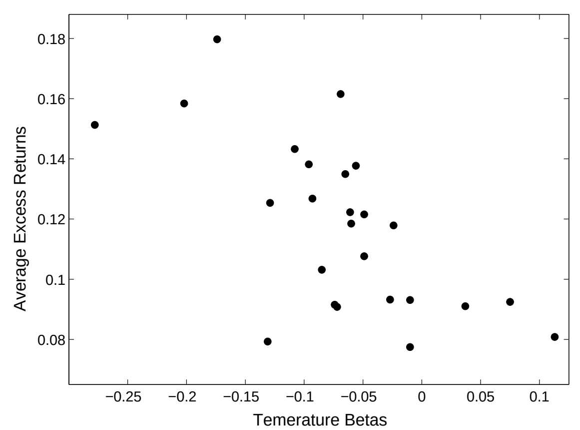
(b) Response to Short-Run Shock

Figure 8. Impulse Responses of Equity Prices to Long- and Short-Run Temperature Risks

Figure 8 presents impulse responses of the price-dividend ratio to long- and short-run temperature risks implied by a first-order VAR. The estimated responses are represented by the solid lines, the shaded areas show the two standard-error bands. Time-horizon on the horizontal axes is measured in years.



(a) Exposure to Variation in Annual Temperature



(b) Exposure to Variation in 5-year MA of Temperature

Figure 9. Exposure to Temperature

Figure 9 presents scatter plots of average excess returns and exposure to temperature variations of 25 size and book-to-market sorted portfolios. Panel (a) shows exposure to the annual change in temperature; Panel (b) presents exposure to the change in the five-year moving-average (MA) of temperature. Temperature betas are computed using market-adjusted returns; the data are annual and cover the 1934-2014 period.

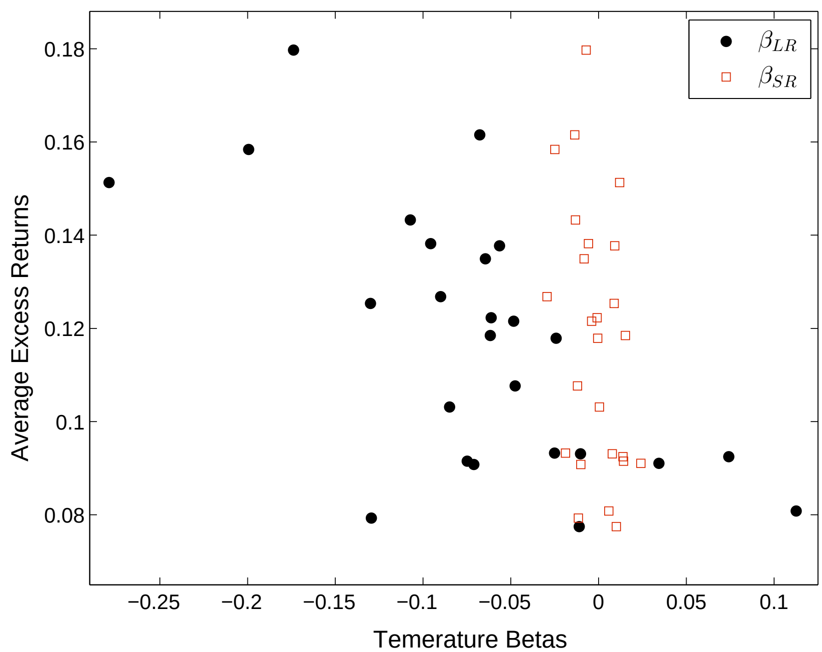
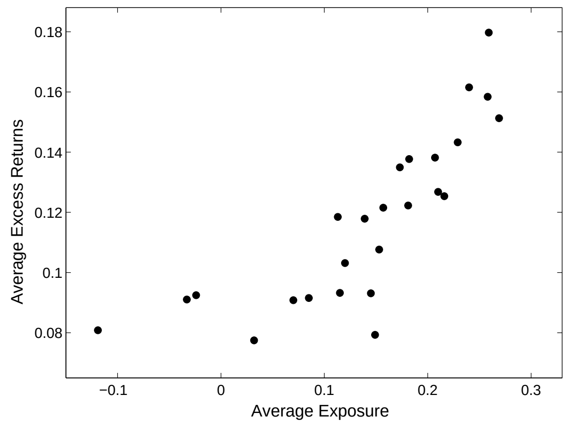
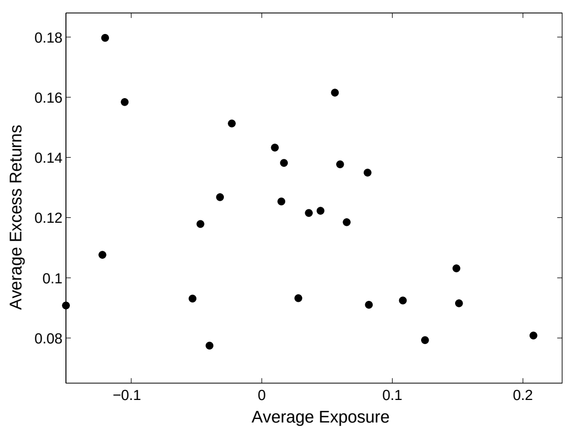


Figure 10. Exposure to Long- and Short-Run Temperature Fluctuations

Figure 10 presents scatter plots of average excess returns of 25 size and book-to-market sorted portfolios and their exposure to long- and short-run temperature fluctuations, β_{LR} and β_{SR}, respectively. Long-run temperature risks are measured by a change in the five-year moving average of temperature, short-run temperature risks are measured by variation in annual temperature orthogonalized with respect to long-run temperature risks. Temperature betas are computed using market-adjusted returns; the data are annual and cover the 1934-2014 period.



(a) Exposure to High Heat-Exposed Industries



(b) Exposure to Low Heat-Exposed Industries

Figure 11. Exposure to High and Low Heat-Exposed Industries

Figure 11 presents scatter plots of average excess returns and average exposure to high and low heat-exposed industries of 25 size and book-to-market sorted portfolios. Temperature betas are computed using market-adjusted returns; the data are annual and cover the 1934-2014 period.