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Climate change financial risks: implications for asset pricing and interest rates

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Abstract

In addition to tail macroeconomic events (e.g. wars, financial crises and pandemics), climate change poses a threat to financial stability – with extreme climatic events increasing in frequency and intensity and policy risks putting pressure on asset valuations. We study the effect of a changing climate on asset prices and interest rates through the lens of a dynamic CAPM with rare disasters, time-varying risk and recursive preferences. A changing climate makes former tail events more frequent and less predictable, increasing the premium of climate risk; interestingly, this change may not be fully reflected in the overall market risk premium that includes both components of risk: macroeconomic and environmental. The same is not true for interest rates and the participation of brown assets in the market portfolio, that are expected to decline unambiguously as the planet warms.

Keywords: Climate change; Tail events; Time-varying risk; Asset pricing; Interest rates
JEL classification: G11, G12, O44, Q51, Q54

1 Introduction

The financial literature has come a long way in explaining market behavior towards risk, and in particular asset pricing puzzles, by introducing models with tail macroeconomic events, recursive preferences and time-varying risk.[1] This approach suggests that a simple explanation for high risk premia and market volatility is that forward-looking risk-averse investors are concerned about market contractions during these low probability - high severity events, but also about the changes in risk itself. It is by now widely accepted that climate change risks pose such a risk to the stability of the financial system, for example, through losses of big levered financial intermediaries or sudden repricing of asset classes.[2] This is especially relevant if the risks of climate change are not properly incorporated in asset pricing and risk management methods that usually draw inferences from historical data, when the effects of climate change were much less pronounced, or even absent.

In the present paper we develop a forward-looking stochastic general equilibrium model to study analytically the asset-pricing implications of the co-existing and time-varying risks of tail events of multiple sources: macroeconomic, and those related to climate change. Our proxy for climate change is the change in global average temperature relative to a given time period, i.e., the temperature anomaly, for which we employ exogenous temperature paths that correspond to the representantive carbon concentration pathways (RCPs) produced by the IPCC (IPCC 2014). We link the time-varying climate-related risks with temperature anomaly and study how they may affect the various market measures, and in particular risk premia, interest rates, and the participation in the market portfolio of assets related to carbon-intensive technologies or processes; henceforth "brown". A motivation for the positive relationship between temperature anomaly and climate change risk is provided by Figure 1, which plots the number of most severe climate-related events against the temperature anomaly using 100 years of environmental disasters data for 42 countries.[3]

There are two types of climate-related risks that worry market participants: physical risks and transition risks (NGFS 2020). Physical risks, associated with physical damages to assets, could also be of two sorts: acute (e.g. droughts, floods, storms, wildfires), or chronic, related to long term climate shifts (e.g. sea level rise and changes in weather patterns). In our model we treat acute climate risks as infrequent shocks to the economy[4]; chronic risks are treated as gradual shifts of the climate risk distribution, increasing both the probability and the uncertainty of environmental events as a result of the rising global temperature, similar to the tipping points literature.[5] Transition risks include, among other components, policy risks which emerge from potential introduction of more stringent environmental policies that can affect the return

[1] Models with tail events include Rietz (1988), Barro (2006, 2009), Wang and Bidarkota (2009), Pindyck and Wang (2013), Jin (2015); examples of models with recursive preferences and time-varying risk are Gourio (2012), Wachter (2013), Seo and Wachter (2018), Gomes et al. (2018).

[2] E.g. Carney (2015), Stolbova et al. (2018), Bolton et al. (2020), Brunetti et al. (2021), Zenios (2021).

[3] See Hsiang et al. (2017) and Francis (2017) for the frequency and intensity of climate-related events.

[4] This has become a standard practice in climate-economic modelling; e.g. Bansal et al. (2016), Bretschger and Vinogradova (2018), Hambel et al. (2020), Giglio, Maggiori, Rao, Stroebel and Weber (2021).

[5] E.g. Cai et al. (2014), Lemoine and Traeger (2014), Cai and Lontzek (2019).

of brown assets.[6] Although it is unequivocal that such policies should (and will) be introduced, this may happen unexpectedly and only when extreme natural catastrophes affect public opinion (Bretschger and Soretz 2021). Such a situation of high transition risk with delayed stringent policies underlies for example the *disorderly transition scenario* of the NGFS network.[7] To capture this effect in our model we link policy risk with the risk of extreme environmental events and, therefore, policy risk is higher on a higher temperature path.

We adapt the multi-asset general equilibrium model with shocks of Ahn and Thompson (1988) to include recursive preferences, and stochastic, time-varying intensities of Poisson events in the spirit of Wachter (2013), yet of two kinds, macroeconomic and environmental. Including both sources of risk proves important. First, including time-varying macroeconomic risks allows us to calibrate our model to match observed risk premia, equity volatility and interest rates, for accepted values of risk aversion. Second, with closed-formed solutions, we expose the subtle feature of asset pricing models with time-varying risk of multiple sources that tend to overestimate aggregate risk premia when standard linear approximations are employed (Tsai and Wachter 2018). The same holds true for models with static disaster risk, or models that include only one source of risk of extreme events (e.g. Bansal et al. 2016, Giglio, Maggiori, Rao, Stroebel and Weber 2021)). This is of importance because as the climate changes, increases in the climate risk premium may not be fully reflected in the change of the aggregate market's risk premium that compensates investors for both sources of risk.

While the above implies that the equilibrium excess return on the market portfolio does not need to increase as climate changes, we show that the asset allocation decisions should. In addition to the two sources of risk, we consider two types of risky production opportunities: a general and a brown one. Macroeconomic and physical climatic events affect all assets homogeneously, while transition risks affect only the brown. Investors who care about consumption possibilities in the event of a downside risk optimally reduce their portfolio exposure to brown assets due policy uncertainty. Policy uncertainty has been shown to carry a premium in Pástor and Veronesi (2012), Sen and von Schickfus (2020) and Gala et al. (2020), while exposure to brown assets decreases in Hambel et al. (2020) by the social investor who internalizes the climate change externality, and in Pástor et al. (2021) when agents have preferences for green investments, while our result is driven by risk aversion.

Our results above relate also to recent empirical work documenting that climate change risks are considered by investors in their portfolio decisions. A survey about risk perceptions by Krueger et al. (2020) shows that most of the participants believe in portfolio management rather than exclusions for hedging against long-run climate change risks. De Haas and Popov (2019) show that carbon emissions are lower in countries which are more equity-funded and that stock-markets reallocate investments towards less polluting assets. Pérez-González and Yun (2013) use firm-level weather-hedging contracts and show that climate hedgers have higher valuations. Bolton and Kacperczyk (2021) find a positive and significant risk premium associated with

[6]For example, Batten et al. (2016) find contrasting cumulative abnormal returns experienced by a petroleum refining company and a wind turbine manufacturer the day after the announcement of the Paris agreement in December 2015.

[7]`https://www.ngfs.net/ngfs-scenarios-portal/`

carbon emissions. Only transition risks are found to be priced in Faccini et al. (2021). A positive carbon premium is associated with firms that demand more carbon permits in Oestreich and Tsiakas (2015). Ilhan et al. (2020) show larger option prices for extreme weather protection for firms with more carbon-intensive business models – especially at times when public attention to climate change is high (Pástor et al. 2021). Positive risk premia from climate change are also evident in Bansal et al. (2016), in a similar study to ours, yet without macroeconomic and transition risks. In comparison to us, they find that climate change unambiguously increases the excess return on the market portfolio. We show that this result is a limiting case in our model. Bretschger and Vinogradova (2018) and van der Ploeg and van den Bremer (2019) develop macroeconomic models with only climate-related disasters and static disaster risk.

With regards to interest rates, our model supports the hypothesis that the equilibrium real interest rate may keep declining as the planet warms (Bylund and Jonsson 2020, Schnabel 2021). This is due to the increasing harm to productivity and economic growth from physical climate-related events, transition risks (while transition risks decrease with lower exposure to brown assets), and due to the growing uncertainty of the underlying risks that follows the chronic shifts of temperature anomaly. All these forces tend to increase precautionary savings of risk-averse investors, feeding into the expectation that interest rates will remain low (Blanchard 2019, Rachel and Summers 2019), and hence unconventional monetary policy could persist (Schnabel 2021, ECB 2021).[8]

We also include a probability of government default due to macroeconomic and environmental disasters and study in closed-form the yield on short-term sovereign debt. The return on government debt features two opposing effects: a downward-sloping trend from the risk-free rate, and an opposing force from the default premium that grows with temperature. Our contribution remains methodological and seeks to advance the understanding of these forces in light of climate change. For example, there is a growing strand of literature that documents a positive relationship between climate change risk exposure and the cost of debt financing[9], that however tends to neglect the general equilibrium effects of a changing climate on the real interest rate, which is part of our contribution. Relevant to the above, Zenios (2021) performs a meticulous sovereign debt sustainability analysis with physical and transition risks, combining outputs from integrated assessment models with the debt-financing model of Zenios et al. (2021), yet abstracts from the effects of climate change risks on the real rate of interest. We show that with our disaster risk model and calibration based on historical data, the spread of sovereign debt may stay unaltered while benchmark historical calibration

To the best of our knowledge, this is the first paper to incorporate the stochastic and time-varying risk of extreme events related to both macroeconomic events and climate change in a general equilibrium dynamic asset pricing framework with Poisson shocks and to provide exact

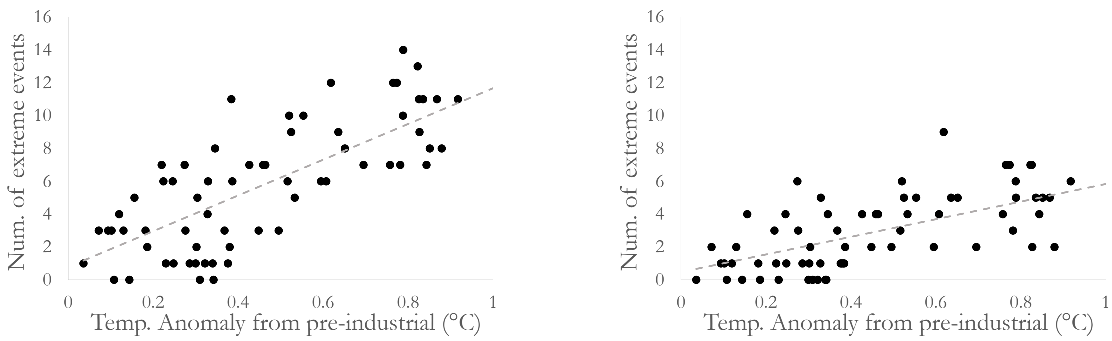
[8]Bylund and Jonsson (2020) also show that interest rates may keep declining, using a static disaster risk model with only one source of risk, calibrated to macroeconomic and not to environmental events as in the present paper. There is also a strand of literature that explores the role of environmental policies for monetary policy in the context of New-Keynesian models; e.g. Annicchiarico and Di Dio (2017), Economides and Xepapadeas (2018). A literature review can be found in Diluiso et al. (2021).

[9]E.g. Capelle-Blancard et al. (2019), Cevik and Tovar Jalles (2020), Battiston and Monasterolo (2021), Böhm (2021), Kling et al. (2021), Klusak et al. (2021), Lorans and Moussavi (2021).

closed-form solutions. The paper is organized as follows. The next section builds the theoretical framework and formally shows how climate change risks can affect various market measures such as risk premia, the riskfree rate and sovereign debt in our general equilibrium asset pricing model. Section 3 deals with simulations; it presents our numerical methodology and results. Section 5 concludes by summarizing our findings, discussing the limitations of our model and proposing possible avenues of further research. Proofs and specifics on calibration are relegated to the Appendix.

Figure 1: **Severe environmental events vs. temperature anomaly**; time period 1915-2015. The figure shows the yearly number of severe environmental events relative to changes in global temperature since pre-industrial. Panel (a) shows the top quintile in severity; slope coeff. 10.89, P-value < 0.001, Adj.$R^2 = 0.55$. Panel (b) shows the top decile in severity; slope coeff. 5.37, P-value < 0.001, Adj.$R^2 = 0.37$. The *severity index* is calculated as in Loayza et al. (2012); see Appendix E for more information.

(a) Top 20% in severity (b) Top 10% in severity



2 Theoretical foundations

2.1 Model setup

We build on the general equilibrium model of Cox et al. (1985a) and include jumps in the production possibilities of the economy as in Ahn and Thompson (1988) and time-varying risk as in Wachter (2013).[10] Yet we go one step ahead by including two sources of time-varying risk, i.e., pure macroeconomic disasters and disasters due to climate change, both due to physical and to transition risks.

Time is continuous and denoted by subscript t. Let there be a single physical numeraire good which may be allocated to consumption or investment. For parsimony, the production possibilities of the good comprise two distinct linear activities: a brown activity (B) which is subject to risk of stringent climate policy and a general activity (G) which differs from B in the

[10] The attractive feature of the model of Cox et al. (1985a) is that it provides a more rigorous general equilibrium representation of uncertain economic activity with endogenous production than the endowment economy setting, popularized by Lucas (1978).

sense that is not subject to any climate policy. The transformation of an investment of a vector $\theta = [Y_G, Y_B]^T$ of amounts of the numeraire good in the two production processes is governed by the following stochastic differential equations:

$$d\theta_t = \begin{bmatrix} Y_{Gt}\Big(\mu_G dt + \sigma_G dW_{Gt} + \sum_{j\in\{M,E\}}(e^{Z_G^j} - 1)dQ_t^j\Big) \\ Y_{Bt}\Big(\mu_B dt + \sigma_B dW_{Bt} + \sum_{j\in\{M,E\}}(e^{Z_B^j} - 1)dQ_t^j + (e^X - 1)dQ_t^X\Big) \end{bmatrix}. \tag{1}$$

The diffusion term $\mu_i Y_i dt + \sigma_i Y_i dW_i$ represents the behavior of production process $i = \{G, B\}$ in normal times (when no disasters take place), such that $\Delta \log Y_i$ over an interval Δt is normally distributed with mean $(\mu_i - \sigma_i^2/2)\Delta t$ and variance $\sigma_i^2 \Delta t$; W_i a standard Wiener process representing diffusion risk. Additionally, our model features two types of uncorrelated Poisson shocks that result in economic losses, namely macroeconomic (M) and environmental (E). Macroeconomic shocks are events like wars, economic crises and pandemics, while environmental shocks are severe events related to climate change like huricanes, droughts, floods and wildfires. Each shock Q_j, with $j \in \{M, E\}$, has a time-varying arrival rate λ^j. Brown production possibilities are also exposed to an infrequent policy shock Q^X that makes production less economically efficient. As the planet deviates from a path consistent with a low-temperature future, the increasing frequency and intensity of climate-related disasters are expected to accelerate the introduction and stringency of policies towards the transition to a low-carbon economy (Bretschger and Soretz 2021). To capture this correlation, we assume that the Poisson intensity of policy risk is related to the intensity of environmental disasters by $\lambda^X = \pi\lambda^E$, $\pi \in [0, 1]$.

Processes are denoted by subscripts and shocks by superscripts, i.e., $Z_i^j < 0$ denotes the drop in $\log Y_i$, $i \in \{G, B\}$, when an event of type $j \in \{M, E\}$ occurs. For ease of exposition, we assume that each firm operates in the same macroeconomic and natural environment and is subject to the same physical shock $Z^j < 0$; its time-invariant distribution z^j comes from the data and is independent of all other processes. The above discussion implies that $Z_G^M = Z_B^M = Z^M$, $Z_G^E = Z_B^E = Z^E$. When effective, stringent policy acts to further reduce the return on brown production by $X < 0$, which we assume certain for simplicity.[11] The operator $\mathbb{E}$ represents expectation with respect to the underlying distribution.

The system (1) of the available production opportunities specifies the growth of an initial investment when the output of each process is continuously re-invested in the same process, such that Y_{it} is also cumulative production within time period $[0, t]$ of the i-th process. While it does not mean that individuals will indeed re-invest this way, in the presence of stochastic returns to investment there exists a diversification motive that pushes investors to invest in both technologies in equilibrium, while as we show, this diversification motive is not enough to deter investors from reducing exposure to brown assets when climate policy risk is priced.

With regards to macroeconomic events Q^M, we follow Wachter (2013) and assume the

[11] The policy stringency X could in turn be an increasing function of the intensity of climate damages Z^E. However, this assumption would not alter the quality of the results, while it would impair the tractability of the model.

following mean-reverting process for the Poisson intensity λ^M:

$$d\lambda_t^M = \kappa^M(\bar{\lambda}^M - \lambda_t^M)dt + \sigma_\lambda^M \sqrt{\lambda_t^M} dW_{\lambda t}^M. \tag{2}$$

Variable W_λ^M is a standard Brownian motion, independent of all other processes. Parameter κ^M represents the adjustment speed of the process towards its mean $\bar{\lambda}^M$; σ_λ^M is a volatility parameter. The solution to (2) leads to a Gamma stationary distribution for λ^M, provided that both κ^M and $\bar{\lambda}^M$ are positive, which we will assume. This process has the attractive feature that λ^M can never become negative. Moreover, the square root in (2) implies that the resulting stationary distribution is highly right-skewed generating tail events, while at the same time, high realizations of λ^M make the process more volatile, and thus even higher realizations more likely, compared to a standard autoregressive process. Positive feedbacks are particularly relevant for climate-related risks (Melillo et al. 2017), the process of which we introduce now.

Our proxy for climate change is temperature anomaly T, i.e., the change in global average temperature relative to a given time period (e.g. for year 2015, T was about 1^oC compared to the mean of the pre-industrial period 1850-1900). Following the tradition of the time-varying risk literature, we assume a process similar to (2) for the arrival rate of natural disasters, while based on observations (Figure 1), the expected probability of natural disasters is an increasing and linear function of temperature anomaly. We, therefore, have:

$$d\lambda_t^E = \kappa^E(\bar{\lambda}^E(T_t) - \lambda_t^E)dt + \sigma_\lambda^E \sqrt{\lambda_t^E} dW_{\lambda t}^E, \tag{3}$$

with $\bar{\lambda}^E(T) \equiv \tilde{\lambda}^E + \xi T$ and $\{\tilde{\lambda}^E, \xi\}$ non-negative numbers; variable W_λ^E represents a standard Brownian motion, independent of all other processes. Note that, in comparison to (2), although this autoregressive process features mean reversion, the mean itself is changing with temperature anomaly. When temperature keeps rising out of balance natural disasters are becoming more frequent in expectation but less predictable, increasing climate change risk even further. Given temperature anomaly T, the solution of (3) has also a Gamma stationary distribution, where the constant mean and variance are increasing in T (proof in Appendix A).

Finally, the representative agent has the continuous-time analogue of recursive Epstein-Zin preferences, as formulated by Duffie and Epstein (1992a). Accordingly, we use the following recursion to define the utility function U,

$$U_t = \mathbb{E}_t \int_t^\infty f(C_s, U_s) ds, \tag{4}$$

where

$$f(C_t, U_t) = \rho(1-\gamma)U_t \left(\log C_t - \frac{1}{1-\gamma} \log((1-\gamma)U_t) \right). \tag{5}$$

Parameter $\rho > 0$ is the subjective rate of time preference, and $\gamma > 0$ measures relative risk aversion. We assume for simplicity that our utility function features a unitary elasticity of intertemporal substitution (EIS). We will conventionally focus on the case of $\gamma > 1$, which implies a preference for early resolution of uncertainty (Bansal and Yaron 2004).

2.2 Optimality conditions

We consider a representative investor who maximizes lifetime utility by allocating her wealth, net of consumption, among investments in the risky production opportunities and a riskless asset with an instantaneous rate of return r. Let $\{n_B, n_G\}$ be the fractions of wealth A invested in the brown and general risky technologies, respectively. Wealth then follows the process:[12]

$$\begin{aligned} dA_t =& \Big(\sum_{i\in\{G,B\}} n_{it} A_t(\mu_i - r_t) + A_t r_t - C_t \Big) dt + \sum_{i\in\{G,B\}} n_{it} A_t \sigma_i dW_{it} \\ &+ \sum_{i\in\{G,B\}} n_{it} A_t \Big(\sum_{j\in\{M,E\}} (e^{Z^j} - 1) dQ_t^j \Big) + n_{Bt} A_t (e^X - 1) dQ^X. \end{aligned} \tag{6}$$

Let $V(A, \lambda^M, \lambda^E)$ be the value function (maximized utility) in states $\{\lambda^M, \lambda^E\}$ with wealth A. Using (2), (3), (6), and Itô's Lemma, controls $v = \{C, n_i\}$, i.e., optimal consumption expenditure, and portfolio choices must satisfy the following Hamilton-Jacobi-Bellman equation (Duffie and Epstein 1992a):

$$\sup_v \{L^v(V(A, \lambda^M, \lambda^E)) + f(C, V(A, \lambda^M, \lambda^E))\} = 0 \tag{7}$$

with $L^v(\cdot)$ a differential operator defined as

$$\begin{aligned} L^v(V) =& V_A \Big(\sum_{i\in\{G,B\}} n_i A(\mu_i - r) + Ar - C \Big) + \frac{1}{2} V_{AA} A^2 \sigma^2 \\ &+ \sum_{j=\{M,E\}} \Big(V_{\lambda^j} \kappa^j (\bar{\lambda}^j - \lambda^j) + \frac{1}{2} V_{\lambda^j\lambda^j} (\sigma_\lambda^j)^2 \lambda^j + \lambda^j\, \mathbb{E}_{z^j}[\tilde{V}^j - V] \Big) + \pi \lambda^E [\tilde{V}^X - V]. \end{aligned} \tag{8}$$

The subscripts of V denote partial derivatives, i.e., $V_x = \partial V / \partial x$. Moreover,

$$\sigma = \sqrt{n_B^2 \sigma_B^2 + n_G^2 \sigma_G^2 + 2 n_B n_G \sigma_{GB}}, \tag{9}$$

$\sigma_{GB} \equiv \sigma_G \sigma_B \text{corr}[dW_G, dW_B]$; $\tilde{V}^j \equiv V(A(1 + \sum_{i\in\{G,B\}} n_i (e^{Z^j} - 1)), \lambda^M, \lambda^E)$, for $j \in \{M, E\}$; $\tilde{V}^X \equiv V(A(1 + n_B(e^X - 1)), \lambda^M, \lambda^E)$, the value function after the arrival of either disasters (or both together since they are uncorrelated) and policy, and $\bar{\lambda}^E = \tilde{\lambda}^E + \xi T$. Assuming an interior solution $(C, n_i > 0)$ we get the first order conditions w.r.t to C, n_G, n_B:

$$f_C = V_A, \tag{10}$$

$$r = \mu_G + \frac{V_{AA} A}{V_A} (n_G \sigma_G^2 + n_B \sigma_{GB}) + \sum_{j=\{M,E\}} \lambda^j\, \mathbb{E}_{z^j} \Big[\frac{\tilde{V}_A^j}{V_A} (e^{Z^j} - 1) \Big], \tag{11}$$

[12] Let $\mathcal{B}$ be the part of wealth A held in the riskless asset with an instantaneous rate of return r and denote with $d\mathcal{R}^A$ the stochastic gross return on wealth such that wealth accumulation follows $dA = d\mathcal{R}^A - Cdt$. The gross return to investment reads $d\mathcal{R}^A = dY_B + dY_G + r\mathcal{B}dt$. Defining as $\{n_B, n_G\}$ the fractions of wealth held in the brown and general risky activities the above with (1) leads to (6).

$$
r = \mu_B + \frac{V_{AA}A}{V_A}(n_B\sigma_B^2 + n_G\sigma_{GB}) + \sum_{j=\{M,E\}} \lambda^j \, \mathbb{E}_{z^j}\left[\frac{\tilde{V}_A^j}{V_A}(e^{Z^j}-1)\right] \\
+\pi\lambda^E \frac{\tilde{V}_A^X}{V_A}(e^X - 1). \quad (12)
$$

Equation (10) is the usual envelope condition for the price of consumption. The system of equations (11) and (12) solves the investor's risky portfolio allocation problem given the riskfree rate, risk and policy. In equilibrium it holds that the riskfree asset is in zero net supply such that $n_B + n_G = 1$. Using this for n_G and equating the right hand sides of (11) and (12) yields a no-arbitrage condition between risky assets; after adjusting for their relative risk, each risky asset should yield the same marginal expected return:

$$
\mu_B + \frac{V_{AA}A}{V_A} n_B(\sigma_B^2 - \sigma_{GB}) + \pi\lambda^E \frac{\tilde{V}_A^X}{V_A}(e^X - 1) = \\
\mu_G + \frac{V_{AA}A}{V_A}(1-n_B)(\sigma_G^2 - \sigma_{GB}). \quad (13)
$$

Equation (13) will be used to calculate the optimal portfolio allocation n_B. Note that as in Hambel et al. (2020) there are two opposing effects relevant for portfolio composition. On the one hand both assets are needed in general for a diversified portfolio; in particular, from (9) portfolio volatility in times without disasters is a convex quadratic function of n_B, which takes its minimum value at $n_{B,min} = \frac{\sigma_G^2 - \sigma_{GB}}{\sigma_G^2 + \sigma_B^2 - 2\sigma_{GB}}$, with $\sigma_{GB} = \sigma_G\sigma_B \mathrm{corr}[dW_G, dW_B]$. The magnitude of this diversification motive against diffusion risk is less pronounced for high values of the correlation coefficient; zero correlation amplifies the diversification motive, which is most pronounced for negative values of the correlation coefficient. On the other hand, since both assets are equally exposed to extreme Poisson events of either type, the investor reacts only to policy risk on climate-sensitive assets, which reduces the diversification motive and lowers n_B.

2.3 The value function

In Appendix B we derive the value function in closed form.

Proposition 1 *(Value function) For preferences defined by* (4) *and* (5)*, the value function that solves* (7) *reads*

$$
V(A, \lambda^M, \lambda^E) = \frac{A^{1-\gamma}}{1-\gamma} e^{a + \sum_{j\in\{M,E\}} b^j \lambda^j}, \quad (14)
$$

with

$$
\begin{aligned}
b^M &= \frac{\kappa^M+\rho}{(\sigma_\lambda^M)^2} - \sqrt{\left(\frac{\kappa^M+\rho}{(\sigma_\lambda^M)^2}\right)^2 - 2\frac{\mathbb{E}_{z^M}\left[e^{(1-\gamma)Z^M}-1\right]}{(\sigma_\lambda^M)^2}},\\
b^E &= \frac{\kappa^E+\rho}{(\sigma_\lambda^E)^2} - \sqrt{\left(\frac{\kappa^E+\rho}{(\sigma_\lambda^E)^2}\right)^2 - 2\frac{\mathbb{E}_{z^E}\left[e^{(1-\gamma)Z^E}-1\right]+\pi[(1+n_B(e^X-1))^{1-\gamma}-1]}{(\sigma_\lambda^E)^2}},\\
a &= (1-\gamma)(\log\rho-1) + \frac{1-\gamma}{\rho}\left(\sum_{i\in\{G,B\}} n_i\mu_i - \frac{1}{2}\gamma\sigma^2\right) + \sum_{j\in\{M,E\}} b^j\frac{\kappa^j\bar{\lambda}^j}{\rho}.
\end{aligned}
\tag{15}
$$

The propensity to consume out of wealth is constant and equal to ρ, i.e., $C=\rho A$.
□

The fact that the quantities under the root of (15) have to be positive places a joint restriction on the severity of disasters, the risk aversion, the rate of time preference and the volatility of disasters (Seo and Wachter 2018). For $\gamma > 1$ that we assume, $b_j > 0$, $j \in \{M, E\}$, such that draws of higher risk (higher λ^j) reduce the indirect utility of the risk-averse representative agent – and thus increase the marginal utility, i.e. $V_{\lambda^j} < 0$ and $V_{A\lambda^j} > 0$. Equity premia arise from the co-movement of the marginal utility with the price process of the underlying asset, such that increases in marginal utility should be compensated by higher premia when market prices drop in light of such risk.[13]

2.4 The riskfree rate and the return on government debt

Let m denote the state-price density (or pricing kernel) – with the same risk properties as the marginal utility of the risk-averse investor as discussed above. Long-lived assets with a dividend stream $D_t dt$ can be priced according to the usual asset pricing equation $P_t = \mathbb{E}_t\left[\int_t^\infty \frac{m_s}{m_t} D_s ds\right]$. In Appendix C we prove the following expressions:

Proposition 2 *(State-price density and riskfree rate) Let $dW_m = [dW_B, dW_G, dW_\lambda^M, dW_\lambda^E]$, and $dQ = [dQ^M, dQ^E, dQ^X]$. The state-price density has the following dynamics:*

$$
\frac{dm}{m} = \mu_m dt + \sigma_m dW_m^T + (e^{Z_m}-1)dQ^T, \tag{16}
$$

with

$$
\mu_m = -r - \sum_{j\in\{M,E\}} \lambda^j\,\mathbb{E}_{z^j}\left[e^{-\gamma Z^j}-1\right] - \pi\lambda^E\left[(1+n_B(e^X-1))^{-\gamma}-1\right], \tag{17}
$$

$$
\sigma_m = [-\gamma n_B\sigma_B, -\gamma(1-n_B)\sigma_G, b^M\sigma_\lambda^M\sqrt{\lambda^M}, b^E\sigma_\lambda^E\sqrt{\lambda^E}], \tag{18}
$$

and

$$
e^{Z_m}-1 = [e^{-\gamma Z^M}-1, e^{-\gamma Z^E}-1, (1+n_B(e^X-1))^{-\gamma}-1]. \tag{19}
$$

[13] The conditions for the sign of the climate risk premium are discussed in Dietz et al. (2018) and Giglio, Kelly and Stroebel (2021).

The risk-free rate reads:

$$r = \underbrace{\rho + g - \gamma\sigma^2}_{\text{standard model}} + \sum_{j=\{M,E\}} \underbrace{\lambda^j \, \mathbb{E}_{z^j}\left[e^{-\gamma Z^j}(e^{Z^j} - 1)\right]}_{\text{macroec. \& environ. risk}} + \underbrace{\pi\lambda^E\left[(1 + n_B(e^X - 1))^{-\gamma} n_B(e^X - 1)\right]}_{\text{policy risk}} \tag{20}$$

with $g \equiv \sum_{i\in\{G,B\}} n_i\mu_i - \rho$*, the growth rate of consumption in an economy without risk,* $b_M, b_E > 0$ *from* (15)*,* $n_B + n_G = 1$ *and* n_B *at its optimum level from* (13)*.*
□

Since $e^{Z_m} - 1 \geq 0$, according to (16), in the event of a macroeconomic, environmental, or policy shock marginal utility jumps upwards, increasing investor's required compensation for bearing risk in times of weaker growth prospects. In general, higher risk induces precautionary savings, which reduces the riskfree rate; the greater the risk aversion γ the greater is this effect. Volatility aside, the risk-free rate is decreasing in the time-varying disaster probabilities λ^j and in the exposure to these disasters through Z^j. A high future temperature path increases the probability of natural disasters λ^E and environmental policy, both reducing the riskfree rate. Equation (20) can be readily used to infer possible evolutions of the riskfree rate for various temperature scenarios (that effectively change the distribution of λ^E), portfolio composition n_B (which may, or may not, be set at its optimal value from (13) given (14)) and distributions z^j of disaster magnitutes.

In the expectation that disasters may coinside with at least partial default on government securities, one can use equation (20) to also deduce their effect on sovereign credit risk. Specifically, following Barro (2006) and Tsai and Wachter (2015), we assume that in the event of a disaster $j \in \{M, E\}$ there will be a default on government liabilities with probability q^j and when default happens the percentage loss is equal to the percentage decline in consumption; consumption follows (29) in the Appendix. Let r^L denote the instantaneous return on government credit if there were no default (face value), so the observed premium on government debt in samples without disasters is given by

$$r^L - r = \sum_{j=\{M,E\}} q^j \lambda^j \, \mathbb{E}_{z^j}\left[e^{-\gamma Z^j}(1 - e^{Z^j})\right] + \pi q^E \lambda^E\left[(1 + n_B(e^X - 1))^{-\gamma} n_B(1 - e^X)\right], \tag{21}$$

while the instantaneous expected return on government debt can be written as

$$r^b \equiv r^L + \sum_{j=\{M,E\}} q^j \lambda^j \, \mathbb{E}_{z^j}\left[e^{Z^j} - 1\right] + \pi q^E \lambda^E\left[n_B(e^X - 1)\right].$$

From the above, the spread of the government bond against the riskfree rate reads

$$\begin{aligned} r^b - r = &\sum_{j=\{M,E\}} q^j \lambda^j \, \mathbb{E}_{z^j} \left[(e^{-\gamma Z^j} - 1)(1 - e^{Z^j}) \right] \\ &+ \pi q^E \lambda^E \left[((1 + n_B(e^X - 1))^{-\gamma} - 1) n_B (1 - e^X) \right], \end{aligned} \tag{22}$$

where the first term captures macroeconomic and physical environmental disasters while the second captures the transition risk due to e.g. the abrupt repricing of large climate-sensitive assets in public ownership such as coal mines or energy utilities (Zenios 2021). Both terms are positive since they have the interpretation of a disaster risk premium for sovereign risk: the percentage change in marginal utility is multiplied by the percentage loss on the government debt claim.

Equations (20) and (22) show that the riskfree rate is expected to decline as the planet warms due to increasing climate risks, while sovereign bond yield spreads should increase, especially for governments with greater exposure to brown assets, i.e., higher n_B, because of climate policy that responds to deviations from low temperatures (Lorans and Moussavi 2021). This may be of particular importance in an already low-interest environment because it leaves less room to central banks for effective inflation targeting via the standard Taylor rule and hence unconventional monetary policy could persist (Schnabel 2021, ECB 2021).

2.5 The market premium of climate change risk

In order to price climate change risks for long-lived assets we follow Abel (1999), Campbell (2003), Wachter (2013) and assume that the aggregate market pays a dividend D, being leveraged consumption, i.e., $D = C^\eta$; in the event of a negative shock dividends fall more than consumption when $\eta > 1$ which we assume (Longstaff and Piazzesi 2004). Equity premia arise from the co-movement of marginal utility of the risk-averse investor with the price of the underlying asset or portfolio, both in normal times and times of disasters. Let R be the expected return on equity; the risk-premium is then calculated by $R - r = -\sigma_m \sigma_P^T - [\lambda^M, \lambda^E, \lambda^{pol}] \, \mathbb{E}[(e^{Z_m} - 1) \circ (e^{Z_P} - 1)]^T$, with σ_P and $(e^{Z_P} - 1)$ denoting, respectively, the volatility and the expected drop vectors of the corresponding price process for the dividend claim D, $\lambda^{pol} = \pi \lambda^E$, the Poisson intensity of the policy shock, σ_m and $(e^{Z_m} - 1)$ from Proposition 2, and $\circ$ denoting element-wise multiplication. We prove in Appendix D the following proposition regarding the price of such dividend claim, along with the aggregate risk premium:

Proposition 3 *(Prices and risk premium) Let the aggregate market's dividend be leveraged consumption $D = C^\eta$ with $\eta > 1$. The price-dividend ratio for the aggregate market $G \equiv P/D$ is calculated exactly by:*

$$G(\lambda^M, \lambda^E) = \int_0^\infty e^{a_\eta(s) + b_\eta^M(s)\lambda^M + b_\eta^E(s)\lambda^E} ds, \tag{23}$$

with $a_\eta(s), b^j_\eta(s)$ solutions to the following system of differential equations:

$$a'_\eta(s) = \mu_D - g - \rho + (1-\eta)\gamma\sigma^2 + \sum_{j\in\{M,E\}} \kappa^j \bar{\lambda}^j b^j_\eta(s), \tag{24}$$

$$\begin{aligned}(b^M_\eta)'(s) &= \frac{1}{2}(\sigma^M_\lambda b^M_\eta(s))^2 + (b^M(\sigma^M_\lambda)^2 - \kappa^M)b^M_\eta(s) + \mathbb{E}_{z^M}\left[e^{(\eta-\gamma)Z^M} - e^{(1-\gamma)Z^M}\right],\\ (b^E_\eta)'(s) &= \frac{1}{2}(\sigma^E_\lambda b^E_\eta(s))^2 + (b^E(\sigma^E_\lambda)^2 - \kappa^E)b^E_\eta(s) + \mathbb{E}_{z^E}\left[e^{(\eta-\gamma)Z^E} - e^{(1-\gamma)Z^E}\right]\\ &\quad +\pi\left[(1+n_B(e^X-1))^{\eta-\gamma} - (1+n_B(e^X-1))^{1-\gamma}\right],\end{aligned} \tag{25}$$

$a_\eta(0) = b^M_\eta(0) = b^E_\eta(0) = 0$, and $\mu_D = \eta g + \frac{1}{2}\eta(\eta-1)\sigma^2$. The market's risk premium reads:

$$\begin{aligned}R - r = \eta\gamma\sigma^2 - \sum_{j\in\{M,E\}} \overbrace{\lambda^j \frac{1}{G}\frac{\partial G}{\partial\lambda^j}}^{\epsilon_j} b^j(\sigma^j_\lambda)^2 - \sum_{j\in\{M,E\}} \lambda^j\, \mathbb{E}_{z^j}\left[(e^{-\gamma Z^j} - 1)(e^{\eta Z^j} - 1)\right]\\ -\pi\lambda^E\left[(1+n_B(e^X-1))^{-\gamma} - 1\right]\left[(1+n_B(e^X-1))^{\eta} - 1\right].\end{aligned} \tag{26}$$

□

Since for $s = 0$ an asset should pay its current dividend, boundary conditions are $a_\eta(0) = b^M_\eta(0) = b^E_\eta(0) = 0$. For $\eta > 1$, both $a_\eta(s)$ and $b^j_\eta(s)$ are well defined functions of s such that the infinite integral G converges. The solution to (25) with the previous boundary conditions yields $b^j_\eta(s) < 0$, $j \in \{M, E\}$. According to (23), this implies that, ceteris paribus, draws of high disaster risk – macroeconomic, environmental, or policy-related– reduce valuations. Since marginal utility also increases during these times, risk premia should be positive.

The first two terms in the risk premium represent the correlated movement between the pricing-kernel and market prices in times without disasters, while the third term represents the same thing in the event of an economic shock – triggered either from rare macroeconomic disasters such as wars and financial crises, or from natural disasters; the last term captures policy risk, i.e., the policy premium. While the first term, the risk premium in the standard CAPM, is very small for acceptable values of the risk aversion coefficient, the second term that arises from the time variation in disaster risk is substantial (Wachter 2013). In addition, in our model the gradual temperature increase shifts the distribution of climate risk λ^E to higher draws and at the same time increases its volatility (Figure 4 in the next section), making future growth prospects even more uncertain, thus increasing the share of climate change risks in the equity premium.

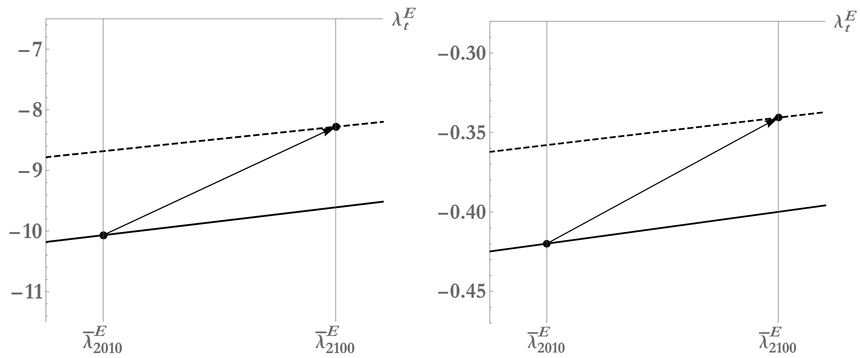
Of importance is the term $\epsilon_j \in [-1, 0]$, defined in (26). Loosely speaking, this term represents the risk "elasticity of valuations", i.e., the variation in the price-dividend ratio in response to variations in macroeconomic and/or climate risk. This term can be decomposed in two parts: the "semi-elasticity of valuations", $\Delta \log G/\Delta\lambda^j$, measuring the percentage change in G from a unit increase in λ^j; and the risk λ^j itself. On the one hand, from (23) and (24), with rising temperatures the increasing expected risk of environmental events ($\bar{\lambda}^E$) puts a downward pressure on equity valuations, which leaves less room for prices to react to high draws of risk of either type. This level effect reduces the magnitude of the semi-elasticity of valuations for both types of disasters (Figure 2). On the other hand, as climate changes, the distribution of climate risk shifts to higher draws, while the one of macroeconomic risk stays unaltered, which increases the magnitude of the elasticity of valuations for climate risk through its second part, i.e. the risk itself, and also the relative importance of this type of risk even in times without disasters (Figure 3). The equity premium of climate change (whatever multiplies λ^E in (26)) is increasing but this increase is mitigated by the losing importance of macroeconomic events. Since, however, the risk of rare macroeconomic events makes up the largest part of the equity premium, the magnitude of the aggregate equity risk premium may only be minimally affected, while – depending on calibration – it might also decline. This result suggests that, as climate changes, assets that feature relatively lower climate change (but possibly higher macroeconomic) risk work as a hedging strategy against the risk of climate change and should therefore be rewarded with a lower premium.

The above subtle relationship between sources of time-varying risk, that works through equity valuations on risk premia, is obscured in models with log-linearization of the price-dividend ratio (Tsai and Wachter 2018). To see this, suppose a log-linear approximation of (23) in the state variables in the spirit of Campbell and Shiller (1988), i.e. $\log G(\lambda^M, \lambda^E) \approx \tilde{a}_\eta + \sum_j \tilde{b}^j_\eta \lambda^j$, with $\tilde{a}_\eta, \tilde{b}^j_\eta$ scalars and $\tilde{b}^j_\eta < 0$. The semi-elasticity in this case is just a constant, i.e. $\Delta \log G/\Delta\lambda^j \approx \tilde{b}^j$, while the elasticity of valuations in (26) is a linear function of λ^j, i.e. $\epsilon_j \approx \tilde{b}^j \lambda^j$. The overall equity premium now reads:

$$R - r \approx \eta\gamma\sigma^2 - \sum_{j\in\{M,E\}} \lambda^j \tilde{b}^j (\sigma^j_\lambda)^2 - \sum_{j\in\{M,E\}} \lambda^j \,\mathbb{E}_{z^j}\left[(e^{-\gamma Z^j} - 1)(e^{\eta Z^j} - 1)\right] \\ -\pi\lambda^E \left[(1 + n_B(e^X - 1))^{-\gamma} - 1\right]\left[(1 + n_B(e^X - 1))^{\eta} - 1\right],$$

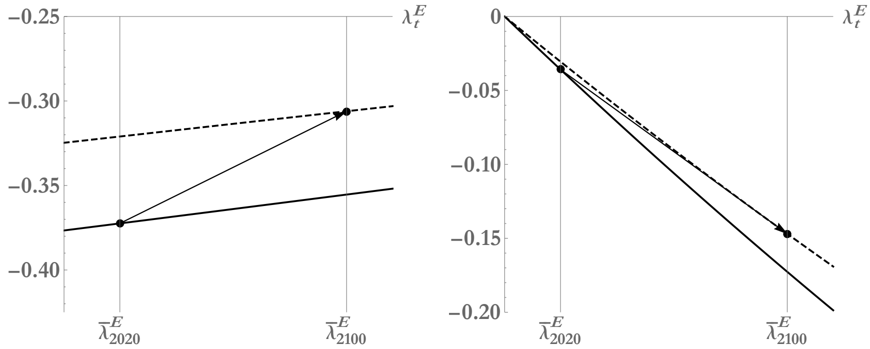
which is unambiguously increasing in both λ^E and λ^M.

Figure 2: **"Semi-elasticity" of valuations $\frac{1}{G}\frac{\partial G}{\partial \lambda^j}$ as climate changes.** Assuming temperature path follows RCP8.5 (IPCC 2014), the figures show this term as a function of the probability of extreme environmental events λ^E_t. The solid line shows this term for $\bar{\lambda}^E_{2010}$; the dashed line for $\bar{\lambda}^E_{2100}$; the arrow shows the transition. Macroeconomic risk λ^M_t is set at its equilibrium value $\bar{\lambda}^M$. See Appendix E for specifics on calibration.



(a) $j = M$ (b) $j = E$

Figure 3: **"Elasticity of valuations"** $\epsilon_j = \lambda^j \frac{1}{G}\frac{\partial G}{\partial \lambda^j}$ **as climate changes.** Assuming temperature path follows RCP8.5 (IPCC 2014), the figures show this term as a function of the probability of extreme environmental events λ_t^E. The solid line shows this term for $\bar{\lambda}_{2010}^E$; the dashed line for $\bar{\lambda}_{2100}^E$; the arrow shows the transition. Macroeconomic risk λ_t^M is set at its equilibrium value $\bar{\lambda}^M$. See Appendix E for specifics on calibration.



(a) $j = M$ (b) $j = E$

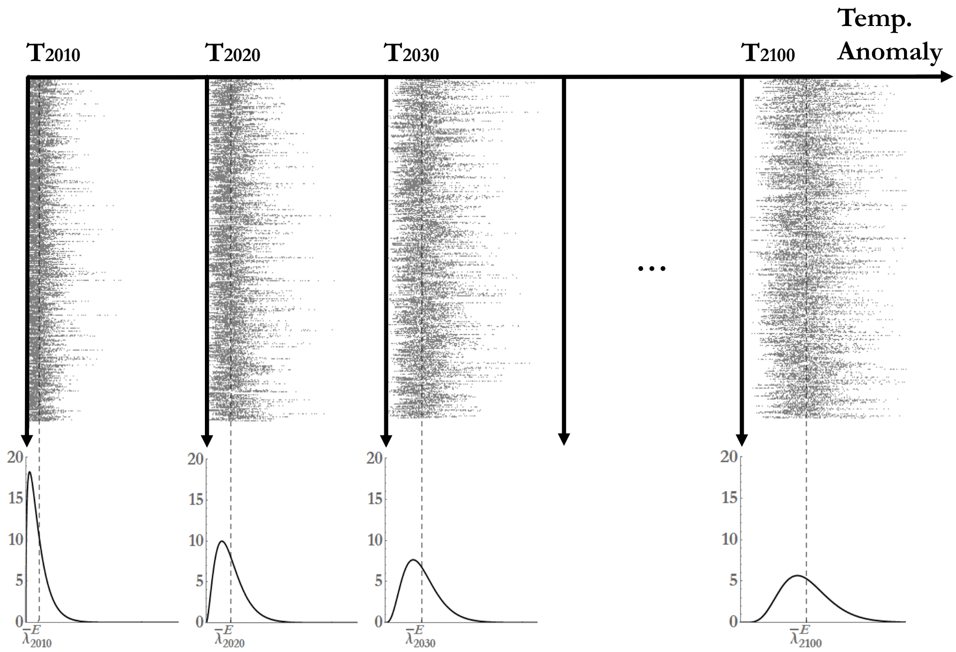
3 Numerical part

In this section we calibrate our model using historical data on GDP contractions from extreme macroeconomic and environmental events and make forward-looking projections for temperature anomalies that follow scenarios RCP2.6 and RCP8.5 of the IPCC (IPCC 2014). Details on the calibration can be found in Appendix E. This section two parts. First, we explore for the two scenarios the effect of the physical risk of extreme environmental events on the various market measures by setting policy to zero ($X = 0$). We show that in our calibration that matches US historical data, the equity risk premium increases as the planet warms, the riskfree rate drops, while the spread on short-term sovereign debt is only minimally impacted. Second, we include policy ($X < 0$) and show that a slow portfolio decarbonization, in contrast to right-off exclusion of brown assets, yields the optimal solution for the investor. In the next section we discuss our results, possible extensions of the benchmark model in terms of modeling assumptions, calibration and applications to different economies.

3.1 Methodology

The usual methodology in asset pricing models assumes time-invariability of the system under study. This allows for a straightforward Monte-Carlo simulation using a large number of random realizations of the relevant stochastic variables. A changing climate, however, changes the distribution of climate risk λ^E, such that our model is not time-invariant; see equation (3) and Appendix A. We circumvent this issue by assuming that our model is time-invariant for each given level of temperature and simulate the model for each $\bar{\lambda}^E(T)$. We divide our time horizon (2010-2100) in decades, and sample each decade 100,000 times. Figure 4 presents our methodology along with the resulting stationary Gamma distribution for λ^E for increasing temperature anomaly.

Figure 4: **Schematic of the simulation methodology.** For each decade (2010-2019, 2020-2029, ...) we keep temperature at the projected mean of the period and draw 100,000 samples. The figure assumes an a temperature path consistent with RCP8.5 (IPCC 2014).



3.2 Simulation results

3.2.1 The physical risk of climate change

In this part we explore the pure effects of climate change risk on market fundamentals, with a focus on the equity premium and interest rates. Figure 5 presents the effect of the two RCP scenarios on risk premia. The risk premium on the aggregate market (left panel) increases only a little with global warming from its current value of 7.1% to 7.9% p.a. for the worst case scenario (RCP8.5); its change is insignificant in the best case scenario (RCP2.6) where temperature in the end of the century reaches 1.5^oC. From (26) we can get the part of the equity premium that is solely due to climate change risk. As the right panel of Figure 5 shows, with our calibration the risk premium of climate change amounts to about 0.5% in 2020; the remaining part of the aggregate equity premium is mainly due to the risk of rare macroeconomic disasters, and only a very small part is due to the standard CAPM's diffusion risk. The climate risk premium from extreme environmental events increases to about 1.8% p.a. by the end of the century in the worst case scenario (RCP8.5).

According to our discussion in section 2.5, from (23) and (24), higher temperatures – which increase $\bar{\lambda}^E$ – affect the way in which valuations react to the different kinds of risk. With our calibration, climate warming reduces valuations (see Appendix D) and the magnitude of the risk elasticity of valuations for macroeconomic disasters ϵ^M in (26), while it increases the one for environmental ϵ^E. Therefore, increasing temperatures, change the relative importance of the two sources of risk in normal times and alongside their contribution to the premium of the aggregate market. With regards to interest rates, higher temperatures unambiguously decrease the riskfree rate in our model, while with our calibration the spread on short-term government debt due to extreme climatic events is positive but only minimally affected by temperature changes; see Figure 6.

Figure 5: **Aggregate equity premium – left; climate risk premium – right (percent p.a.)**

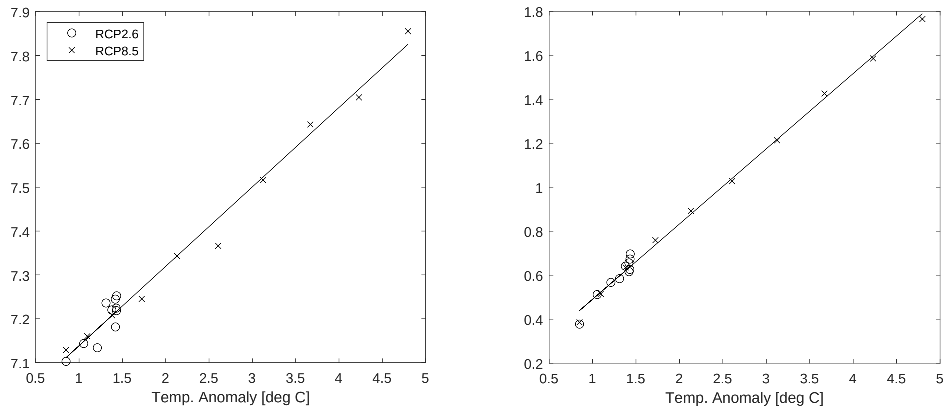
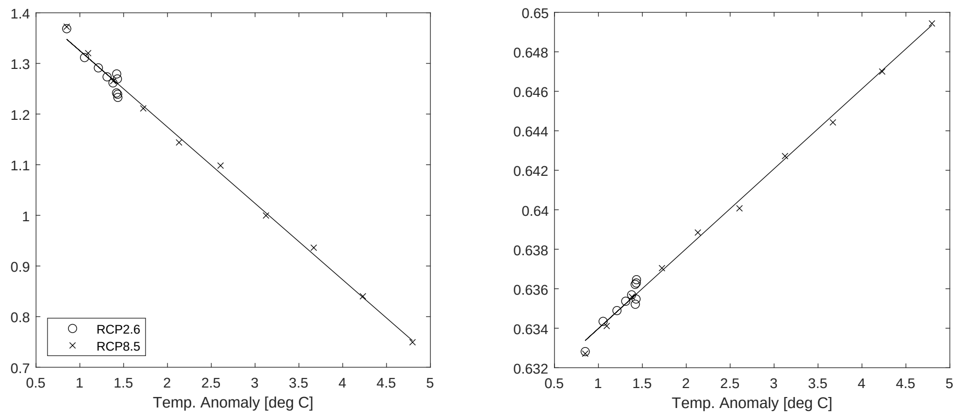


Figure 6: **Riskfree rate – left; spread on sovereign debt – right (percent p.a.)**



3.2.2 Policy risk and portfolio participation of brown assets

Our benchmark calibration assumes that there is no additional policy risk on brown assets, the share of which we calibrate to $n_B = 0.3$ by choosing appropriately the model parameters;

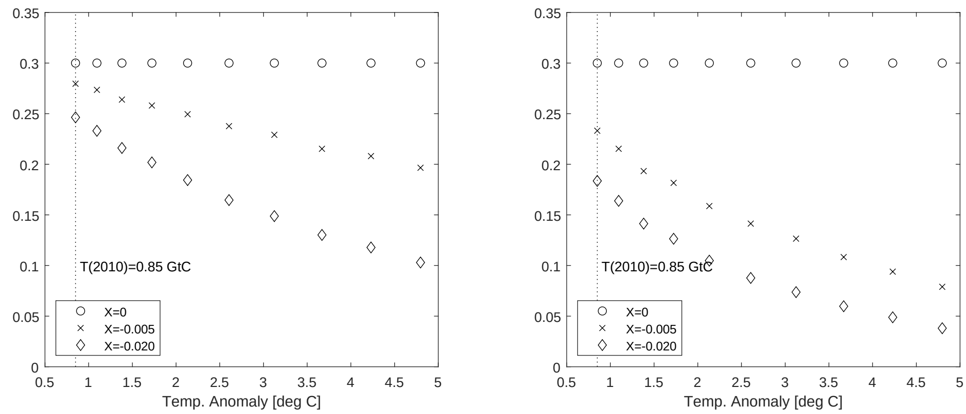
see Appendix E for calibration. In this paragraph we relax this by assuming the existence of abnormal returns following the announcement of green policies.[14] Ramiah et al. (2013) study the existence of such returns in Australia and document negative mean abnormal returns on the order of −2.8% across 10 industries, including mining, oil, gas and real estate. We measure abnormal returns as the mean difference in actual returns on equity at the time the policy strikes for a carbon-intensive portfolio ($n_B = 1$) whose expected return is evaluated neglecting policy risk.

Using the above we calibrate $X = -0.005$ that leads to abnormal returns of −2.5%. As the probability of extreme environmental events changes with temperature, investors optimally reallocate their portfolio by choosing n_B according to (13). Figure 7 presents the simulated portfolio participation of brown assets for the worst IPCC scenario (RCP8.5) for $X = 0, X = -0.005$ and for $X = -0.02$, the latter leading to abnormal returns of −6%. We also examine the role of the diversification motive of the risk averse investor on portfolio allocation, by simulating (13) for different values of the correlation coefficient between assets (see section 2.2).

First, irrespective of the diversification motive, including the risk of stringent climate policy substantially reduces the participation of brown assets in the market portfolio as temperatures increase. However, our result speak in favor of a gradual decarbonization of the market portflio, and therefore are in line with the common belief that portfolio management instead of a right-off exclusion of brown assets is more appropriate Krueger et al. (2020). Second, for every level of temperature and policy stringency, a lower correlation between assets increases the diversification motive and leads to a higher share of brown assets in the market portfolio; yet lower than in the benchmark.

Figure 7: **The effect of policy risk on portfolio participation of brown assets**. Temperature follows RCP8.5; we use different values for the correlation coefficient of diffusion risk $\text{corr}[dW_G, dW_B]$ to examine the effect of the diversification motive on portfolio composition.

(a) $\text{corr}[dW_G, dW_B] = -0.5$ (b) $\text{corr}[dW_G, dW_B] = 0.5$



[14]For specific stocks or portfolios, abnormal returns measure the performance difference on given dates or time periods from expected returns that are calculated by an asset-pricing model.

4 Concluding discussion

We develop a general equilibrium asset pricing model with climate shocks and time-varying probabilities to study the asset-pricing implications of climate change, when also tail macroeconomic events are priced. Our main contribution lies in establishing the link between carbon concentrations / temperature anomaly and the stochastically-varying risk of climatic events, that allows us to make forward-looking assessments of risk premia and interest rates using climate scenarios. We also study the participation of brown assets in the market portfolio, when environmental policy reacts to climate change.

With regards to our methodology, we model the acute component of physical risks as shocks to the evolution of per capita GDP/consumption, while the slow-moving component of climate change is captured by a gradual shift in the distribution of climate-related events as the planet warms. In our model investors price not only extreme events, but also continuous changes in the risk of these events and therefore there is a continuous impact of a changing climate on the economy. Similarly, although stringent regulations that affect the return on investment in brown assets may be introduced unexpectedly in our model, we link policy risk to the risk of climate shocks. Accordingly, investors look at a continuum with regards to policy risk as well, optimally reducing their exposure to brown assets as temperature rises.

We confirm the result in the literature that climate change entails a positive and increasing risk premium. We provide closed-form solutions and show that the extend to which this ultimately carries over to the aggregate equity premium depends on the time variation of risk but also on the severity of environmental events, the distribution of which we estimate from historical disasters data on fourty-two countries. Since the magniture of climate-change risk is expected to be far greater in the future, our history-based calibration might be underestimating the effects of climate change on the market measures of interest. For example, our expected percentage loss in GDP per capita in the event of a climate shock is calibrated to -1.6 %, with the maximum of the distribution being -5 %. Both numbers seem plausible for the present but low for the future (e.g. see Lorans and Moussavi 2021, Lancesseur and Lorans 2021). A possible improvement in our calibration would then be to include a deterministic productivity component in our equation (1) as a function of temperature anomaly and use recent estimates for the future evolution of GDP per capita (e.g. Burke et al. 2015). This is left for future work.

For future work we also leave the possibility to link the probability of default on sovereign debt with climate change. In the present model we set up the asset pricing methodology and include the exogenous probability of the government defaulting on its short-term debt obligations and calculate its default premium. There is by now substantial empirical literature that documents the link between sovereign bond yields and climate change which can be used for this purpose; see footnote 9. To this end, there is an obvious extension of the present setup in which transition risks are linked to adaptation and mitigation expenditures for brown assets. For instance, a carbon tax that follows the NGFS scenarios (NGFS 2020) may be introduced in equation (6) that reduces the return of investors proportional to their exposure to brown assets. The *double materiality* of climate change risk may be also taken into account by the *social* investor, who internalizes the impact of her portfolio on climate change. Accordingly, both adaptation and mitigation expenditures could be linked to the probability of default in the present setup, especially in countries with high exposure to brown assets (Lorans and Moussavi 2021).

Appendix

A – Mean and variance of climate risk

Following Cox et al. (1985b), we can show that given a value of temperature anomaly T, the expected value and variance of λ^E at time s, conditional on its value at time $t < s$ (for s close to t), is given by: $\mathbb{E}[\lambda_s^E|\lambda_t^E] = \lambda_t^E e^{-\kappa^E(s-t)} + (\tilde{\lambda}^E + \xi T)\left(1 - e^{-\kappa^E(s-t)}\right)$ and $\mathrm{Var}[\lambda_s^E|\lambda_t^E] = \lambda_t^E \frac{(\sigma_\lambda^E)^2}{\kappa^E}(e^{-\kappa^E(s-t)} - e^{-2\kappa^E(s-t)}) + (\tilde{\lambda}^E + \xi T)\frac{(\sigma_\lambda^E)^2}{2\kappa^E}(1 - e^{-\kappa^E(s-t)})^2$. The steady-state mean and variance are $\tilde{\lambda}^E + \xi T$ and $(\tilde{\lambda}^E + \xi T)\frac{(\sigma_\lambda^E)^2}{2\kappa^E}$, respectively, both increasing in T.

B – Deriving the value function

The value function $V(A, \lambda^M, \lambda^E)$ satisfies (7), while, in equilibrium the riskfree asset is in zero net supply, i.e., $n_B + n_G = 1$. Substitute our conjecture (14) and (5) into (10) to get $C = \rho A$. With this, (14), $i \in \{B, G\}$ and $j \in \{M, E\}$ the instantaneous utility reads

$$f(A, \lambda^M, \lambda^E) = \rho A^{1-\gamma} I(\lambda^M, \lambda^E)\left(\log\rho - \frac{\log I(\lambda^M, \lambda^E)}{1-\gamma}\right), \tag{27}$$

with $I(\lambda^M, \lambda^E) = e^{a + \sum_j b^j \lambda^j}$. Substitute (27) in the optimized HJB equation (7) to get

$$\begin{aligned}(1-\gamma)\rho(\log\rho - 1) - \rho\left(a + \sum_j b^j\lambda^j\right) + (1-\gamma)\left(\sum_i n_i\mu_i - \frac{\gamma}{2}\sigma^2\right)\\ + \sum_j b^j\kappa^j(\bar{\lambda}^j - \lambda^j) + \frac{1}{2}(b^j)^2(\sigma_\lambda^j)^2\lambda^j + \lambda^j\,\mathbb{E}_{z^j}[e^{(1-\gamma)Z^j} - 1]\\ + \pi\lambda^E[(1 + n_B(e^X - 1))^{1-\gamma} - 1] = 0,\end{aligned} \tag{28}$$

Collecting terms in λ^j implies a quadratic equation for each b^j giving (15) in the main text; the solution with the negative sign in front of the square root is the one with reasonable economic properties (Wachter 2013). Collecting constant terms gives equation for a.

C – Pricing kernel

From Itô's Lemma on $C = \rho A$ using (6) and $n_G + n_B = 1$ in equilibrium, consumption follows:

$$\frac{dC}{C} = gdt + \sum_i n_i\sigma_i dW_i + \sum_{j=\{M,E\}}(e^{Z^j} - 1)dQ^j + n_B(e^X - 1)dQ^X, \tag{29}$$

with $g = \sum_{i=\{B,G\}} n_i \mu_i - \rho$. Note that without the stochastic terms, consumption growth is g, i.e. the Keynes-Ramsey rule with EIS=1 in the deterministic environment.

Multiply (11) with n_G and (12) with n_B, then add the two and substitute our conjecture (14) and $n_B + n_G = 1$ to get equation (20) in the main text.

The state-price density for preferences as given by (4) and (5) in continuous time is given by (Duffie and Epstein 1992b, Duffie and Skiadas 1994):

$$m_t = \exp\left[\int_0^t f_U(C_s, U_s) ds\right] f_C(C_t, U_t). \tag{30}$$

Itô's Lemma (and employing optimality) implies:

$$\frac{dm}{m} = f_V dt + \frac{df_C}{f_C}. \tag{31}$$

For f_C from (5) and C following (29), the Poisson jump of m reads $\tilde{m}/m = \tilde{f}_C/f_C = (\tilde{C}/C)^{-\gamma}$. Itô's Lemma imply equation (16). It also follows from no-arbitrage:

$$\mu_m = -r - \sum_{j\in\{M,E\}} \lambda^j \, \mathbb{E}_{z^j}\left[e^{-\gamma Z^j} - 1\right] - \pi\lambda^E \left[(1 + n_B(e^X - 1))^{-\gamma} - 1\right]. \tag{32}$$

D – Pricing climate change risk

The aggregate market pays a dividend D, being leveraged consumption, i.e. $D = C^\eta$. From Itô's Lemma it follows directly that

$$\frac{dD}{D} = \mu_D dt + \eta \sum_i n_i \sigma_i dW_i + (e^{Z_D} - 1) dQ^T, \tag{33}$$

where $\mu_D = \eta g + \frac{1}{2}\eta(\eta - 1)\sigma^2$,

$$e^{Z_D} - 1 = [e^{\eta Z^M} - 1, e^{\eta Z^E} - 1, (1 + n_B(e^X - 1))^\eta - 1]. \tag{34}$$

We can also show (see Wachter (2013), Seo and Wachter (2018)) that the price for D reads $P = DG(\lambda^M, \lambda^E)$ with G from (23) in the main text. Itô's Lemma on $P = DG$ using (33) and (23) leads to the process for prices $dP/P = \mu_P dt + \sigma_P dW_m^T + (e^{Z_P} - 1)dQ^T$, with $Z_P = Z_D$ and

$$\sigma_P = \left[\eta n_B \sigma_B, \eta(1 - n_B)\sigma_G, \frac{1}{G}\frac{\partial G}{\partial \lambda^M}\sigma_\lambda^M \sqrt{\lambda^M}, \frac{1}{G}\frac{\partial G}{\partial \lambda^E}\sigma_\lambda^E \sqrt{\lambda^E}\right]. \tag{35}$$

Variations in λ^j, $j \in \{M, E\}$ create variations in G and thus in stock prices, reflected by the second and third term of (35). Equity premia arise from the co-movement of marginal utility of the risk-averse investor with the price of the underlying asset or portfolio, both in normal times and times of disasters. Let R be the expected return on equity; the risk-premium is then calculated by $R - r = -\sigma_m \sigma_P^T - [\lambda^M, \lambda^E, \lambda^{pol}]\, \mathbb{E}[(e^{Z_m} - 1) \circ (e^{Z_P} - 1)]^T$, with σ_P and $(e^{Z_P} - 1)$ denoting, respectively, the volatility and the expected drop vectors of the corresponding price process, $\lambda^{pol} = \pi\lambda^E$, the Poisson intensity of the policy shock, σ_m and $(e^{Z_m} - 1)$ from Proposition 2, and $\circ$ denoting element-wise multiplication. Using (18), (19), (34), and (35), we get (26) in the main text. The drift of the price process μ_P can be calculated from the definition of the expected return, which comprise the drift, the dividend yield, and the expected drop in prices should an extreme macroeconomic, environmental, or policy event occur.

$$R \equiv \mu_P + \underbrace{D/P}_{G^{-1}} + \sum_{j \in \{M,E\}} \lambda^j \, \mathbb{E}_{z^j} \left[e^{\eta Z^j} - 1 \right] + \pi\lambda^E \left[(1 + n_B(e^X - 1))^\eta - 1 \right]. \tag{36}$$

E – Calibration

Table 1 collects the parameters used in the calibration, while Table 2 presents the results of our benchmark period simulation in contrast to historical post-WWII US data from Wachter (2013); specifics on calibration follow below. Our model and its calibration matches observed moments of interest very well: the riskfree rate is 1.36% in comparison with 1.34% in the data, the equity premium generated matches the observed 7.06% p.a., while simulated equity volatility is 18.3% p.a., compared to the observed 17.7% p.a.

Table 1: **Parameters for the benchmark calibration**

All values are in annual terms

Parameters for the stochastic processes	
Average probability of macroeconomic disasters λ^M	0.0369
Slope of the linear $\bar{\lambda}^E(T)$ curve ξ	0.0915
Speed of mean reversion for risk $\kappa^M = \kappa^E$	0.08
Volatility parameter for macroeconomic disasters σ_λ^M	0.073
Volatility parameter for environmental disasters σ_λ^E	0.334
Drift parameter for the general asset μ_G	0.0405
Drift parameter for the brown asset μ_B	0.0395
Volatility parameter for both assets $\sigma_G = \sigma_B$	0.0263
Correlation coefficient corr(dW_B, dW_G)	0
Leverage parameter η	2.36
Probability of government default $q_M = q_E$	0.4
Probability of policy reaction to extreme climatic events π	0.6
Utility parameters	
Relative risk aversion γ	3.5
Intertemporal discount rate ρ	0.014

Temperature anomaly

Our proxy for climate change is the change in global average temperature relative to a given time period, i.e., the temperature anomaly. Exogenous temperature paths in this case could be regarded as the ones that correspond to different emissions scenarios as the Representative Concentration Pathways (RCPs) produced by the IPCC (IPCC 2014), that project different GHG concentration pathways up to 2100. The latest modelling convention links temperature

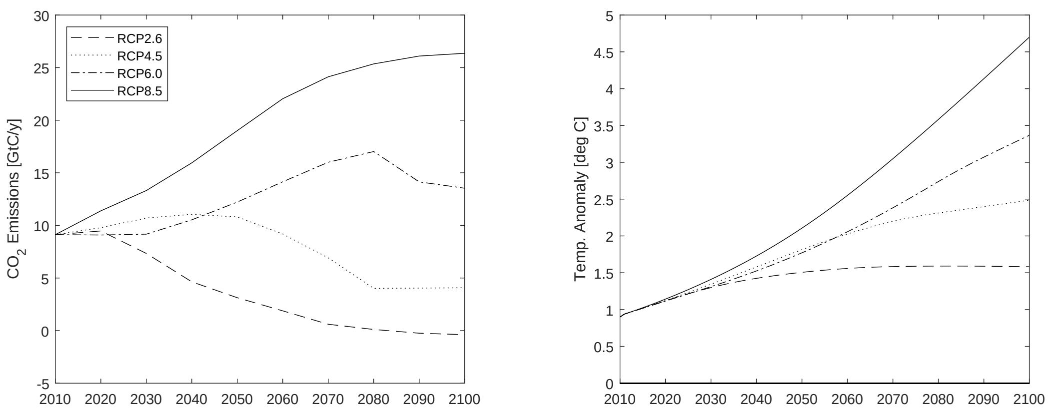
Table 2: **Moments from simulated vs. historical data.** R^f is the riskfree rate, R^e the gross return on equity, $AR1[P-D]$ is the first order autocorrelation of the price-dividend ratio and SR the Sharpe ratio. With exception of the SR and AR1[P-D], moments are in percentage terms.

All values are in annual terms

Moments	Simulation	US Data (1947-2010)
$\mathbb{E}[R^f]$	1.37	1.34
$\sigma(R^f)$	2.22	2.66
$\mathbb{E}[R^e - R^f]$	7.13	7.06
$\sigma(R^e)$	18.62	17.72
$AR1[P-D]$	0.92	0.92
SR	0.38	0.40

anomaly T to carbon concentration (cumulative emissions CE) within a particular time period, in a rather linear fashion, i.e., according to $T_t - T_{t_0} \approx \Lambda \times CE_t$, for $t > t_0$ and t_0 being the reference year.[15] For example for t_0 corresponding to pre-industrial times (with $T_{t_0} \approx 0$), T_{2015} was about 1^oC. Parameter Λ measures the Transient Climate Response to cumulative carbon Emissions (TCRE) and is estimated to be in the range of $[0.0008, 0.0024]^oC/GtC$; see Leduc et al. (2016), Matthews et al. (2018). To match the RCP projections we set $\Lambda = 0.002^oC/GtC$ and calculate the various temperature paths based on the corresponding RCP emissions according to the above equation (Figure 8).

Figure 8: **IPCC RCP carbon emissions and (calibrated) temperature anomaly paths**; source: (IPCC 2013) (emissions) and own calculation (temperature anomaly).



Distributions of macroeconomic and environmental disasters

The percentage decline in per capita consumption features both environmental and macroeconomic shocks that need to be calibrated to the data. Hence, we need to construct a separate dataset for each of the two types of shocks; from these datasets we can then calculate the

[15]See Matthews et al. (2009, 2012), Knutti (2013), Knutti and Rogelj (2015), MacDougall et al. (2017), Brock and Xepapadeas (2018), Matthews et al. (2018), Dietz and Venmans (2019).

distribution of percentage drops as well as the average of the Poisson intensities $\bar{\lambda}^j$, $j \in \{M, E\}$.

To do so we make use of different data sources as follows. As a first source we extend until 2015 the Barro and Ursúa (2010) dataset, that collects consistent data on GDP per capita for 42 countries for the period 1911-2008.[16] For our purposes this dataset holds the real reported y-o-y changes in GDP per capita, i.e., after accounting of any (negative) growth effects of climate-related events. In order to calculate these growth effects of climate change we act in the following way. We first collect from the international disasters database EM-DAT (2018), all climate-related events for these 42 countries and for the 1915-2015 time period; we consider only events relevant to climate change.[17] We then follow the methodology of Loayza et al. (2012) and calculate the negative growth effects on GDP per capita of extreme environmental events (top 10% in each event category according to the severity index defined in that paper) for each country and each year; from these we keep extreme events that resulted in GDP p.c. drops of more than 1%.[18] This is our first dataset including data on environmental damages. To calculate pure macroeconomic damages we add the – absolute value of – environmental damages to growth entries of the extended Barro-Ursúa dataset. This yields the real GDP per capita if no extreme climate-related events had occured. To construct our second dataset containing pure macroeconomic damages we then follow the peak-to-trough methodology for cumulative fractional declines in real GDP per capita as explained in Barro and Ursúa (2008). As in the aforementioned contribution, and in Wachter (2013), we include only peak-to-trough events that resulted in GDP drops more than 10%.[19]

Following Barro and Ursúa (2008) the frequency of large declines in GDP per capita in our pure macroeconomic dataset is calculated $\bar{\lambda}^M = 0.0369$ while the mean drop size of its time-invariant distribution is -22.1%. In order to construct the linear relationship $\bar{\lambda}^E = \tilde{\lambda}^E + \xi T$ for the time-varying mean of the stochastic process in (3), we divide our sample in ten decades starting from 1915 and calculate $\bar{\lambda}^E$ for each decade; we use the middle year to indicate a given decade, e.g., 1920 refers to the decade 1916-1925. The fitted line gives $\tilde{\lambda}^E = 0.0006$ and $\xi = 0.0915$. The frequency distribution of climate-related damages has a mean drop size of -1.58%.

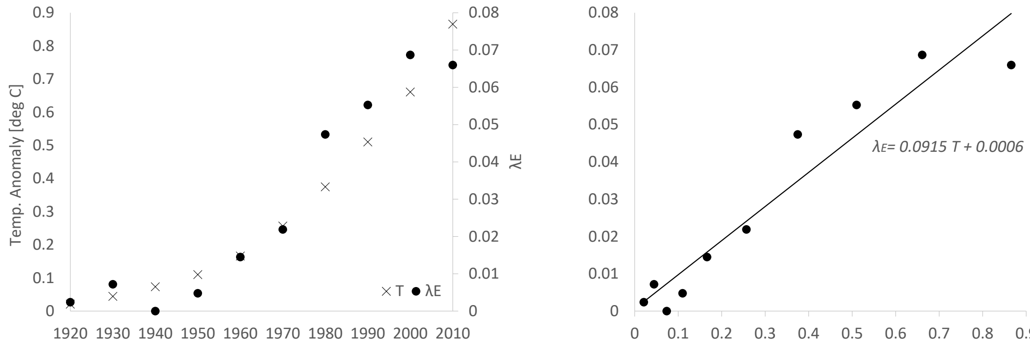
[16]We use percentage changes in GDP per capita, instead of consumption per capita, as a proxy for damages. Both Barro (2009) and Wachter (2013) find similar results for their CAPMs with rare disasters whether they calibrate to the consumption or GDP data.

[17]According to the EM-DAT categories we consider meteorological events (storms/extreme temperatures), hydrological events (floods/avalanches), and climatological events (droughts/wildfires).

[18]Loayza et al. (2012) show that extreme climate-related events (top 10%) are always bad for economic growth and calculate the growth elasticities of different event types on different economic sectors: manufacturing; services; agriculture. Using World Bank data we calculate the sectoral shares of GDP for each country and then using these growth elasticities we calculate the country-specific climate-related damages on GDP per capita for each year. The effect of an extreme natural disaster on GDP per capita is robustly negative also in Cavallo et al. (2013) and Felbermayr and Grschl (2014).

[19]Using the peak-to-trough methodology for macroeconomic, and not for environmental events, we implicitly make the assumption that macroeconomic events, such as wars or crises, have memory, while climate-related events are memory-less.

Figure 9: **Calibration of the $\bar{\lambda}^E(T) = \tilde{\lambda}^E + \xi T$ curve.** Right: Adj.$R^2 = 0.91$, P-value $(T) < 0.001$.



Other parameters

We set the coefficient of relative risk aversion to $\gamma = 3.5$ and the intertemporal discount rate to $\rho = 0.014$, both widely accepted values in the literature; Barro (2009) sets $\gamma = 4$, while Wachter (2013) $\gamma = 3$. We follow Wachter (2013) and set the mean reversion parameters of the intensities of disasters to $\kappa^M = \kappa^E = 0.08$; this leads to an autocorrelation of the price-dividend ratio of 0.92, its value in the data. The leverage parameter is set to $\eta = 2.36$ to match the observed market equity premium and volatility; this leads to a dividend growth rate in times without disasters of 6% (Wachter (2013) sets $\eta = 2.6$).

We define assets with exposure to transition risk as "brown" and follow Prudential Regulation Authority (2015) to set $n_B = 0.3$ for 2010 in the benchmark.[20] We assume that in the benchmark the policy risk channel is not active, i.e. $X = 0$; we subsequently calibrate the policy risk parameter and study the effect of policy risk on the portfolio allocation. In order to calculate the probability π that climate change policy becomes effective after an extreme climate-related event, we use the Grantham-LSE (2018) database that includes all laws and legislations since the 1960s related to climate change, covering 95% of global emissions. In this database there are in total 519 laws for our 42 countries, a quarter of which refers to low carbon transition laws (Nachmany et al. 2017); with 213 severe events (top 10% ever recorded) in our dataset we calculate $\pi \approx 0.25 \times 519/213 = 0.609$. With regards to the correlation between assets in times without disasters, we follow Cochrane et al. (2007) and set corr$[dW_G, dW_B] = 0$.

We also set $\sigma_B = \sigma_G$ and solve (9) for $n_B = 0.3$ and zero correlation such that $\sigma = 0.02$ (Wachter 2013), giving $\sigma_B = \sigma_G = 0.2626$. The values of μ_B and μ_G are estimated by solving $n_B\mu_B + n_G\mu_G - \rho = g = 0.0252$ (Wachter 2013) and (12) again for $n_B = 0.3$ and $X = 0$ in the benchmark. Note that the different drift parameters for the two assets are not important for the case without policy risk as it is the aggregate market drift and volatility that matter. Moreover, we need to calibrate the volatility parameters σ_λ^M and σ_λ^E for processes (2) and (3), respectively.

[20] In addition, Oestreich and Tsiakas (2015) investigate empirically the effect of EU-ETS on German stock returns in the period 2003-2012. They divide their sample of 65 firms in clean and dirty depending on whether they received free carbon allowances or not; dirty firms occupy about 35% of that sample.

As in Seo and Wachter (2018) volatility parameters are calculated by choosing the discriminant of (15) for both types of disasters to be zero. This yields $\sigma_\lambda^M = 0.073$ and $\sigma_\lambda^E = 0.334$ in the benchmark simulation with $X = 0$. Finally, we follow Barro (2009) and Wachter (2013) and set the probability of government default for either disasters to $q_M = q_E = 0.4$.

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