Asset Pricing with Disagreement about Climate Risks*

Thomas Lontzek[†] Walter Pohl[‡] Karl Schmedders[§]

Marco Thalhammer[¶] Ole Wilms[‖]

May 24, 2023

Abstract

This paper analyzes how climate risks are priced on financial markets. We show that climate tipping thresholds, disagreement about climate risks, and preferences that price in long-run risks are crucial to an understanding of the impact of climate change on asset prices. Our model simultaneously explains several findings that have been established in the empirical literature on climate finance: (i) news about climate change can be hedged in financial markets, (ii) the share of green investors has significantly increased over the past decade, (iii) investors require a positive, although small, climate risk premium for holding "brown" assets, and (iv) "green" stocks outperformed "brown" stocks in the period 2011–2021. The model can also explain why investments in mitigating climate change have been small in the past. Finally, the model predicts a strong, non-linear increase in the marginal gain from carbon-reducing investments as well as in the carbon premium if global temperatures continue to rise.

JEL Codes: G11, G12, Q54.

Keywords: Asset pricing, carbon premium, climate news, climate risk, heterogeneous beliefs, long-run risk, risk sharing.

*We are indebted to Ravi Bansal, Nicole Branger, Lars Hansen, Ralph Koijen, Esteban Rossi-Hansberg, and Christoph Schneider for helpful discussions on the subject. We thank seminar audiences at the 2022 Stanford SITE Workshop, ETH Zurich, WWU Münster, RWTH Aachen, and the 'Workshop on Climate, Macroeconomic Uncertainty and Policy' at the University of Chicago as well as poster audiences at the 2022 MFR Summer Session for Young Scholars and the 2023 MFR/IMSI Conference on Assessing the Economic and Environmental Consequences of Climate Change, both at the University of Chicago, for comments. We are grateful to Dave Brooks for excellent editorial support.

[†]RWTH Aachen. E-mail: lontzek@econ.rwth-aachen.de.

[‡]NHH Bergen. E-mail: walter.pohl@nhh.no.

[§]IMD Lausanne. E-mail: karl.schmedders@imd.org.

[¶]RWTH Aachen. E-mail: marco.thalhammer@rwth-aachen.de.

[‖]Universität Hamburg and Tilburg University. E-mail: ole.wilms@uni-hamburg.de.

1 Introduction

A rapidly growing literature in climate science has identified specific temperature thresholds beyond which we can expect to see significant and potentially irreversible changes to the planet's ecosystems and the services they provide, such as food production, water resources, and natural habitats. For example, the Intergovernmental Panel on Climate Change (IPCC) has highlighted the importance of limiting global warming to 1.5°C above preindustrial levels to avoid the most severe impacts of climate change. There is, however, an ongoing scientific debate over the uncertainty surrounding the precise magnitude and timing of these thresholds and the exact impacts that will result from exceeding them.

While natural scientists debate the likelihood and magnitude of climate disasters linked to temperature thresholds, there remains a widespread and often contentious public debate about climate change and its risks. This disagreement is reflected in the diverse range of views and opinions evident among policymakers regarding the appropriate response to climate change, with positions ranging from inaction to drastic carbon-reduction policies. This ongoing debate has generated uncertainty about the potential economic impact of policy responses to climate change, affecting asset values and investment decisions.

In this paper, we integrate temperature thresholds and divergent beliefs about climate change and policy responses into an asset-pricing model with long-run risks (Bansal and Yaron 2004) and two types of investors (Pohl et al. 2021). The persistent global average temperature anomaly, reflecting the degree of warming above preindustrial levels, creates long-run risk in the model. The two investor types—"green" and "brown"—hold opposing views on the extent to which changes in global temperature impact consumption disaster probabilities. While both groups have identical Epstein–Zin preferences with a preference for the early resolution of risk, green investors believe that climate change has a larger effect on disaster probabilities, whereas brown investors believe in a smaller impact. We use our asset-pricing model to examine the pricing of assets with different exposures to climate risks. "Green" assets have a relatively smaller exposure to such risks than "brown" assets.

Our asset-pricing framework with its novel interplay of temperature thresholds, disagreement about climate change, and Epstein–Zin preferences provides several insights into how climate-related risks are priced on financial markets. First, the model reveals a new channel for risk sharing: not only is climate risk itself priced, but the risk of receiving bad news today about the future climate is also priced. Brown investors implicitly sell insurance against this climate news risk to green investors. Importantly, climate news risk is only priced if agents care about long-run risks (Epstein–Zin preferences). In contrast, under expected utility, climate change news is not traded by investors. Second, bad news about the climate, such as an unexpected acceleration of the global temperature increase, increases the market share of green investors because they benefit from buying insurance against such news shocks. Third, brown stocks carry a larger risk premium ("carbon premium") compared to green stocks, as the former are more exposed to climate risks. Fourth, if the temperature threshold to trigger disaster events is sufficiently far away from the current temperature anomaly, then the corresponding carbon premium is only small. (For expected utility, the carbon premium is zero below that threshold.) In such a scenario, the news-channel effect dominates the carbon-premium effect, and the model shows an outperformance of green over brown stocks in response to bad climate news.

Our asset-pricing model provides a simultaneous explanation for several findings on the impact of climate risks on financial markets. Notably, the model delivers the following stylized facts, which have been established[1] in recent empirical studies: (i) news about climate change can be hedged in financial markets (Engle et al. 2020; Ardia et al. 2023); (ii) the market share of green investors has increased significantly over the past years (Global Sustainable Investment Alliance 2020; van der Beck 2022); (iii) investors require a premium for holding assets that are exposed to climate change risk, implying a positive carbon, or more generally, climate risk premium (Bolton and Kacperczyk 2021; 2022; Bansal et al. 2021; Hsu et al. 2023); (iv) in contrast, the past decade has shown a strong outperformance of green over brown stocks (Huij et al. 2021, Pástor et al. 2022).

The model analysis also highlights the significance of temperature thresholds in shaping the impact of climate investments. In the absence of such thresholds, where disasters can occur at any time and temperature, the marginal gain from investments to slow down climate change would initially be large but decrease as climate risks rise. By contrast, if disasters can only occur after a temperature threshold has been crossed, the marginal gain from investments is small for low temperatures as the likelihood of crossing the threshold in the (near) future is low. As temperatures rise and approach the threshold, however, the marginal gains from such investments increase significantly and become very large. The model predicts that the market share of green investors, the carbon premium, and the gains from climate investments will significantly increase if climate risks continue to rise over time, highlighting the importance of temperature thresholds in shaping market outcomes.

Climate financial risks are a direct consequence of two broad types of risk associated with climate change. First, physical risks arise because climate change can potentially trigger large-scale catastrophic events. Such events have the potential to cause major disruptions in our ecosystem leading to severe weather events such as global droughts, floods, heatwaves, or hurricanes, which may damage assets and infrastructure, impair productive assets, and disrupt supply chains and business operations (IPCC 2014). Second, transition risk is caused by policy measures, technological changes, and reputational concerns. The introduction of

[1]Recent years have seen a surge in research examining the impact of climate financial risks on asset prices; see Giglio et al. (2021a) for an overview of this literature.

new regulations, laws, carbon costs, or other policies related to climate change can have a dramatic impact on companies' operations and cash flows. As the world transitions toward renewable energy sources and other sustainable technologies, companies that fail to adapt or adopt these technologies may face increased costs or declining market share. Companies that are perceived as not taking climate change seriously may face reputational damage, leading to a loss of customers, partners, or employees.

In this paper, we use the term climate financial risks to describe the financial risks stemming from both physical and transition risk. If a severe climate disaster materializes, there are likely also going to be strong governmental responses. In the past, governments have often been reluctant to introduce effective policies to slow down climate change, such as a large, globally binding carbon tax or outright restrictions on energy consumption. However, the actual experience of a climate disaster is likely going to lead to immediate action to slow down climate change.[2]

Our asset-pricing model builds on previous finance literature that incorporates climate risks into financial models. The global temperature anomaly[3] is modeled as a highly persistent long-run risk process as in Bansal and Yaron (2004). Bansal et al. (2021) provide evidence that long-run temperature changes are reflected in equity valuations. Climate financial risks depend on the global temperature anomaly and are modeled as catastrophic events as in Barro (2006), Gabaix (2012), and Wachter (2013). The key difference between our paper and the standard approaches to modeling catastrophic events in asset pricing is our inclusion of climate tipping points, which we show is crucial to an understanding of how climate risks are priced on financial markets. Giglio et al. (2021b) use real estate data to estimate discount rates for the valuation of investments in climate change abatement. In their model, they do not include a temperature process but instead use a persistent process for an endogenous climate

[2]For example, throughout the twentieth century, Australia experienced destructive wildfires. But only following the devastating bushfires ("Black Summer") of July 2019 to March 2020 did the Australian Government announce a broad plan aimed at addressing the impacts of climate change and reducing the risk of future wildfires—the "Australian Bushfire & Climate Plan" of July 2020; see `https://emergencyleadersforclimateaction.org.au/australian-bushfire-climate-plan/`, last accessed April 7, 2023. Another instance of a strong policy response following physical damage related to climate change occurred in the United States in the spring of 2023, when the Pacific Fishery Management Council unanimously approved the closure of fall-run (Chinook) salmon fishing from northern Oregon to the California–Mexico border. (Limited recreational salmon fishing was allowed off southern Oregon in the fall of 2023.) Clearly, some overfishing may have contributed to the problem, but essentially a long drought in California (made worse by climate change) and reckless water usage (due to a policy of the previous federal administration) resulted in physical environmental damage—namely, the huge decline in the population of Chinook. In response to this physical damage, the regulatory body closed an entire branch of the local fishing industry; see `https://www.nbcbayarea.com/news/local/salmon-fishing-ban-west-coast/3200108/`, last accessed April 10, 2023. This policy will not mitigate climate change, but aims to reduce the damage to the fish population.

[3]Climate scientists examine a wide range of natural processes to describe climate change. These include greenhouse gas concentrations, atmospheric circulation patterns, ocean currents, and changes in solar radiation, and many others. In public discourse, however, climate change is often simply described by the increase in the global temperature compared to its value in the preindustrial era.

disaster probability. They show that the term structure of discount rates for climate-hedging investments is upward sloping, but bounded above by the risk-free rate.

Our model also builds on the existing literature that analyzes the impact of disagreement on financial markets with Epstein–Zin investors. Borovička (2020) analyzes the incentives to trade risks for models with recursive utility when agents disagree about the expected growth rate of consumption. He shows that optimistic investors with fundamentally wrong beliefs can survive in the long run so that the classical market selection hypothesis no longer holds for models with recursive utility. Pohl et al. (2021) show that even small belief differences have large effects in models with long-run risks and recursive preferences and that the disagreement can help to explain several asset-pricing puzzles. Chen et al. (2012) and Branger et al. (2020) analyze the impact of disagreement about disaster risks on financial markets. While the former show that disagreement about disaster risk generates strong risk sharing motives such that even a small share of optimists is sufficient to significantly reduce the disaster risk premium, the latter analyze how market incompleteness affects risk sharing incentives.

Pástor et al. (2021) provide an alternative explanation of how the outperformance of green over brown stocks in the last decade can be reconciled with a positive carbon risk premium, based on the premise that investors enjoy holding green assets. Our explanation in turn is solely based on differences in beliefs about the impact of climate change. Ardia et al. (2023) construct a climate concern index based on newspaper articles on climate risks and show that bad news about the climate increases the value of green firms and decreases the value of brown firms. Moreover, their climate index allows them to analyze whether climate news affects the valuations of green and brown assets through changes in expectations about the future cash flows of the firms or through changes in investors' preferences. They find that returns are affected via both channels and hence provide evidence for both theories, the one presented in this paper as well as the model in Pástor et al. (2021).

The remainder of this paper is organized as follows. Section 2 documents empirical findings on the impact of climate risks on financial markets as well as the key underlying assumptions for our climate economy. In Section 3 we present our model, as well as the key mechanism via which climate risks are traded in response to belief differences. Section 4 discusses the outcomes of our model and relates them to the data. Section 5 concludes.

2 Climate Change: Selected Empirical Findings

Our asset-pricing model draws upon established insights from the climate change literature that have not yet received much attention in finance. In Section 2.1 we provide a brief review of the pertinent literature. Our model produces testable implications for the pricing of climate risks, which we contrast with empirical evidence from the finance literature, in Section 4. For this purpose, we document several stylized facts from financial markets, in Section 2.2.

2.1 Temperature Thresholds and Differences of Opinion

Our asset-pricing model relies on two fundamental assumptions derived from the climate change literature. First, we include a temperature threshold beyond which climate-induced consumption disasters can occur. Second, we model two distinct groups of investors that have divergent views on the probability of occurrence of those disasters.

Climate scientists use the term *climate system tipping point* to refer to a critical threshold in crucial components of the Earth's climate system—the *tipping elements*—beyond which rapid and irreversible changes can occur (Lenton et al. 2008). For example, Arctic sea ice has been shrinking rapidly in recent decades due to global warming. As the ice cover reduces, more sunlight is absorbed by the ocean, leading to further warming and the melting of the remaining ice. This positive feedback loop could eventually lead to the Arctic becoming ice-free in the summer, which would have significant consequences for the climate, ecosystems, and human societies in the region and beyond. Other potential tipping elements in the climate system include the collapse of the West Antarctic Ice Sheet, the slowdown of the Atlantic meridional overturning circulation (AMOC), and the release of methane from thawing permafrost and clathrates in the ocean.

Several works in climate economics have developed models incorporating climate system tipping points; see, for example, Lemoine and Traeger (2014), Lontzek et al. (2015), van der Ploeg and de Zeeuw (2018), and the discussion in Cai (2021). Typically these models address a specific tipping element or an ensemble of tipping elements. Cai et al. (2017) and Cai and Lontzek (2019) in turn assume a representative tipping element, whose nature is stochastically evolving. Consequently, these models embed for each tipping element a distinct tipping point. Recently, Armstrong McKay et al. (2022) presented an updated assessment of the location of tipping points for major tipping elements, considering both regional and global tipping elements. While a few tipping elements may be triggered within the 1.5°C–2°C range, most tipping points are expected to be located beyond 2°C, with a considerable range of uncertainty regarding the location of that critical internal threshold. Building on this literature, our asset-pricing model also integrates the concept of a critical threshold. However, in contrast to the abovementioned studies we define a temperature threshold beyond which catastrophic events can be triggered. We do not model any particular tipping element but rather the direct adverse impacts on the economy resulting from catastrophic events. Thus, our temperature threshold can be viewed as a generic tipping point, and in the subsequent discussion we will use the term "tipping point" in that sense. Since the likelihood of a climate-induced consumption disaster is zero as long as the global temperature anomaly remains below this tipping point temperature, we are assuming a safe operating space in that temperature range. Once the global average temperature exceeds its tipping point level, the risk of a disaster occurring increases significantly. The existence of tipping points with regard to climate disasters distinguishes our model from the conventional approach to modeling consumption disasters in asset pricing, which allows potential disasters to occur at any time; see, for example, Barro (2009), Wachter (2013), and Gabaix (2012). We demonstrate that this difference has significant consequences for the pricing of assets that are vulnerable to climate risks.

Models with tipping points have previously been proposed in the asset-pricing literature. Bansal et al. (2016) set a temperature threshold of 2°C for a tipping point, after which a quadratic loss function (in temperature) describes the expected disaster size, and the probability of disaster increases linearly with temperature. Daniel et al. (2016) introduce a model with a positive probability of a tipping point, leading to a large negative shock to consumption as soon as the temperature rises above its 2015 level; in our model, this approach corresponds to an immediate disaster risk.

The scientific consensus on climate change is that it is real, primarily caused by human activities, and poses a significant threat to planet Earth and its inhabitants. This consensus is shared by an overwhelming majority of climate scientists and scientific organizations. However, some individuals and organizations, often those with significant political and financial influence, reject this scientific evidence and consensus, often for ideological or economic reasons. Therefore, despite the emergence of a scientific consensus in recent years there is still considerable debate regarding the potential impact of global warming on the real economy, as documented by an extensive literature.

In his book *Why We Disagree about Climate Change*, Hulme (2009) sheds light on the factors that contribute to such disagreement, arguing that while climate change is a physical phenomenon, it has also taken on social, cultural, and political dimensions. These additional dimensions have resulted in varying beliefs and attitudes to climate change, as reflected in public surveys such as that of Saad (2017). Despite an increase in the proportion of Americans who express concern over climate change and acknowledge its anthropogenic causes, a significant portion of the US population still does not share these concerns or recognize the consequences of climate change.

For a wide range of tipping elements Armstrong McKay et al. (2022) show that the probability of exceeding climate tipping points rises with higher temperature levels. There is, however, a high degree of uncertainty regarding future emission paths and thus regarding future climate change. This uncertainty in turn affects the likelihood of climate-induced disasters. Using the expert elicitation study of Kriegler et al. (2009), Lontzek et al. (2015) develop a method to compute contemporaneous, temperature-dependent hazard rates of triggering various tipping points. Cai et al. (2016) use this method to compute cumulative probabilities of triggering major global tipping points. With 2.8°C in 2100 the likelihood of having crossed at least one of five major tipping points is 46.3 percent. In another scenario with 4.7°C in 2100 that likelihood is 87.11 percent. Yet in a very optimistic scenario with 1.5°C in 2100 that likelihood is only 11.49 percent. These findings reveal considerable disagreement about the probability of a climate-induced disaster, particularly as global temperatures rise.

Bernstein et al. (2022) provide insights into differences in beliefs regarding the impact of climate change, based on real estate market data. Through a comparison of individual properties in the same US zip code, the authors find that houses with higher exposure to sea level rise due to climate change are more likely to be owned by Republicans than by Democrats. This suggests that Republicans are less concerned about climate risks, and therefore more willing to hold assets that are exposed to high climate risk. In a similar vein, Baldauf et al. (2020) use an equilibrium model of housing choice to demonstrate that house prices reflect heterogeneity in beliefs regarding long-term climate change risks.

Given the existence of varying beliefs regarding the severity and future scenarios of climate change, it is reasonable to assume that investors may hold different beliefs about the associated risks. In our asset-pricing model, we account for this fact by explicitly allowing for heterogeneous beliefs among two groups of investors.

2.2 Empirical Findings on Financial Markets

In recent years there has been a notable growth in the literature exploring the impact of climate-related financial risks on the pricing of financial assets. For an overview of this rapidly growing research area, see Giglio et al. (2021a). In the following we limit our focus to a review of the most pertinent literature that directly relates to the research presented in the present paper. In particular, we discuss four stylized facts.

First, news about climate change can be hedged on financial markets. Engle et al. (2020) show how to construct portfolios that provide a hedge against news about climate change. They measure the "greenness" of a stock by its environmental score from environmental, social, and governance (ESG) ratings and show that green stocks are less exposed to climate news compared to brown stocks. Using a mimicking portfolio approach to construct portfolios, Engle et al. (2020) show that a portfolio that is long in green stocks and short in brown stocks can efficiently hedge climate change news. Furthermore, to test the theory of Pástor et al. (2021), Ardia et al. (2023) construct a climate change concern index based on newspaper articles and show that brown stocks are more exposed to climate concern shocks than green stocks are. Hence, a portfolio long in green and short in brown stocks can be used to hedge climate news. Moreover, the authors' climate index allows them to analyze whether climate news affects the valuations of green and of brown assets through changes in expectations regarding the future cash flows of the firms or through changes in investor preferences as suggested by Pástor et al. (2021). They find that returns are affected via both channels.

Second, the market share of green investors has increased significantly over the past decade. The Global Sustainable Investment Alliance (2020) reports that the market share of sustainable investments increased by 8% from 2016 to 2020. While 27.9% of global assets under management were sustainable investments back in 2016, this figure had increased to 35.9% by 2020. Figure 1 from the Alliance's Review (2020) shows the share of investments in sustainable assets for different countries.[4] From 2014 to 2021, the market share of sustainable investments increased in Canada, the United States, Australia/New Zealand, and Japan. Europe is the only exception, the share of green investing having decreased over the years.[5] These summary statistics are consistent with van der Beck (2022), who provides extensive evidence of significant fund flows toward sustainable funds.

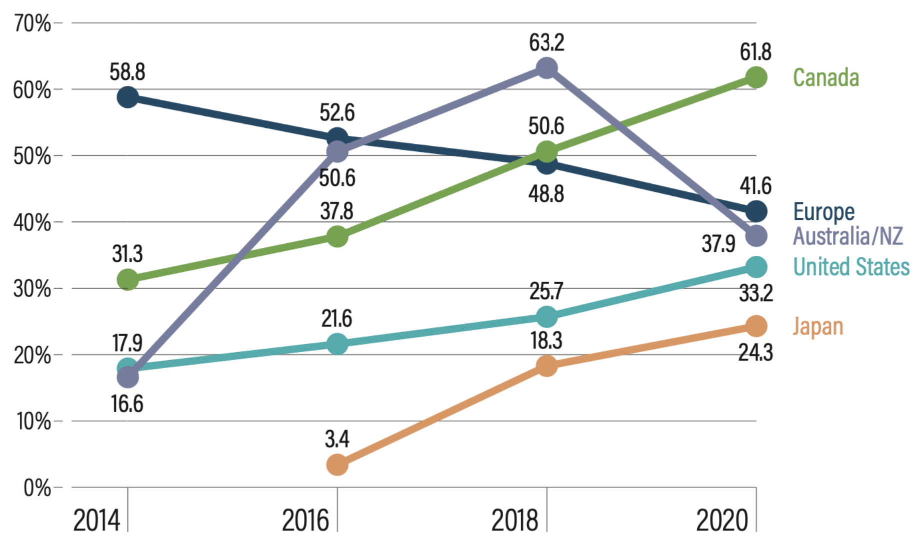


Figure 1: The share of investments in sustainable assets for different countries. Source: Global Sustainable Investment Alliance (2020).

Asset managers' willingness to invest in sustainable investments has experienced a significant upswing in recent years. Figure 2, sourced from Principles of Responsible Investment (2021), highlights the rise in the number of Principles of Responsible Investment (PRI) investor signatories and the collective assets under management from 2006 to 2021. The number of signatories has consistently grown in the past decade, with the collective assets under management represented by all 3,826 PRI signatories (comprising 3,404 investors and 422 service

[4]Note that sustainable assets here contain all ESG classifications. However, given the rising climate concerns of the past decade, it seems plausible to assume that these results are not purely driven by increases in investments in assets with high S and G scores.

[5]EU regulation resulted in the declassification of previously sustainable investment as no longer sustainable, which explains the downward trend in Europe; see *Regulation (EU) 2019/2088 of the European Parliament and of the Council* of 27 November 2019, `https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32019R2088&from=EN#d1e1107-1-1`.

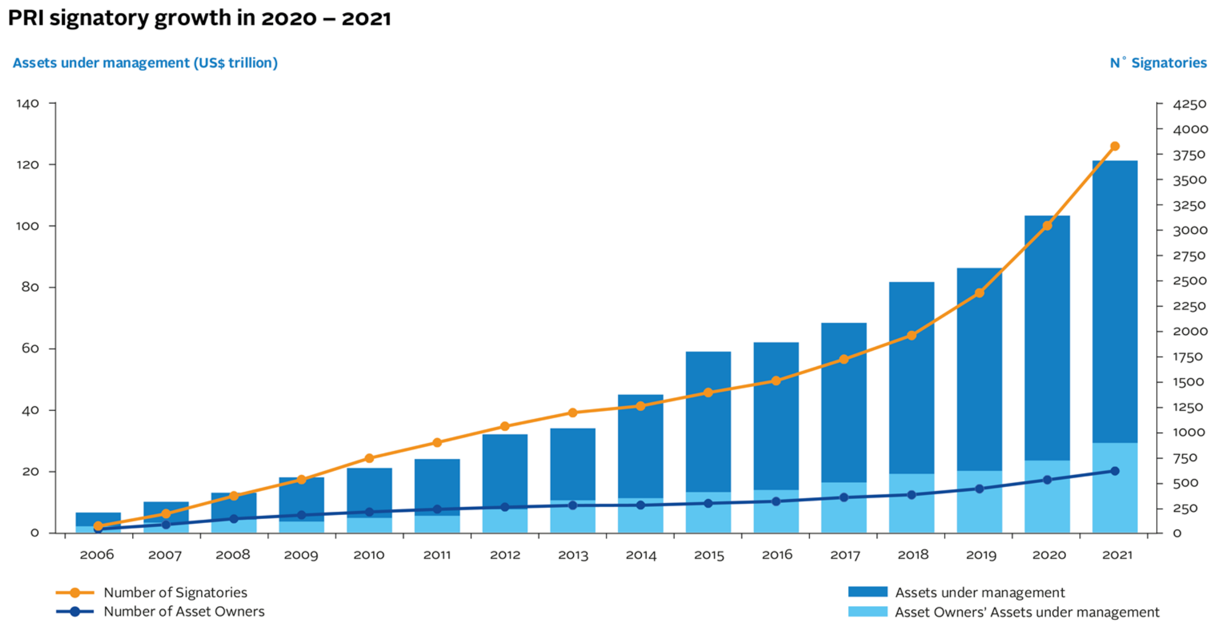


Figure 2: The development of the number of PRI investor signatories and collective assets under management, 2006 to 2021. Source: Principles of Responsible Investment (2021).

providers as of 2021) amounting to approximately US $121 trillion as of March 31, 2021. It is, however, important to note that these commitments do not automatically translate into better ESG scores for signatory companies everywhere. This is demonstrated by Gibson Brandon et al. (2022), who find that such a translation only applies to institutions outside the US. In the US, meanwhile, there is a disconnect between what institutional investors claim to do and what they actually do, which could be interpreted as a form of "greenwashing" by US PRI signatories.

Third, investors demand a premium for holding assets that are exposed to climate change, either due to higher carbon emissions or to greater sensitivity to long-term temperature changes, indicating a positive carbon—or more generally—climate risk premium (Bolton and Kacperczyk 2021, 2022; Bansal et al. 2021). However, the observed magnitude of the climate risk premium has been limited in the past decade, and some alternative studies (Aswani et al. 2022; Bauer et al. 2022) have failed to identify a positive climate risk premium. As we explain below, our model offers an explanation for why climate risk premia have remained relatively small in the past but are likely to increase significantly in the future.

Fourth, green stocks outperformed brown stocks during the decade prior to the COVID-19 pandemic. This finding is robust to either using environmental scores from ESG ratings as a measure of greenness, as used by Pástor et al. (2022), or directly using emissions data to assess the carbon footprint of a company, as employed by Huij et al. (2021). Both studies report an outperformance of a portfolio of green stocks over a portfolio of brown stocks, of 59% and 45% from 2010 until 2021, respectively.[6] van der Beck (2022) provides evidence of significant fund flows toward sustainable funds and shows that the temporary outperformance of green over brown stocks can be explained by the price pressure arising from these fund flows.

We return to these four stylized facts in the discussion of the key implications of our asset-pricing model in Section 4. In addition, our model has further implications. Investments and policies aimed at curbing global carbon emissions have been insufficiently effective in significantly slowing down climate change, rendering a climate catastrophe increasingly probable according to numerous climate experts. While we recognize that there may be various reasons, particularly political ones, for the tardy response to climate change that we do not consider in our model, it provides a partial, market-based rationale for the historically low levels of investment in carbon-reducing technologies in financial markets. Furthermore, our model predicts that the marginal benefit of mitigating climate change is set to rise exponentially as the average global temperature (anomaly) approaches the climate tipping point.

3 The Economy

We consider an endowment economy where changes in global temperature can potentially trigger climate-induced disasters. Log consumption growth $\Delta c_{t+1} \equiv \log\left(\frac{C_{t+1}}{C_t}\right)$ is given by

$$\Delta c_{t+1} = \mu_c + \sigma_\eta \eta_{t+1} + D_{t+1}, \tag{1}$$

where $\eta_{t+1} \sim i.i.d.\ N(0,1)$ and D_{t+1} are climate-induced consumption disasters. Similar specifications to model the impact of climate change on the economy have also been used in Bansal et al. (2021), Giglio et al. (2021b), and Giglio et al. (2021a). As in Wachter (2013), we assume that

$$D_{t+1} = N_{t+1} d, \tag{2}$$

where d is the disaster-induced decline in consumption growth and N_{t+1} is a Poisson counting process with time-varying intensity π_t. In line with the climate economics literature (see, for example, Lontzek et al. (2015)), we assume that disaster probabilities depend on climate change:

$$\pi_t = g(T_t), \tag{3}$$

where T_t denotes the global temperature anomaly measured in degrees Celsius—so, temperature rise above preindustrial levels. Note that the true temperature process is irrelevant for asset prices but that what matters are the beliefs of investors about climate risks. For

[6] We would like to thank the authors for providing us with their portfolio return series.

example, Choi et al. (2020) show that investors update their beliefs about climate change in response to abnormally hot weather and Acharya et al. (2022) provide direct evidence that physical climate risk in the form of heat stress affects asset prices. The latter argue that this effect could be driven either by increased physical risk itself or by increased investor awareness of these kinds of risks, in line with our interpretation of climate risks.

So, T_t can be viewed more broadly as what investors believe about the global temperature anomaly. Hence, events such as extremely high temperatures or climate events such as the Paris Agreement are likely to shift the attention of investors and affect their beliefs about climate change. We do not adopt a specific stance on how investors form their expectations, but simply assume that climate change news is subsumed in the innovations to T_t.

The true function $g(T_t)$ is unknown and there are two groups of investors, $h \in \{G, B\}$, who disagree over how much changes in global temperature affect the probability of a consumption disaster. We assume that the green investor, G, believes that climate change has a large impact on disaster probabilities while the brown investor, B, believes in a smaller impact:

$$g^G(T_t) \geq g^B(T_t), \tag{4}$$

where $g^h(T_t) = \pi_t^h$ denotes the beliefs of agent h about the probability of a climate-induced disaster. We assume that

$$g^h(T_t) = \begin{cases} 0, & \text{if } T_t < T_{tipp} \\ l^h T_t, & \text{otherwise,} \end{cases} \tag{5}$$

where $l^G > l^B$. T_{tipp} denotes the threshold temperature above which climate-induced disasters can occur. Hence, as long as global temperature, T_t, is below the tipping point T_{tipp}, the climate-induced disaster probability is zero.[7] Only if the tipping point is crossed do disaster probabilities increase proportionally to temperature. Investors disagree on the magnitude of this effect.

As argued in Section 2.1, climate experts disagree significantly regarding the probability of climate-induced disasters and their impacts on the economy. Furthermore, also in line with our model assumptions, that disagreement is growing with rising temperature levels.

We assume that global temperature, T_t—or, more precisely, what investors believe about the dynamics of global temperature—follows an AR(1) process and is given by

$$T_{t+1} = \mu_T(1 - \nu) + \nu T_t + \sigma_\zeta \zeta_{t+1}, \tag{6}$$

[7]We acknowledge that, in general, threshold temperature levels are unknown and today's temperature level might lie beyond a safe operating space. In fact, we assume a positive but negligible probability if $T_t < T_{tipp}$. A state with 0 probability is not possible as the subjective distribution $dP^B_{t,t+1}$ in (11) would no longer be absolutely continuous with respect to $dP^G_{t,t+1}$.

where $\zeta_{t+1} \sim i.i.d.\ N(0,1)$. As argued above, from an investor perspective the shocks ζ_{t+1} can be viewed as news about climate change. Note that in the climate economics literature it is common practice to model emissions, which then affect global temperature, and that emissions might themselves be a function of consumption growth. To demonstrate our main findings, we abstract from such feedback loops in our model, although they do constitute an interesting avenue for future research.

We consider the pricing of two different assets: a green and a brown stock. We argue that brown stocks should be more exposed to climate financial risks for the following reason: Assume that a climate disaster such as a significant increase in sea level that causes large-scale flooding materializes. Such an event will put pressure on governments to take immediate actions to slow down climate change. So even though policymakers might have in the past been reluctant to put stringent climate policies in place, they are likely to do so if severe damage due to climate change materializes. Hence, brown stocks will not only be exposed to the physical disaster itself, but additionally their future cash flows should decrease due to more stringent climate policies.

Hence, we assume that the log dividend growth, $\Delta d^i_{t+1} \equiv \log\left(\frac{D^i_{t+1}}{D^i_t}\right)$, of asset i is given by

$$\Delta d^i_{t+1} = \mu_d + \Phi\sigma_\eta\eta_{t+1} + k^i D_{t+1}, \tag{7}$$

where the market portfolio has a climate exposure of $k^i = 1$, brown stocks are more exposed to climate disaster risks with $k^i > 1$, and green stocks have $k^i < 1$. Mean log dividend growth is represented by μ_d and Φ denotes the leverage parameter to account for the excess volatility of dividend growth over consumption growth.

3.1 Investors

We assume that there are two groups of investors, $h \in \{G, B\}$, with Epstein–Zin preferences (see Epstein and Zin (1989) and Weil (1989)). We argue below that this is crucial to obtaining risk sharing dynamics in line with the empirical evidence on the hedging of climate risks. Let V^h_t denote agent h's continuation utility. We normalize this function by aggregate consumption, $v^h_t = V^h_t / C_t$, so that

$$v^h_t = \left[(1-\delta)(s^h_t)^\rho + \delta R^h_t\left(v^h_{t+1} \cdot e^{\Delta c_{t+1}}\right)^\rho\right]^{\frac{1}{\rho}}, \quad h \in \{G, B\}, \tag{8}$$

with $s^h_t = \frac{C^h_t}{C_t}$, and $R^h_t(x) = \left(E^h_t\left(x^\alpha\right)\right)^{\frac{1}{\alpha}}$ being the certainty equivalent operator. $E^h_t(.)$ denotes the expectation of agent h conditional on information at time t. While agents have different beliefs, they share the same preference parameters.[8] The subjective discount factor is denoted

[8]This assumption could be relaxed, as, for example, shown in Pohl et al. (2021).

by δ, $\rho = 1 - \frac{1}{\psi}$ determines the elasticity of intertemporal substitution ψ, and $\alpha = 1 - \gamma$ determines the relative risk aversion, γ, of the agents. By setting $\alpha = \rho$ we obtain the special case of CRRA preferences.

3.2 Equilibrium

We solve for the equilibrium consumption shares using the numerical procedure proposed by Pohl et al. (2021). The social planner maximizes the weighted sum of the individual agents' utilities where λ_t^h denotes the optimal weights (also called Negishi weights) that are determined in equilibrium. Pohl et al. (2021) show that the Negishi weights are linked to the individual consumption shares s_t^h via

$$\frac{\lambda_t^G}{\lambda_t^B} = \left(\frac{s_t^G}{s_t^B}\right)^{\frac{1}{\psi}}. \tag{9}$$

Note that the weights are monotone in s_t, and hence that an increase in λ_t^h implies an increase in s_t^h. Market clearing requires

$$s_t^G + s_t^B = 1 \tag{10}$$

and the dynamics of the Negishi weights in equilibrium are given by

$$\frac{\lambda_{t+1}^B}{\lambda_{t+1}^G} = \frac{\lambda_t^B}{\lambda_t^G}\frac{dP_{t,t+1}^B}{dP_{t,t+1}^G}\left(\frac{(v_{t+1}^B)}{R_t^B(v_{t+1}^B e^{\Delta c_{t+1}})}\frac{R_t^G(v_{t+1}^G e^{\Delta c_{t+1}})}{(v_{t+1}^G)}\right)^{\frac{1}{\psi}-\gamma}, \tag{11}$$

where $P_{t,t+1}^h$ denotes the subjective distribution of the state at $t+1$ conditional on time t information. The term $dP_{t,t+1}^B/dP_{t,t+1}^G$ is the Radon–Nikodym derivative of $P_{t,t+1}^B$ with respect to $P_{t,t+1}^G$. Note that in our model investors disagree about climate disaster probabilities, which depend on the state of the economy T_t. However, they agree on the dynamics of temperature itself as well as on the normal shocks to consumption. Hence, the only relevant elements (non unit elements) in $dP_{t,t+1}^B/dP_{t,t+1}^G$ arise from the disagreement about D_{t+1}. The subjective distribution for the disaster term is given by

$$P^h(N_{t+1} = x|\pi_t^h > 0) = \frac{(\pi_t^h)^x}{x!}e^{-\pi_t^h}. \tag{12}$$

In the special case $\pi_t^h = 0$, it trivially holds that $P^h(N_{t+1} = 0|\pi_t^h = 0) = 1$ and $P^h(N_{t+1} = x|\pi_t^h = 0) = 0$ for $x > 0$. It follows that

$$\frac{dP_{t,t+1}^B}{dP_{t,t+1}^G} = \begin{cases} \left(\frac{\pi_t^B}{\pi_t^G}\right)^x e^{-\pi_t^B + \pi_t^G} & \pi_t^B, \pi_t^G > 0 \\ 1 & \pi_t^B = \pi_t^G = 0. \end{cases} \tag{13}$$

3.3 Climate Risk Sharing

In the following we explain how investors with Epstein–Zin utility share risks—that is, both shocks to news about climate change modeled by changes in global temperature and climate disaster risks depending on the climate tipping point. In particular, we show that, in line with the financial market data, investors share temperature risks, while climate disaster risks are only traded once the tipping point is crossed. Furthermore, we argue below that these risk sharing dynamics can explain the empirical findings on the performance of brown and of green assets and the shares of brown and of green investors.

For this, we first consider the special case of CRRA preferences. In this case, equation (11) simplifies to

$$\frac{\lambda_{t+1}^B}{\lambda_{t+1}^G} = \frac{\lambda_t^B}{\lambda_t^G}\frac{dP_{t,t+1}^B}{dP_{t,t+1}^G}.$$

Hence, for CRRA preferences all that matters for the next period's consumption shares is the disagreement about the state in the subsequent period. Assume that $T_t < T_{tipp}$. In this case $\pi_t^B = \pi_t^G = 0$ and hence $\lambda_{t+1}^h = \lambda_t^h$. So investors have no incentive to trade with one another as they agree on the subsequent state of the economy. Hence, the wealth shares of brown and green investors would stay constant under these assumptions. In contrast, if $T_t \geq T_{tipp}$, investors disagree about the probability of a climate disaster and we obtain

$$\frac{dP_{t,t+1}^B}{dP_{t,t+1}^G} = \left(\frac{l^B}{l^G}\right)^x e^{(l^G - l^B)T_t}.$$

As $l^G > l^B$, it follows that $\lambda_{t+1}^B > \lambda_t^B$ if $x = 0$. Intuitively, the brown investor believes in a lower probability of disaster. Hence, he is willing to speculate that no disaster occurs in the subsequent period. If in fact no disaster materializes, his consumption share will increase. In contrast, $\lambda_{t+1}^B < \lambda_t^B$ if $x > 0$. The green investor believes in a larger disaster probability and hence her consumption share will increase if a disaster materializes. This is the speculation motive highlighted in Borovička (2020) and Pohl et al. (2021). This has interesting implications for the market shares of investors. It implies that as long as no disaster occurs, the share of brown investors must either stay constant or increase over time, which contrasts with recent evidence on the increasing market shares of green investors; see Section 2.2.

For Epstein–Zin preferences, there arises an additional risk sharing motive in equation (11), captured by the term

$$\left(\frac{(v_{t+1}^B)}{R_t^B(v_{t+1}^B e^{\Delta c_{t+1}})}\frac{R_t^G(v_{t+1}^G e^{\Delta c_{t+1}})}{(v_{t+1}^G)}\right)^{\frac{1}{\psi}-\gamma}.$$

We focus on the case where $\gamma > \frac{1}{\psi}$, which implies that investors have a preference for the early resolution of risks—a common assumption in modern asset-pricing models (see, for example, Bansal and Yaron (2004) and Wachter (2013)). Suppose that a state materializes that the green investor particularly dislikes, such that

$$\frac{(v^B_{t+1})}{R^B_t(v^B_{t+1}e^{\Delta c_{t+1}})} > \frac{(v^G_{t+1})}{R^G_t(v^G_{t+1}e^{\Delta c_{t+1}})}.$$

This implies

$$\left(\frac{(v^B_{t+1})}{R^B_t(v^B_{t+1}e^{\Delta c_{t+1}})}\frac{R^G_t(v^G_{t+1}e^{\Delta c_{t+1}})}{(v^G_{t+1})}\right)^{\frac{1}{\psi}-\gamma} < 1$$

so that the consumption share of the brown investor decreases and, in turn, the share of the green investor increases. So investors trade insurance against states that they particularly dislike based on their beliefs. This is what Borovička (2020) and Pohl et al. (2021) call the risk sharing motive. In our model, green investors particularly dislike increases in temperature as these increase the probability of a climate disaster. Hence, the green investor would like to buy insurance against these increases such that she gets compensated by a larger consumption share when the bad temperature state materializes. Hence, for Epstein–Zin preferences (unexpected) increases in temperature lead to an increase in the consumption share of the green investor. This effect is present even if $T_t < T_{tipp}$ as long-term changes in T_t are priced in by Epstein–Zin investors. In Section 4 we show that this effect is quantitatively large for common calibrations of the model.

Before we do so, we discuss the relation between the consumption shares of the investors and their respective wealth shares or market shares (we use the two terms interchangeably in the following). The wealth share, w^h_t, of investor h is given by

$$w^h_t = \frac{W^h_t}{W_t},$$

where W^h and W_t denote the wealth of investor h and total wealth, respectively. We compute w^h_t using the identity

$$w^h_t = s^h_t \cdot \frac{W^h_t}{C^h_t} \cdot \left(\frac{W_t}{C_t}\right)^{-1}.$$

The aggregate wealth consumption ratio $\frac{W_t}{C_t}$ follows from the standard asset-pricing equation

$$E^h_t(M^h_{t+1}R^i_{t+1}) = 1,$$

where M^h_{t+1} denotes the stochastic discount factor. For Epstein–Zin preferences, M^h_{t+1} is given by

$$M^h_{t+1} = \delta \cdot \left(\frac{s^h_{t+1}}{s^h_t}\right)^{-\frac{1}{\psi}} \left(e^{\Delta c_{t+1}}\right)^{-\gamma} \cdot \left(\frac{v^h_{t+1}}{R^h_t(v^h_{t+1}e^{\Delta c_{t+1}})}\right)^{\frac{1}{\psi}-\gamma}$$

and the wealth consumption ratio of investor h satisfies

$$\frac{W_t^h}{C_t^h} = \frac{1}{1-\delta} \cdot \left(\frac{v^h}{s^h}\right)^{1-\frac{1}{\psi}}. \tag{14}$$

Figure 17 in Appendix A.1 plots the consumption share of the green investor against her wealth share for the calibration of our economy presented in Section 4. We find that there is almost a one-to-one mapping between the two. So, changes in consumption shares imply equivalent changes in wealth shares, and we use the two terms interchangeably.

4 Results and Discussion

In the following we present the predictions of our climate finance economy and show that it can match the climate risk sharing dynamics on financial markets, the market shares of green and of brown investors, and the pricing of green and of brown stocks. Furthermore, our model makes important predictions regarding welfare gains from climate mitigating policies as well as the carbon premium when global temperatures continue to increase. We calibrate the model using key insights from both the climate economics literature and the asset-pricing literature. Note that even though we provide evidence for the specific choices of all model parameters, we are less concerned about finding the best calibration for our model, but rather are interested in the qualitative predictions our model makes and what we can learn from it about the pricing of climate-exposed assets as well as the benefits of climate mitigating policies.

4.1 Calibration

As formulated in equation (6), our modeling framework allows us to include global average temperature as a state variable that dynamically evolves round its long-run average. In our benchmark calibration we assume that the persistence of temperature is given by $\nu = 0.995$. Here, we implicitly assume natural carbon cycle adjustments such as oceanic uptake and carbon uptake by the terrestrial biosphere. For the long-run mean global surface temperature above the preindustrial level we assume $E(T_t) = \mu_T = 2$°C, which according to Nauels et al. (2017) falls between the expected 2300 levels for the RCP2.6 and RCP4.5 paths. The "true" long-run temperature level is unknown and will depend on our future emissions and policy efforts to curb carbon emissions. The latest IPCC report presents five illustrative emission scenarios. Even under the intermediate greenhouse gas emissions scenario, warming of 2°C would very likely be exceeded by the end of the century. Another reason for choosing 2°C is that in the form of the Paris Climate Agreement (COP 21) there is a legally binding international treaty on climate change that, adopted by 196 parties in 2015, introduces the goal of limiting global warming to significantly less than 2°C, or preferably 1.5°C (UNFCCC (2015)).

For the calibration of our consumption and dividend process, we stick to the related literature as closely as possible: in line with the literature on long-run consumption risks (see Bansal and Yaron (2004) and Bansal et al. (2012)), we set $\psi = 1.5$, $\gamma = 8$, $\delta = 0.9763$, $\mu_c = \mu_d = 0.02$, $\sigma_\eta = 0.02$, and $\Phi = 2.6$. The notations μ_c, μ_d, σ_η, and Φ are used to match the mean and volatility of consumption and dividend growth. For example, Bansal and Yaron (2004) use $\mu_c = \mu_d = 0.0180$ to match the average consumption and dividend growth rate of about 2% per year in the United States. Wachter (2013) gives us $\sigma_\eta = 0.02$ and $\Phi = 2.6$ to match the volatility of consumption and dividend growth of about 1.5% and 6.5% per year, respectively. We seek to calibrate our model such that the implied annual asset-pricing moments are in line with empirical findings (see Table 3 in Section 4.4). Furthermore, $\gamma > 1/\psi$ is crucial to matching the moments of asset prices as well as to obtaining climate risk sharing dynamics in line with the data.

We calibrate disaster probability and size to approximately match the findings in Cai et al. (2016).[9] While we prefer to focus on our qualitative results, we take the findings in Cai et al. (2016) as a proxy and assume that in the case of a disaster, the log consumption growth drops by 20% ($d = -0.2$). We assume the subjective temperature-induced disaster probability to be twice as high for the green investor with $l^G = 0.03$ (3% per 1°C of temperature increase) compared to for the brown investor with $l^B = 0.015$ (1.5% per 1°C of temperature increase).[10] This implies a disaster probability of 4.2% (8.4%) per year under the beliefs of the brown (green) investor once the tipping threshold is passed ($T_t = 2.8$°C).

We assume a climate exposure for the green stock of $k^G = 0.75$ and for the brown stock of $k^B = 3.0$. Barro (2006) reports that severe disasters have, in the past, destroyed up 50% of GDP while mild disasters have led to a decrease of 15–20%. Our exposures imply that dividends of brown stocks drop by 45% while dividends of green stocks drop by 15%. Note that our results are robust to variations in the climate exposures and all we require for our qualitative findings to hold is that $k^G < k^B$. We demonstrate the robustness of our findings in Section 4.6. The full calibration of our model is summarized in Table 1.

To demonstrate the key mechanisms of our model, we present two sets of results. Our main results include the distant tipping point with $T_{tipp} = 2.8$°C. We call this model the *Tipping Point* case. Second, we consider a model with immediate climate disaster risks where disasters could occur as of today as has been assumed in many climate finance models; see,

[9] Cai et al. (2016) formulate a stochastic model with interactive climate tipping points. They compute that for approximately ($T_t = 3$°C) the annual average damage caused by disastrous climate change events amounts to a roughly 1.8 percent loss of global GDP.

[10] Here we adopt the findings of Lontzek et al. (2015), who derive hazard rates for optimistic and pessimistic experts based on the elicitation study in Kriegler et al. (2009).

Table 1: Baseline calibration.

Parameter	**Value**	**Interpretation**
γ	8	risk aversion
ψ	1.5	intertemporal elasticity of substitution
δ	0.9763	time discount factor
μ_c	0.02	average consumption growth rate
σ_c	0.02	volatility of i.i.d. normal consumption shock
μ_d	0.02	average dividend growth rate
Φ	2.6	dividend leverage
d	-0.2	disaster size
μ_T	2	long-run mean temperature
ν	0.995	persistence of temperature
σ_ζ	0.1	volatility of i.i.d. normal temperature shock
l^G	0.03	belief parameter green investor
l^B	0.015	belief parameter brown investor
T_{Tipp}	2.8	temperature tipping threshold
k^B	3	climate risk exposure brown stocks
k^G	0.75	climate risk exposure green stocks
k^M	1	climate risk exposure market portfolio

for example, Giglio et al. (2021b,a) and Bansal et al. (2021). This is equivalent to setting $T_{tipp} = 0$°C so that disaster risks can occur as of today. We call this model the *Immediate Disaster Risk* case.

4.2 Hedging Climate News and Climate Disaster Risk

In the following, we show how the different beliefs about the impact of climate change on the real economy affect the hedging incentives of the green and the brown investor. For this, we first present, in Figure 3, the subjective climate disaster probabilities π_t^h as a function of temperature, T_t, for the green investor ($h = G$) as well as for the brown investor ($h = B$). Solid lines show results for the tipping point case. As long as $T_t < T_{tipp}$, both agents agree that the probability of a climate disaster hitting today is zero. In contrast, once the tipping point is crossed, both agents believe in a positive probability of disaster. Green investors, who believe more strongly in climate change, believe in a larger climate disaster probability so that $\pi_t^G > \pi_t^B$. In line with Zickfeld et al. (2007), this difference increases with T_t. In the case of immediate climate disaster risks (dashed lines), disaster probabilities π_t^h are a continuous function of T_t and the difference $\pi_t^G - \pi_t^B$ increases with temperature (assuming $T_t > 0$). Hence, investors disagree even if temperatures are low, which induces strong risk sharing incentives as we show below.

Figure 4 shows changes in the consumption share of the green investor, $s_{t+1}^G - s_t^G$, as

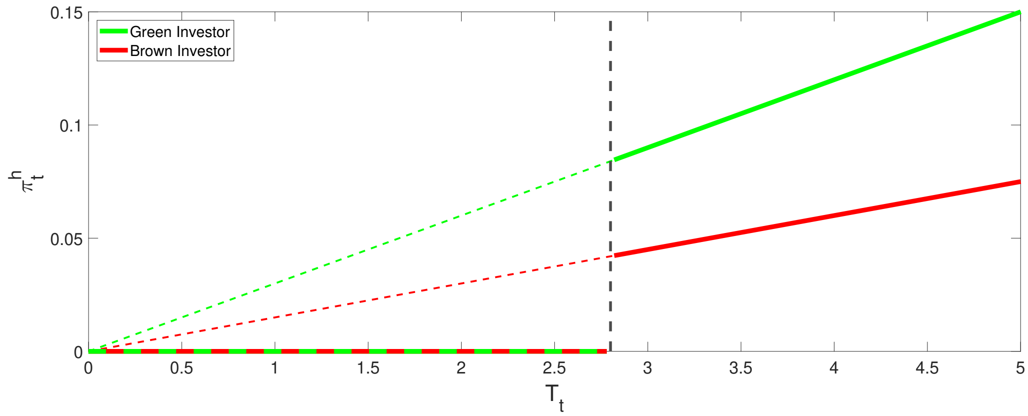


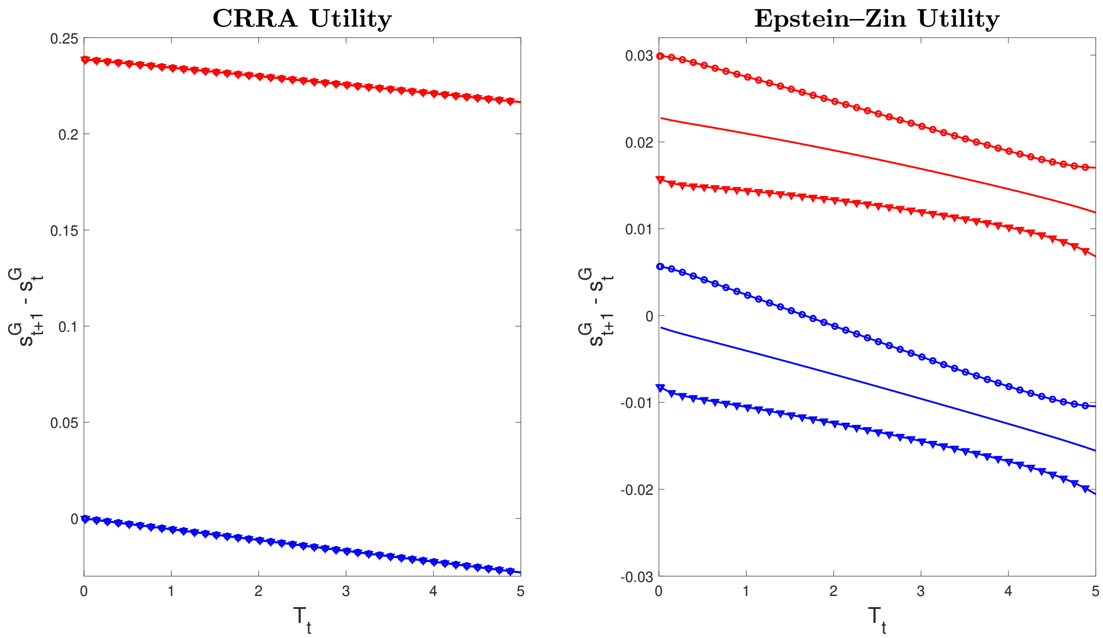
Figure 3: Subjective climate disaster probabilities π_t^h as a function of temperature, T_t, for the green investor as well as for the brown investor. Solid lines show results with the distant tipping threshold ($T_{tipp} = 2.8$°C, marked by the vertical line) and dashed lines results with immediate disaster risk ($T_{tipp} = 0$)°C.

a function of temperature, T_t, for different shocks in period $t+1$. The left panel shows results for CRRA utility where $\gamma = 1/\psi$ and the right panel for Epstein–Zin utility with $\gamma = 8$ and $\psi = 1.5$. Red lines depict the case where a disaster hits in $t+1$ and blue lines the case with no disaster in $t+1$. Lines with circles show the case of a positive shock in T_{t+1} ($T_{t+1} - E_t(T_{t+1}) = +0.0816$°C), lines with triangles that of a negative shock in T_{t+1} ($T_{t+1} - E_t(T_{t+1}) = -0.0816$°C), and the plain solid lines the average change in the consumption share. Results are shown for $s_t^G = 0.5$.

First, consider the immediate disaster risk case with CRRA utility. As shown in Section 3.3, investors only trade based on their beliefs about the probability of a disaster in the next period. However, they do not hedge climate news risk. Hence, independent of the shock to T_{t+1}, the consumption share of the green investor decreases as long as no disaster hits. Only if a disaster materializes does the wealth share of the green investor increase. Hence, in such a model, as long as no climate disaster materializes the wealth shares of brown investors persistently increase over time. In contrast to the empirical evidence in Engle et al. (2020), climate news risk (shocks to temperature in our model) is not traded by the investors in the CRRA case as investors agree on the distribution of global temperature.

For Epstein–Zin preferences this does not hold true. Changes in temperature are a source of long-run consumption risk and hence affect the lifetime utility of the investors. Hence, investors have an incentive to trade temperature risks; see equation (11). In particular, the green investor, who believes in a larger impact of temperature changes on disaster probabilities, has an incentive to hedge positive shocks to temperature. Hence, her consumption share increases when a positive temperature shock materializes (circled lines) compared to the case of a negative temperature shock (lines with triangles). However, as in the CRRA case, as

(a) Immediate Disaster Risk



(b) Distant Tipping Threshold ($T_{tipp} = 2.8$°C)

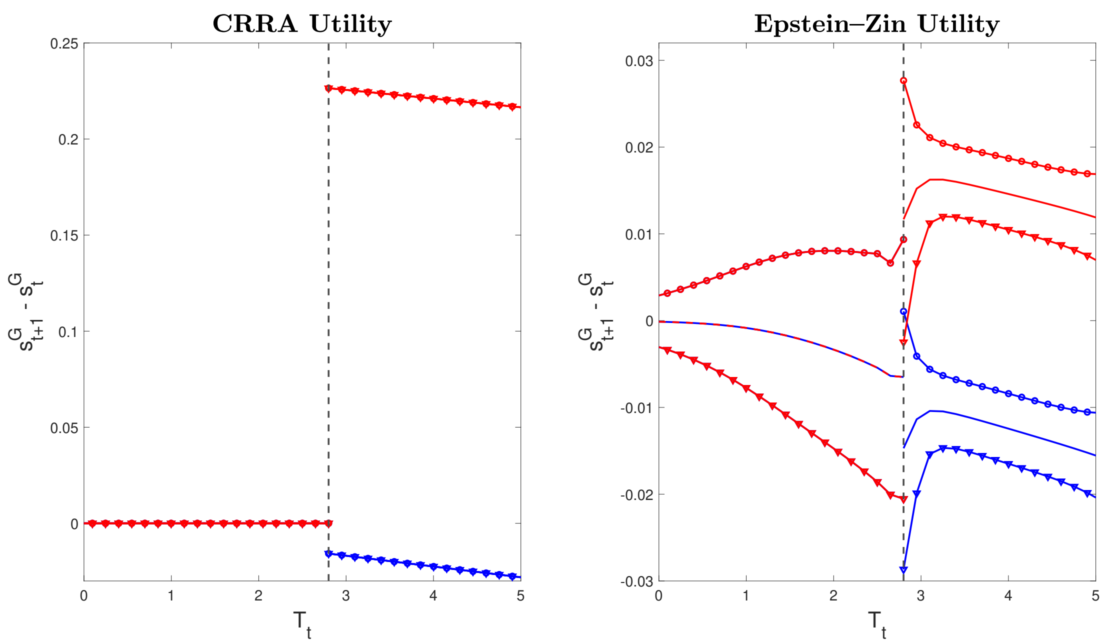


Figure 4: Changes in the consumption share of the green investor, $s^G_{t+1} - s^G_t$, as a function of temperature, T_t, for different shocks in period $t+1$. The left panel shows results for CRRA utility and the right for Epstein–Zin utility. Red lines depict the case where a disaster hits in $t+1$ and blue lines the case with no disaster in $t+1$. Lines with circles show the case of a positive shock in T_{t+1} ($T_{t+1} - E_t(T_{t+1}) = +0.0816$°C), lines with triangles that of a negative shock in T_{t+1} ($T_{t+1} - E_t(T_{t+1}) = -0.0816$°C), and the plain solid lines the average change in the consumption share. Results are shown for $s^G_t = 0.5$ and the vertical line marks the tipping threshold.

climate disasters can potentially occur as of today these risks are traded as well, implying that the average change in the consumption share of the green investor is significantly negative (given no disaster hits) as she is paying to insure against immediate disaster risk.

Panel (b) shows the corresponding results for our benchmark model with a distant tipping point of $T_{tipp} = 2.8$°C. For CRRA preferences, as long as $T_t < T_{tipp}$ investors agree on the distribution of climate disasters and hence have no incentive to trade. Only once the tipping point is crossed do they disagree about the probability of a climate disaster and trade with each other as in the case without the tipping point. Hence, for CRRA preferences climate news has no effect on the equilibrium consumption shares independent of whether the climate disaster risk is immediate or only occurs once the distant tipping point is crossed.

In contrast, for Epstein–Zin preferences temperature risks are traded even if $T_t < T_{tipp}$ as the risk that the tipping point will be crossed in the future is reflected in continuation utility v_t^h. Hence, green investors buy insurance against bad climate shocks so that when temperature increases they can compensate the decline in utility by an increased consumption share. In contrast to the immediate disaster risk case, climate disaster risks are not traded as long as $T_t < T_{tipp}$ as investors agree on disaster probabilities and hence have no incentive to trade these risks. This implies that green investors are also not paying a premium to hedge disaster risks such that the average change in the consumption share is close to 0 for low temperature levels.

So, our model implies that as long as the tipping point has not been crossed the only sources of variation in the market shares of green and of brown investors are climate news shocks. In particular, bad news about the climate (positive shocks to temperature) leads to an increase in the market share of green investors in line with the increase in green investing over the past decade as reported in Section 2.2. We discuss this finding as well as the equilibrium implication for the carbon risk premium in more detail in the following section. As the CRRA model is not consistent with the hedging of climate risks on financial markets, we focus our discussion on the case of Epstein–Zin preferences and the importance of appropriately modeling the tipping point, in the next sections.

4.3 Carbon Premium

Our model yields predictions regarding the pricing of green and of brown assets. Figures 5 and 6 show the carbon premium for CRRA and Epstein–Zin preferences, respectively.[11] We define the carbon premium as the expected return of brown stocks minus the expected return of green stocks, and show the premium as a function of T_t for the beliefs of the brown investor

[11] For CRRA preferences, results are shown for $\gamma = 2$ as for higher degrees of risk aversion existence issues occur (see Pohl et al. (2023) for a detailed discussion of the existence problem). However, while this lowers the carbon premium quantitatively, it does not have any effect on the qualitative conclusions we draw based on these results.

and a fixed wealth share of $w_t^G = 0.5$.[12]

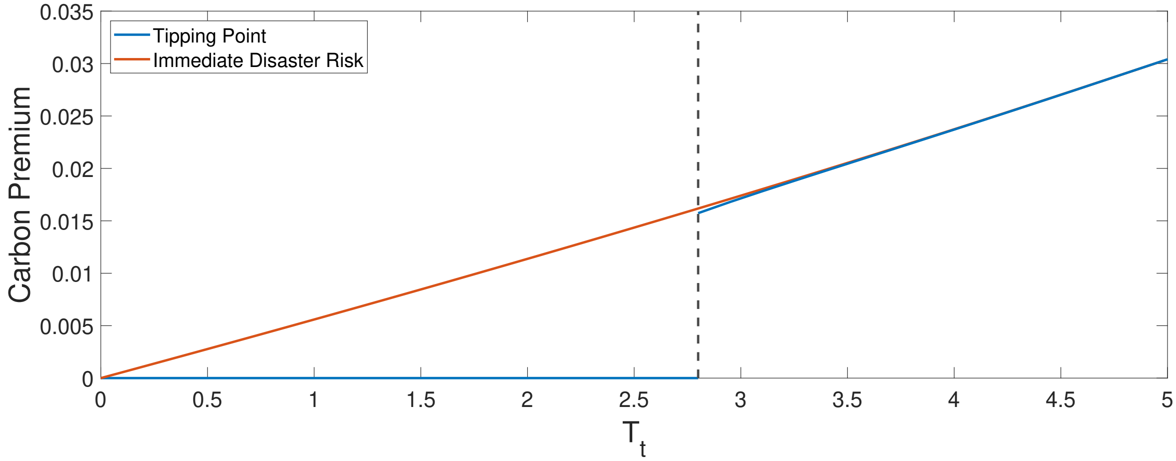


Figure 5: The expected return of the brown stock minus the expected return of the green stock as a function of temperature, T_t, for $w_t^G = 0.5$ for CRRA preferences with $\gamma = 1/\psi = 2$. Results are shown for the case with immediate disaster risk and for the case with the distant tipping threshold for the beliefs of the brown investor. The vertical dashed line marks the tipping threshold.

The red line in Figure 5 shows results for the immediate disaster risk case and the blue line for our benchmark model with the distant tipping point. In the case of CRRA preferences, the carbon premium is zero as long as $T_t < T_{tipp}$. Investors with CRRA preferences do not price in long-term risks and, as the disaster risk can only occur in the future, the premium for assets with different exposures to climate risk is the same across assets and is equal to zero. Only once the tipping threshold is crossed does the carbon premium become large and significant and increase with the disaster probability driven by T_t. Hence, for temperature levels below the temperature threshold as observed in the past decade, CRRA investors would not require a premium for holding assets that are more exposed to climate risks. This is in contrast with the findings of Bolton and Kacperczyk (2021, 2022), who report a significant carbon premium.

In turn, for Epstein–Zin preferences the carbon risk premium is positive as long-run climate risks are priced in and brown stocks have a higher exposure to climate risks ($k^B = 3.0$ versus $k^G = 0.75$). The carbon premium increases with temperature as it positively affects the probability of a disaster. Note that this is true in the tipping point model even if $T_t < T_{tipp}$ as temperature changes are a source of long-run risk, which is priced under Epstein–Zin utility. So even if temperatures are well below the tipping point, an increase in temperature increases the carbon premium.

[12] Figures 18 and 19 in Appendix A.1 show the corresponding results for the beliefs of the green investor, which are qualitatively the same, only the magnitude of the carbon premium decreases.

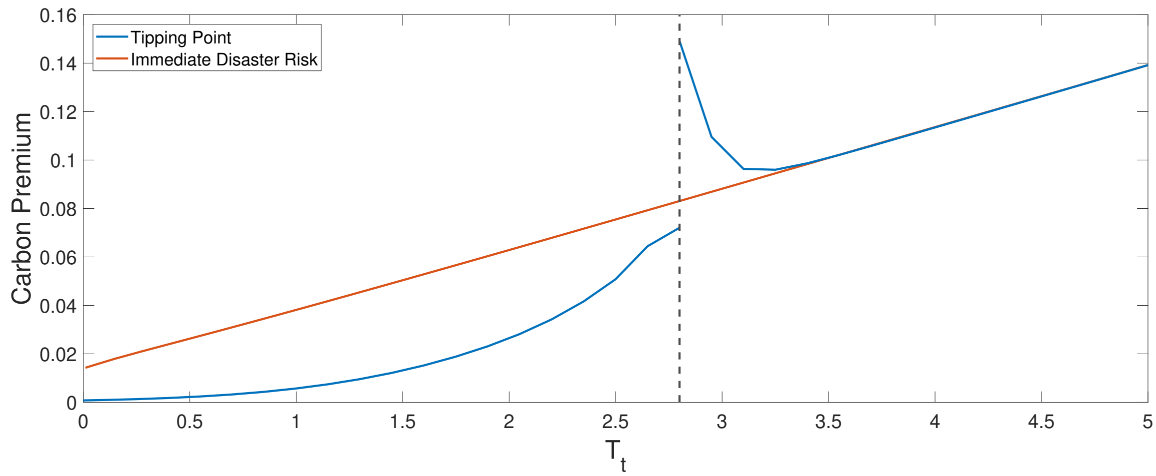


Figure 6: The expected return of the brown stock minus the expected return of the green stock as a function of temperature, T_t, for $w_t^G = 0.5$. Results are shown for the case with immediate disaster risk and for the case with the distant tipping threshold for the beliefs of the brown investor. The vertical dashed line marks the tipping threshold.

If climate disasters pose a potential risk as of today (red line), the carbon premium will be large even for low temperature levels. For example, for the temperature level of 2020 of 1°C the carbon premium is 3.5 percent. In contrast, when we appropriately account for the distant tipping point when modeling climate disaster risks the implied carbon premium is significantly smaller for lower temperatures as the tipping point is sufficiently far away, in line with the small carbon premium reported on financial markets. However, our model predicts that the carbon premium will increase significantly if climate risks increase in the future. These results highlight the importance of appropriately accounting for the specific properties of climate risks in financial models. More precisely, when climate risks are analyzed in financial models, it is crucial to include tipping thresholds when modeling these risks and not to model them as imminent disaster risks, which is standard in the asset-pricing literature. Moreover, for CRRA preferences long-term climate risks are not priced, so it is crucial to use preferences that take long-term trade-offs into account.

The carbon premium depends not only on the temperature level but also on the market share of the green investor. Figure 7 plots the carbon premium as a function of the wealth share of the green investor for a low temperature level, $T_t = 1$°C, and a high temperature level close to the tipping point, $T_t = 2$°C, which—in line with the pessimistic RCP8.5 emission scenario—could be reached in 2050.

Green investors are more afraid of climate risks and hence require a larger premium for holding the brown asset. So in equilibrium, the larger the market share of the green investor, the larger is the carbon premium. While this effect is quantitatively small for the low temper-

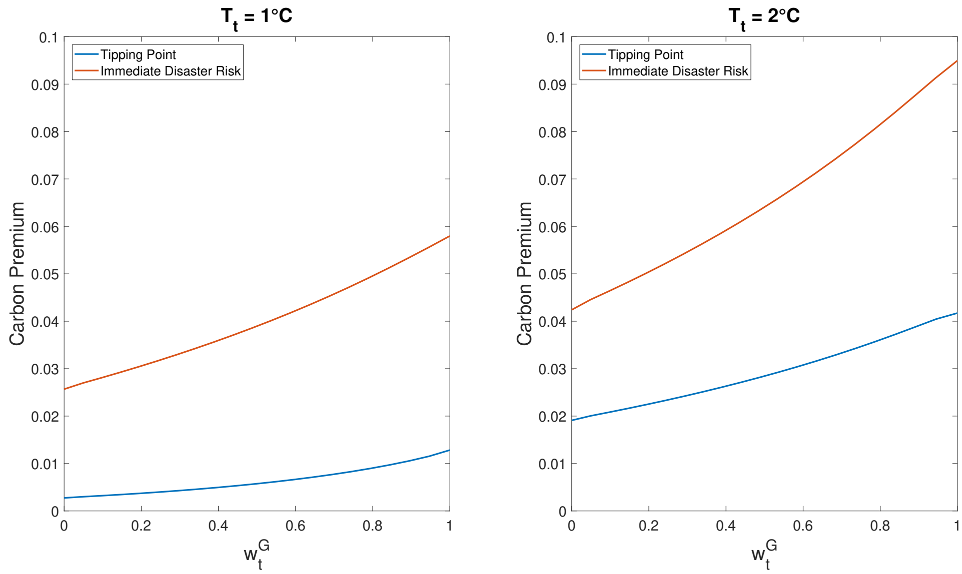


Figure 7: The expected return of the brown stock minus the expected return of the green stock as a function of the wealth share of the green investor, w_t^G, for different levels of temperature, T_t. Results are shown for the case with immediate disaster risk and for the case with the distant tipping threshold for the beliefs of the brown investor.

ature level of today ($T_t = 1$°C), with a carbon premium only slightly above 1 percent for any wealth share of the green investor, it significantly increases once the temperature gets closer to the tipping point, with a carbon premium of up to 4 percent for $T_t = 2$°C.

Our model hence yields a positive carbon premium that increases with temperature risks as well as with the share of green investors. So the increase in the market share of green investors over the past decade has likely contributed to an increase in the carbon premium, and our model predicts that the carbon premium will increase significantly if the market share of green investors keeps rising.

4.4 Green Investing

How can this evidence be reconciled with the recent outperformance of green stocks as for example reported in Huij et al. (2021) and Pástor et al. (2022)? We show that unexpected bad news about the climate drives up the wealth shares of green investors and pushes up the relative valuations of green versus brown firms. Ardia et al. (2023) provide empirical evidence for this mechanism. They construct a climate concern index based on newspaper articles and show that green stocks react more positively to bad climate news compared to brown stocks. Pástor et al. (2022) use this climate concern index and show that forecasting errors have a strong downward trend implying that news about the climate has been consistently worse than expected.

In our model, unexpected bad news about the climate—that is, positive shocks to T_t—has two effects on the pricing of green and brown assets, one direct and one indirect: Positive shocks to T_t lead to a decrease in the price of stocks that have a large exposure to climate risks. In turn, green stocks that provide a (partial) hedge against climate risks increase in value in response to bad climate news; see the left panel of Figure 8, which plots the price–dividend ratios of the green and the brown asset as well as the market portfolio as a function of T_t. Simultaneously, the increase in temperature increases the market share of green investors as argued in Section 4.2. Green investors require a larger compensation for holding brown assets compared to brown investors, and hence the increase in their market share leads to a further decrease in the prices of the brown asset (see the right panel of Figure 8, which plots price–dividend ratios as a function of w_t^G). As a result, increases in temperature endogenously drive up the market share of green investors and lead to an outperformance of green over brown stocks.

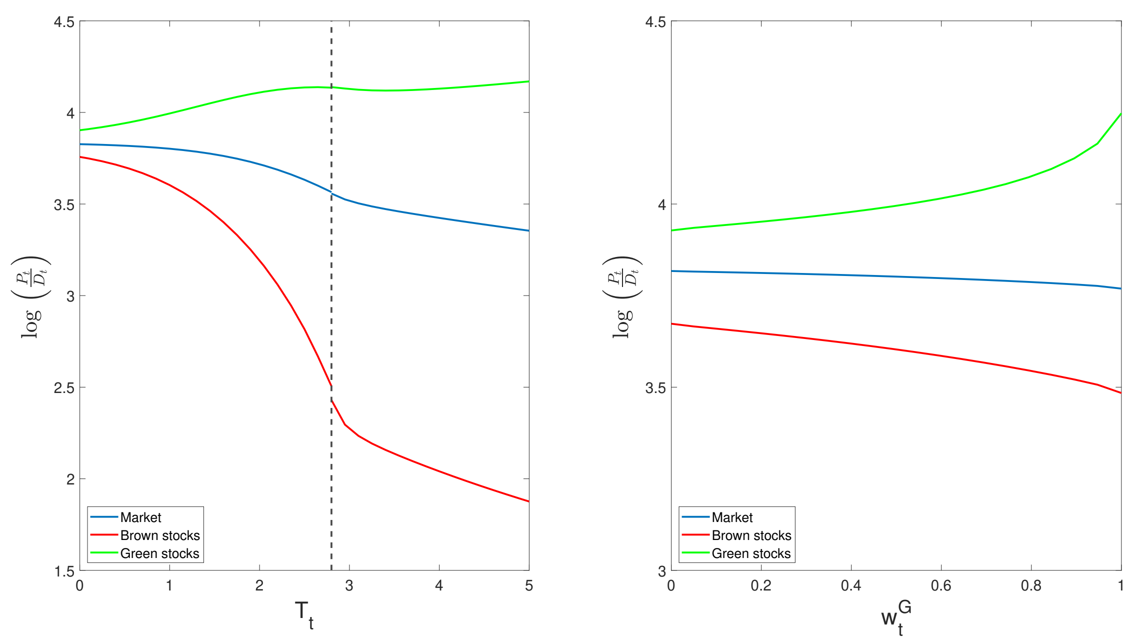


Figure 8: The log price–dividend ratio for the green and the brown stocks and for the market portfolio. In the left panel, the price–dividend (pd) ratios are shown as a function of temperature, T_t, for $w_t^G = 0.5$. The right panel shows the pd ratios as a function of the wealth share of the green investor for $T_t = 1$°C. Results are shown for the baseline calibration with a tipping threshold at 2.8°C.

We demonstrate this mechanism in Figures 9 and 10. Figure 9 shows the impact of a bad climate shock on the market share of the green investor and on the returns of green and of brown stocks. Starting at $T_0 = 1$°C, the temperature level today, and $w_0^G = 0.5$, it shows the effect of a one standard deviation climate shock of $\sigma_\zeta \zeta_{t+1} = +0.1$°C in period 2, assuming that all shocks in other periods are zero.[13] The bad climate shock increases the market share of the green investor, who buys insurance against climate risk from the brown investor as argued in Section 3.3. Hence, a series of bad shocks leads to an increased market share of green investors over time. Green and brown stocks are differently affected by bad climate news. Brown stocks with a large climate exposure depreciate in value when bad news about the climate arrives, as shown in the right panel of Figure 9. In contrast, green stocks provide a (partial) hedge against climate risks such that their prices increase in response to bad news about the climate. Hence, positive shocks to T_t imply an outperformance of green over brown stocks in our model.

Figure 10 shows corresponding results assuming that no news about the climate occurs, but that there is an exogenous shift in the market share of green investors in period 2. Green investors are more afraid of climate risks and hence are willing to pay a lower (higher) price for the brown (green) asset. As a consequence, the increase in market share implies temporarily higher returns for green stocks compared to brown stocks. So, both the bad climate news and the resulting increase in the market share of the green investor lead to an outperformance of green over brown stocks.

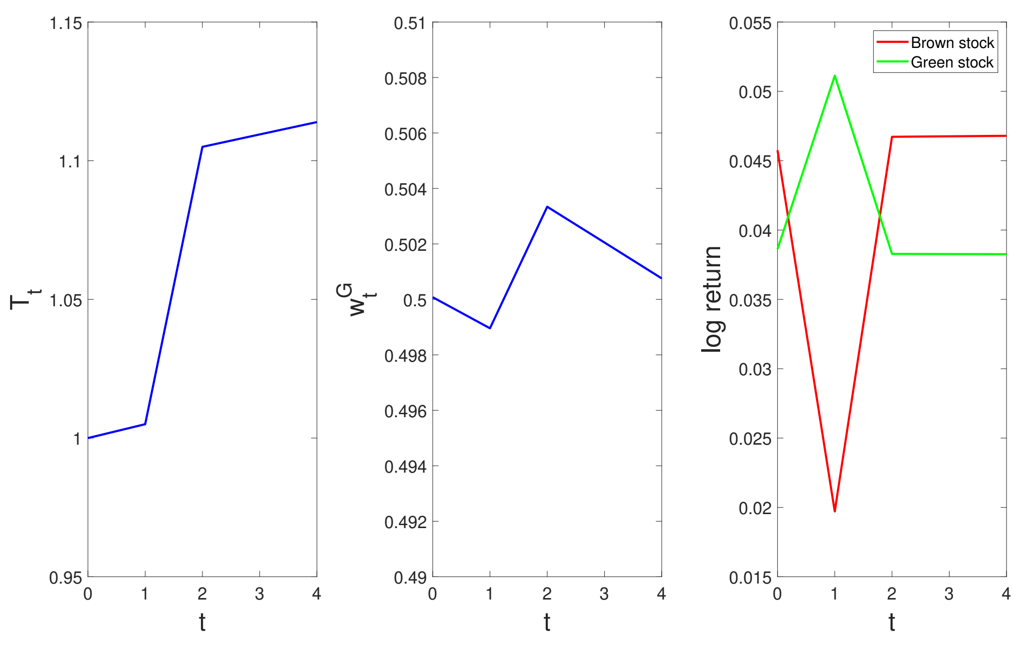


Figure 9: Changes in the wealth share of the green investor and the log returns of green and of brown stocks for a one-time shock in temperature of 0.1°C in period 2. All other shocks are set to zero and results are shown for $w_0^G = 0.5$.

[13]Note that due to mean reversion, T_t is slightly sloping upward and the market share of green investors is sloping downward in the absence of shocks as green investors pay a premium to hedge climate news; see Figure 4.

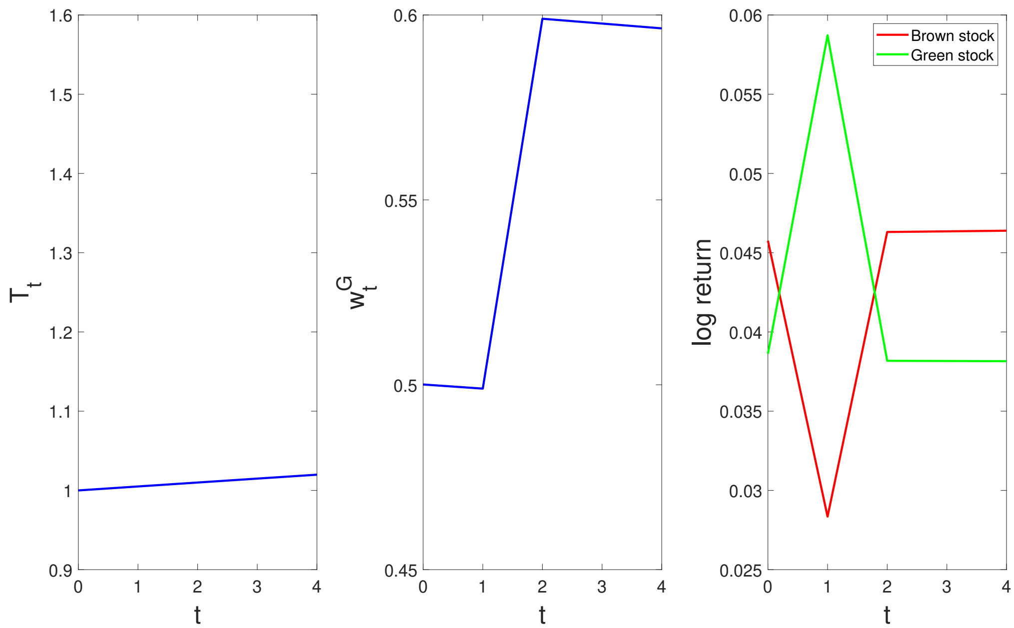


Figure 10: Changes in the wealth share of the green investor and the log returns of green and of brown stocks for a one-time shock in the wealth share of the green investor of 10% in period 2. All other shocks are set to zero and results are shown for $w_0^G = 0.5$.

Ardia et al. (2023) find that there was a series of bad climate news items in the period 2010–2021. Our model predicts that such a series of bad climate news items will lead to an outperformance of green stocks over brown stocks in line with the outperformance of green stocks in the past decade reported by Huij et al. (2021) and Pástor et al. (2022). We demonstrate the impact of a series of bad climate news items in Table 2. For this, we simulate 1,000 sample paths each containing 11 years of data. We consider two scenarios. In the first, climate news shocks ζ_{t+1} are simply drawn from a random normal distribution. This describes a scenario with no particularly bad news about the climate. In the second scenario, in each period we exogenously add a bad climate news shock of $\sigma_\zeta \zeta_{t+1} = 0.1$°C to the temperature process.

Table 2 shows selected annualized asset-pricing moments for the two scenarios. In the first scenario, without unexpectedly bad climate news, brown stocks slightly outperform green stocks reflecting the small but positive carbon premium for low temperature levels reported in Figure 6. As brown stocks are more exposed to climate risks, they have a smaller price–dividend ratio compared to green stocks and are slightly more volatile. The wealth share of green investors is slightly decreasing over time as green investors are paying a premium to insure against climate risks; see Figure 4.

In contrast, a series of bad climate news items leads to a strong outperformance of green stocks. In our calibrated economy, we obtain an annual outperformance of 3.70% with a standard deviation across the sample paths of 1.65%, which is roughly in line with the outperformance of 4.08% reported in Huij et al. (2021) and that of 5.4% reported in Pástor et al. (2022).

Bad climate news leads to a strong increase in the valuations of green assets while the average price–dividend ratio of brown assets is significantly smaller compared to the scenario without unexpectedly bad climate news. As green investors buy insurance against climate shocks, their market share increases in response to the bad climate news resulting in an increase in their market share of about 5 percent over the 11 year period. Furthermore, as brown stocks are more exposed to climate risks their prices react more strongly to climate news leading to a larger volatility of brown stocks compared to green stocks.

Table 2: Annual asset-pricing moments for green and for brown stocks from simulating 1,000 sample paths each containing 11 years of data. We set $T_{start} = 0.6$°C and $w^G_{start} = 0.5$. The top panel shows results when shocks to temperature, ζ_{t+1}, are drawn from a standard normal distribution. In the bottom panel we assume that, additional to the normal shocks, there is bad climate news of +0.1°C per period. Standard deviations of the time series moments across the sample paths are shown in parentheses.

	$E(p^i_t - d^i_t)$	$\sigma(p^i_t - d^i_t)$	$E(log(R^i_t))$	$\sigma(log(R^i_t))$	$R^B_t - R^G_t$	$E(w^G_T)$
Normal Shocks to T_{t+1}						
Green Stock	3.9567 (0.0198)	0.0146 (0.0069)	0.0412 (0.0158)	0.0496 (0.0111)	0.0031 (0.0077)	0.4942
Brown Stock	3.6728 (0.0351)	0.0255 (0.0150)	0.0442 (0.0162)	0.0519 (0.0118)		
Unexpectedly bad climate news						
Green Stock	4.0235 (0.0235)	0.0499 (0.0135)	0.0520 (0.0160)	0.0501 (0.0113)	-0.0370 (0.0165)	0.5559
Brown Stock	3.5173 (0.0738)	0.1353 (0.0600)	0.0151 (0.0205)	0.0605 (0.0145)		

Finally, Table 2 shows annual moments for aggregate consumption growth, dividend growth of the market portfolio, the market risk premium, and the carbon premium, as well as the risk-free rate. As the climate tipping point is not crossed in the simulations, climate shocks have no effect on consumption and dividend growth. Our calibration implies average aggregate consumption growth of about 2% per year with a volatility of 1.88%, in line with the US data. Dividends also have a growth rate of about 2% per year but are significantly more volatile, in line with the moments in the data (see, for example, Wachter (2013)). Our model implies a market risk premium of below 1% per year. Note that climate risks are the only priced risks in our model and hence we do not target a matching of the aggregate market premium of about 7% per year in the US. Finally, the risk-free rate in our model is about 3.45% per year as precautionary savings due to disasters are low for temperature levels significantly below the tipping point. Figure 11 plots the risk-free rate as a function of T_t. In the case of immediate disaster risk, the risk-free rate is monotonically decreasing in T_t, as precautionary savings increase with the probability of a disaster (Wachter, 2013). Precautionary savings only become economically relevant once the tipping point is crossed. Hence, for low temperature levels the risk-free rate is relatively large. Note that the model would produce both a large risk premium and a low risk-free rate if, for example, other consumption disaster risks as in Barro (2009) and Wachter (2013) were added to it. This would increase the disaster risk premium and lower the risk-free rate due to precautionary savings, such that aggregate moments could be matched. As we are primarily interested in the consequences of belief disagreement for the pricing of green and of brown assets, we abstract from this level of complexity here.

Table 3: Annual asset-pricing moments from simulating 1,000 sample paths each containing 11 years of data. We set $T_{start} = 0.6$°C and $w^G_{start} = 0.5$. The top panel shows results when shocks to temperature, ζ_{t+1}, are drawn from a standard normal distribution. In the bottom panel we assume that, additional to the normal shocks, there is an unexpected increase in temperature of +0.1°C per period. Standard deviations of the time series moments across the sample paths are shown in parentheses.

	Δc_{t+1}	Δd^M_{t+1}	$\log(R^f_t)$	$R^M_t - R^f_t$
Normal Shocks to T_{t+1}				
mean	0.0205 (0.0055)	0.0213 (0.0142)	0.0345 (1.1946e-04)	0.0081 (0.0155)
σ	0.0188 (0.0040)	0.0488 (0.0103)	0.0001 (6.8924e-05)	0.0486 (0.0109)
Unexpectedly large climate news shocks				
mean	0.0205 (0.0055)	0.0213 (0.0142)	0.0338 (4.7979e-04)	0.0025 (0.0157)
σ	0.0188 (0.0040)	0.0488 (0.0103)	0.0008 (6.2944e-04)	0.0492 (0.0111)

4.5 Welfare Cost of Carbon

In our asset-pricing model, we measure the impact of climate risks on equity valuations and the wealth of the investors. In line with Bansal et al. (2021), we refer to our measure in the following as the welfare cost of carbon (WCC). We interpret the WCC as a marginal concept—the monetary loss that is caused by an additional metric ton of carbon emissions. It is important to note that carbon emissions only affect the WCC to the extent that they are already reflected in equity valuations. In contrast, the social cost of carbon (SCC) measures

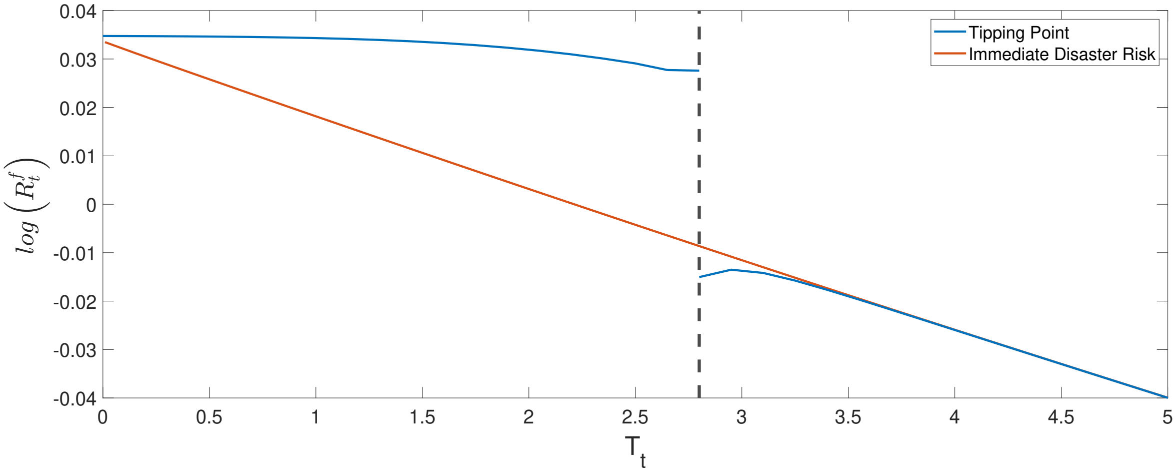


Figure 11: The risk-free rate as a function of temperature, T_t, for $w_t^G = 0.5$. Results are shown for the case with immediate disaster risk and for the case with the distant tipping threshold. The vertical dashed line marks the tipping threshold.

the full extent of emissions' negative externality [14].

Thus, if (a part of) emissions impose(s) a negative externality and are (is) not correctly priced yet, the SCC would exceed the WCC. The WCC sets a lower bound to the "true" SCC in this scenario. This concept of measuring the impact of temperature increases on future wealth is also related to the "welfare cost of consumption uncertainty," introduced by Barro (2009), who shows that society would be willing to reduce GDP by around 20 percent yearly to eliminate the possibility of rare disasters. This is around 15 times as much as the welfare cost of usual economic fluctuations. So as long as $\psi > 1$, we would expect to see a sizeable WCC since agents want to reduce the risk of future consumption disasters.

In our model we do not explicitly include carbon emissions, but instead directly model the dynamics of global temperature, which is affected by increases in emissions. We use the estimate of Bansal et al. (2021) for the sensitivity of global temperature to changes in emissions to quantitatively analyze the WCC implied by our model. We express that cost in terms of a numeraire good, in our case current consumption. Hence, the WCC is defined as the ratio of two marginal values:

$$WCC_t = -\frac{\frac{\partial V_t}{\partial E_t}}{\frac{\partial V_t}{\partial C_t}}. \tag{15}$$

For Epstein–Zin preferences, the value function is a function of the aggregate wealth–consumption

[14] The SCC is an attempt to put a monetary value on the negative consequences of climate change, now and in the future. There is a wide range of different estimates for the SCC in the literature. These differences result mainly from different assumptions of parameter values regarding, for example, preferences, discounting, damage, climate response to emissions, and uncertainties in general.

ratio $Z_t \equiv \frac{W_t}{C_t}$.

$$\frac{V_t}{C_t} = [(1-\delta)Z_t]^{\frac{\psi}{\psi-1}},$$

so that the WCC can be written as

$$WCC_t = \frac{\psi}{\psi-1}\frac{-\partial log Z_t}{\partial T_t}\frac{\partial T_t}{\partial E_t}C_t. \tag{16}$$

In Appendix B we provide the derivations of equation (16). Note that WCC_t measures aggregate welfare effects—that is, how changes in climate risks affect aggregate wealth in the economy. As Bansal et al. (2021), we use a semi-parametric approach to calculate WCC_t. The sensitivity of the log wealth–consumption ratio, $\frac{\partial log Z_t}{\partial T_t}$, follows from our climate economy and depends on both the temperature level and the wealth share of the green and the brown investors at time t. In line with Bansal et al. (2021), we set the temperature sensitivity to cumulative carbon emissions to $\frac{\partial T_t}{\partial E_t} = 1.71°C$ per trillion tonnes of carbon. They obtain the value by matching the mean value of carbon sensitivity to emissions estimated in MacDougall et al. (2017).[15] For C_t we use the purchasing power parity adjusted world gross domestic product, which was about 146.71 trillion international dollars in 2021[16].

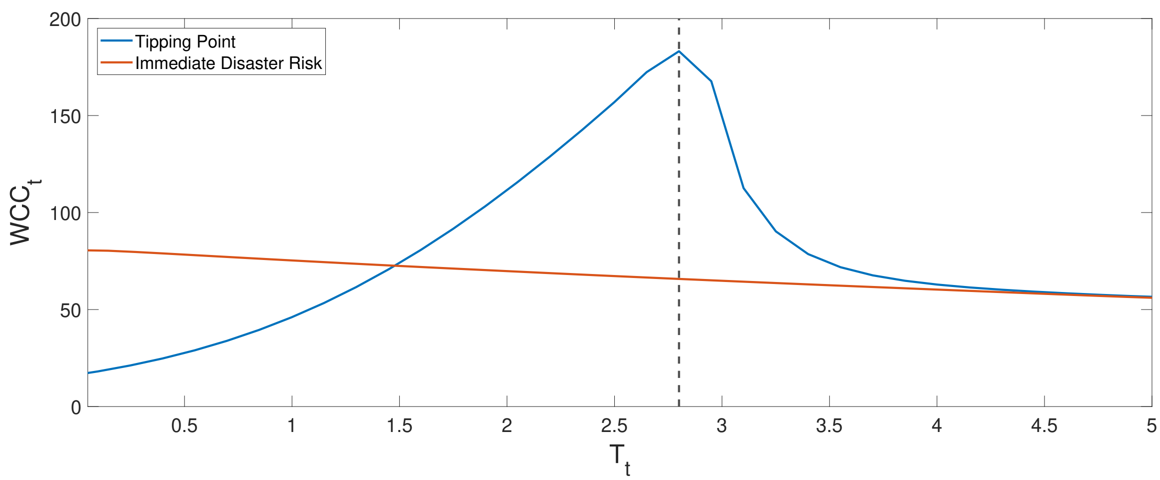


Figure 12: The welfare cost of carbon as a function of T_t for $w_t^G = 0.5$. Results are shown for the case with immediate disaster risk and for the case with the distant tipping threshold. The vertical dashed line marks the tipping threshold.

Figure 12 shows the WCC as a function of global temperature for the benchmark case with a distant tipping point as well as for the case with immediate climate disaster risks. First,

[15] They base their results on the carbon–climate response; see Matthews et al. (2009) for the scientific background to these estimations.

[16] This value is provided by the World Bank, using the current international dollar value (https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.CD).

consider the case with immediate disaster risks. The WCC is slightly decreasing in T_t as the marginal decline in utility due to an increase in T_t is decreasing in temperature. Note that Bansal et al. (2021) report a constant WCC, which, however, only arises as they use a linear approximation to solve the model. Once the model is solved accurately using global methods as proposed by Pohl et al. (2018), the wealth–consumption ratio is a convex function of T_t; see Figure 13. Hence, immediate climate disaster risks imply that the WCC is high as of today, but should decrease in the future if global temperature keeps increasing.

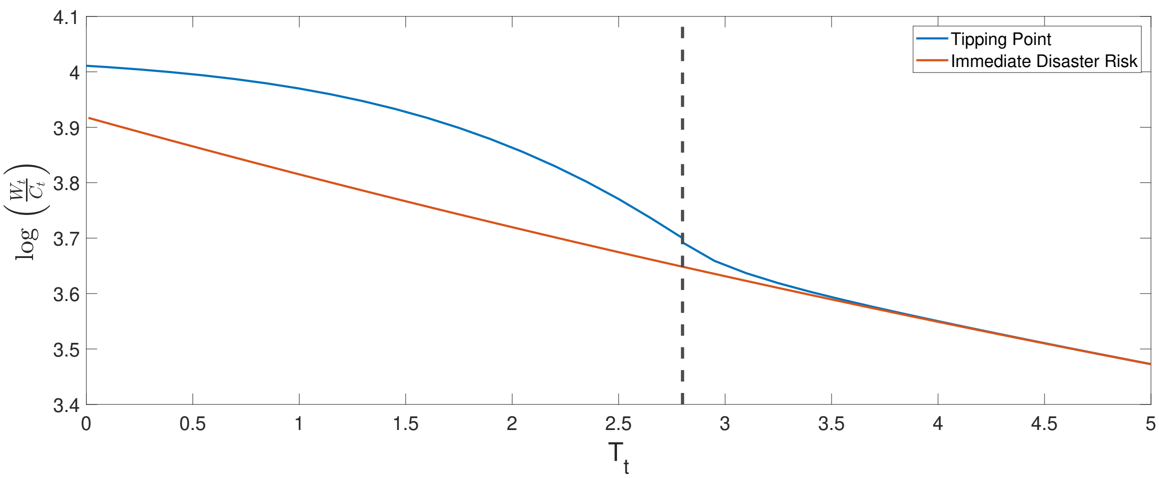


Figure 13: The aggregate log wealth–consumption ratio as a function of T_t for $w_t^G = 0.5$. Results are shown for the case with immediate disaster risk and for the case with the distant tipping threshold. The vertical dashed line marks the tipping threshold.

In contrast, our benchmark model—accounting for the fact that climate disasters can only occur once the tipping point is crossed—implies a low WCC for low temperature levels, as observed until now. The marginal decline in utility due to an increase in temperature is small as long as the tipping point is sufficiently far away. However, once temperature approaches the tipping point, the WCC increases significantly and can almost triple compared to the case with immediate climate disaster risks. Close to the tipping point, a reduction in temperature leads to a large utility gain for the investors as it significantly decreases the probability of crossing the tipping point. So the wealth–consumption ratio is strongly decreasing in T_t close to the tipping point—see Figure 13—such that the WCC is high.

Thus, our model provides a potential explanation of why investments to reduce climate risks have been low in the past: as the tipping point was sufficiently far away, the welfare gains from such investments were small. However, with increasing temperatures, as predicted by climate scientists for the coming years, the WCC is likely to increase significantly. Put differently, the marginal gain from investments to slow down climate change should increase in the future.

Figure 14 plots the WCC as a function of the market share of the green investor for the current temperature level of $T_t = 1°C$ as well as for a global temperature of $T_t = 2°C$. It shows that the WCC strongly increases with the market share of green investors. Green investors believe in a larger impact of temperature increases on the probability of a climate-induced disaster. Hence, their utility increases more strongly in response to a reduction in temperature compared to that of brown investors. This effect is particularly strong once global temperature approaches the tipping point. For $T_t = 2°C$, the WCC is significantly larger for the model with the distant tipping point compared to the immediate disaster risk model and, in particular, the difference increases with the wealth share of the green investor. Hence, the welfare gains from policies to slow down climate change are going to increase if the market share of green investors keeps on increasing in the future.

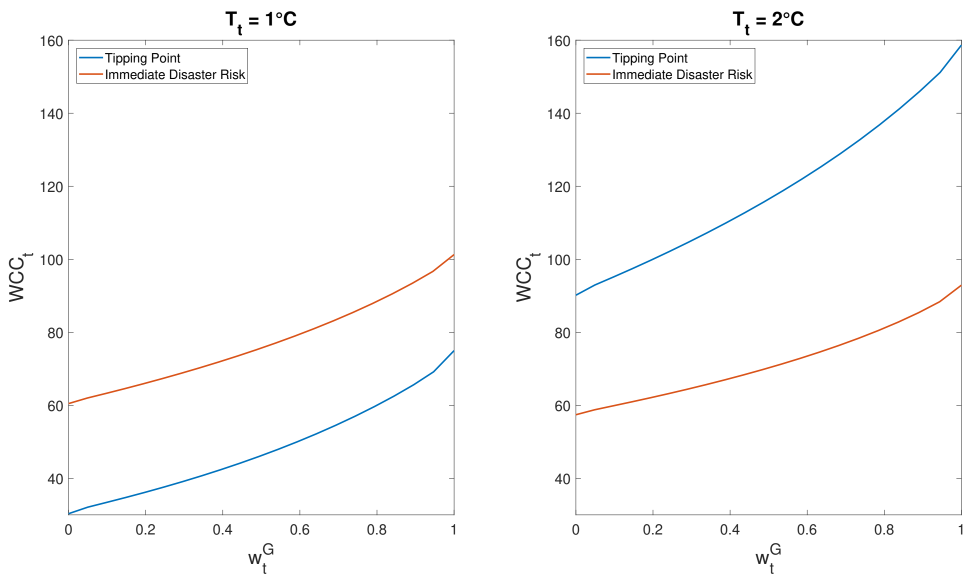


Figure 14: The welfare cost of carbon as a function of the wealth share, w_t^G, of the green investor for different levels of temperature, T_t. Results are shown for the case with immediate disaster risk and for the case with the distant tipping threshold.

4.6 Robustness

In this section we conduct several robustness checks to show that the qualitative conclusions we draw based on our benchmark calibration do not depend on the specific choice of parameters. We consider the following cases: lowering the tipping threshold, changing the degree of disagreement, changing the climate exposure of green and of brown stocks, and changing the risk aversion of the investors. Figures 15 and 16 plot the carbon premium and the WCC as a function of temperature for these different cases. First, consider the case with a lower tipping threshold. A report from the OECD (2022) shows that important tipping points may become “likely” already within the Paris Agreement range of 1.5°C to 2°C of global warming. The possibility that tipping points could already be crossed under moderate levels of global warming adds further urgency to the climate challenge. Hence, we also discuss results for a tipping point of $T_{tipp} = 2.0$°C instead of $T_{tipp} = 2.8$°C as in the benchmark model. All other parameters are kept at the level of the baseline calibration provided in Table 1. The carbon premium plotted in Figure 15 is qualitatively similar to the case with the distant tipping point of 2.8°C with the exception that for low temperature levels it is slightly larger. This larger premium arises as the tipping point is not as far away, so investors demand a higher risk premium for holding more carbon-exposed (brown) stocks. For the WCC plotted in Figure 16 we also find that it is slightly higher for lower temperature levels, as climate disaster risks are a more imminent threat. Otherwise, the results are qualitatively similar to those for the benchmark model.

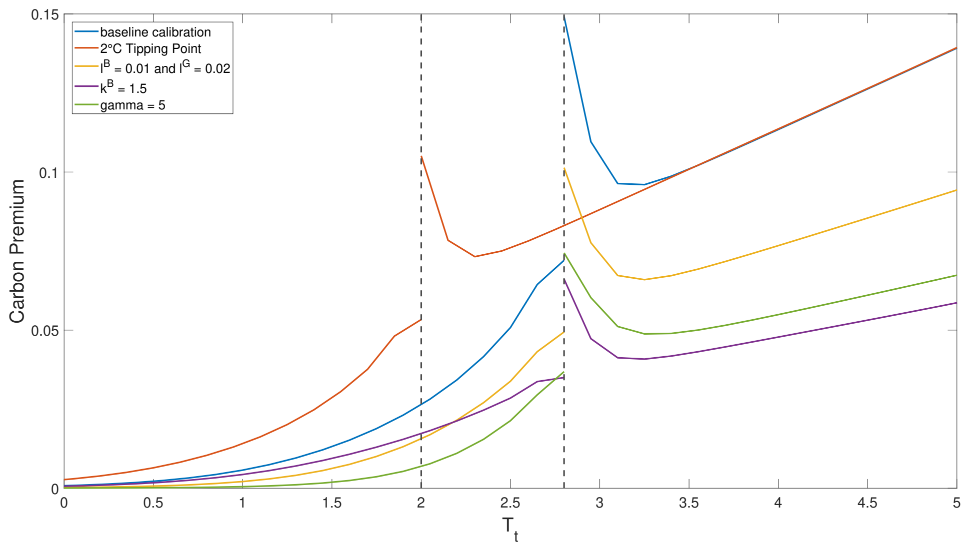


Figure 15: The expected return of the brown stock minus the expected return of the green stock for the beliefs of the brown investor as a function of temperature, T_t, for $w_t^G = 0.5$. The blue line depicts the case of our benchmark model with parameters provided in Table 1. The red line assumes a lower tipping threshold of $T_{tipp} = 2.0°$ C. The yellow line assumes more moderate beliefs about climate change, with $l^B = 0.01$ and $l^G = 0.02$. The purple line depicts the case with less climate exposure of the brown stock, with $k^B = 1.5$, and the green line shows results for a lower risk aversion of $\gamma = 5$.

The other three cases we consider either change the amount of risk by decreasing the parameters that determine the disaster probabilities (l^B from 0.015 to 0.01 and l^G from 0.03 to 0.02) or by decreasing the climate exposure of the brown stock, k^B, from 3 to 1.5, or change the price of risk by decreasing risk aversion, γ, from 8 to 5. All three cases have similar effects

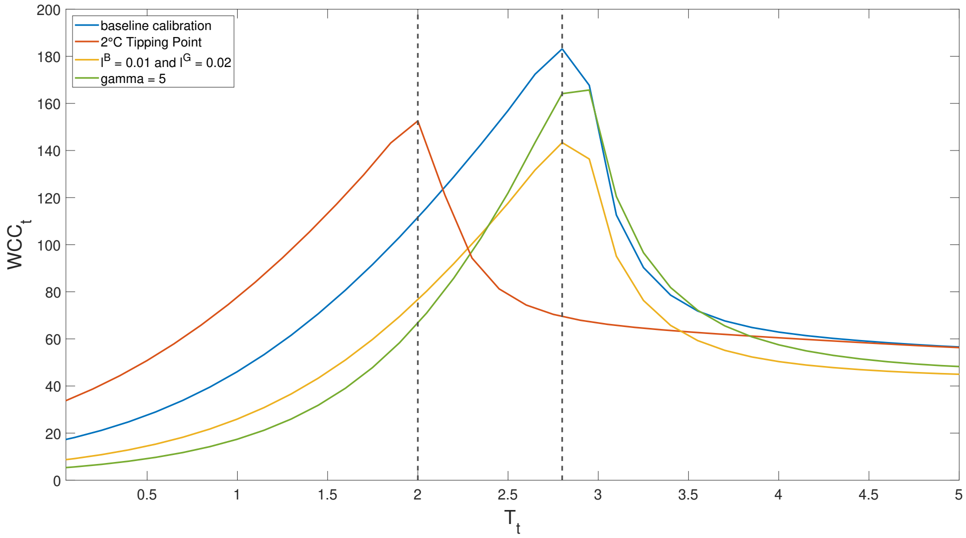


Figure 16: The welfare cost of carbon as a function of temperature, T_t, for $w_t^G = 0.5$. The blue line depicts the case of our benchmark model with parameters provided in Table 1. The red line assumes a lower tipping threshold of $T_{tipp} = 2.0$°C. The yellow line shows the welfare cost of carbon for more moderate beliefs about climate change, with $l^B = 0.01$ and $l^G = 0.02$, and the green line shows results for a lower risk aversion of $\gamma = 5$.

on the carbon premium, leading to a lower premium relative to the benchmark case. However, qualitatively our findings do not change, which also holds for the WCC shown in Figure 16.[17]

We also analyze the impact of different disaster sizes on our results. There is not only uncertainty about disaster probabilities after crossing the tipping threshold, but the impact itself of disasters is also unknown. In Figure 21 in the Appendix, we show how the carbon premium changes when we assume a lower or higher disaster size. Our qualitative results still hold in each of these cases.

[17]Note that changing k^B does not affect the WCC, which is why we do not consider this case in Figure 16.

5 Conclusion

We present an asset-pricing model for the analysis of climate financial risks. The persistent global average temperature anomaly is a natural source of long-run risk in financial markets. In our model, as long as the global temperature is below the temperature threshold of a tipping point, climate-induced disaster cannot occur. Once the global temperature crosses that threshold, disasters become increasingly likely. The economy is populated by two types of investor with divergent beliefs about climate change. Green investors believe that the disaster probability rises considerably faster than brown investors do. Both groups of investors have identical Epstein–Zin preferences with a preference for the early resolution of risk.

The model simultaneously explains several empirical findings that have recently been documented in the literature. First, not only is climate risk itself priced, but the risk of receiving bad news about the future climate is also priced. Brown investors implicitly sell insurance against this climate news risk to green investors. Second, bad news about the climate increases the market share of green investors, because they benefit from buying insurance against such news shocks. Third, brown stocks carry a carbon premium relative to green stocks due to their greater exposure to climate risks. Fourth, if the temperature threshold to trigger disaster events is sufficiently far away from the current temperature anomaly, then the corresponding carbon premium is only small. The news-channel effect dominates the carbon-premium effect and the model thus shows an outperformance of green over brown stocks in response to bad climate news.

The model provides predictions for the future evolution of asset prices. As per our model, there exists a positive carbon premium, which means that the expected return of brown stocks is higher than that of green stocks. For this reason, according to our model past performance is not a good predictor of future performance. While realized returns of green stocks have gone up in response to negative climate news, expected returns have gone down simultaneously. In the absence of further exogenous shocks and climate-induced disasters, our model predicts higher future returns for brown stocks. However, if temperatures continue to rise and approach the tipping point threshold, the potential benefits of investments to slow down climate change increase significantly. In this scenario, our model predicts a significant increase in the market share of green investors and the carbon premium.

References

Acharya, V. V., T. Johnson, S. Sundaresan, and T. Tomunen (2022): "Is physical climate risk priced? Evidence from regional variation in exposure to heat stress," Tech. rep., National Bureau of Economic Research.

Ardia, D., K. Bluteau, K. Boudt, and K. Inghelbrecht (2023): "Climate change concerns and the performance of green versus brown stocks," *Management Science*, forthcoming.

Armstrong McKay, D. I., A. Staal, J. F. Abrams, R. Winkelmann, B. Sakschewski, S. Loriani, I. Fetzer, S. E. Cornell, J. Rockström, and T. M. Lenton (2022): "Exceeding 1.5 C global warming could trigger multiple climate tipping points," *Science*, 377, eabn7950.

Aswani, J., A. Raghunandan, and S. Rajgopal (2022): "Are carbon emissions associated with stock returns?" Research paper, Columbia Business School.

Baldauf, M., L. Garlappi, and C. Yannelis (2020): "Does Climate Change Affect Real Estate Prices? Only If You Believe In It," *The Review of Financial Studies*, 33, 1256–1295.

Bansal, R., D. Kiku, and M. Ochoa (2016): "Price of long-run temperature shifts in capital markets," Tech. rep., National Bureau of Economic Research.

——— (2021): "Climate Change Risk," Tech. rep., National Bureau of Economic Research.

Bansal, R., D. Kiku, and A. Yaron (2012): "An Empirical Evaluation of the Long-Run Risks Model for Asset Prices," *Critical Finance Review*, 1, 183–221.

Bansal, R. and A. Yaron (2004): "Risks for the long run: A potential resolution of asset pricing puzzles," *The journal of Finance*, 59, 1481–1509.

Barro, R. J. (2006): "Rare Disasters and Asset Markets in the Twentieth Century," *Quarterly Journal of Economics*, 121, 823–866.

——— (2009): "Rare disasters, asset prices, and welfare costs," *American Economic Review*, 99, 243–64.

Bauer, M. D., D. Huber, G. D. Rudebusch, and O. Wilms (2022): "Where is the carbon premium? Global performance of green and brown stocks," *Journal of Climate Finance*, 1, 100006.

Bernstein, A., S. B. Billings, M. T. Gustafson, and R. Lewis (2022): "Partisan residential sorting on climate change risk," *Journal of Financial Economics*.

Bolton, P. and M. Kacperczyk (2021): "Do investors care about carbon risk?" *Journal of financial economics*, 142, 517–549.

——— (2022): "Global Pricing of Carbon-Transition Risk," *Journal of Finance, Forthcoming.*

Borovička, J. (2020): "Survival and long-run dynamics with heterogeneous beliefs under recursive preferences," *Journal of Political Economy*, 128, 206–251.

Branger, N., P. Konermann, and C. Schlag (2020): "Optimists and Pessimists in (In)Complete Markets," *Journal of Financial and Quantitative Analysis*, 55, 2466–2499.

Cai, Y. (2021): "The Role of Uncertainty in Controlling Climate Change," in *Oxford Research Encyclopedia of Economics and Finance*, Oxford University Press.

Cai, Y., K. L. Judd, and T. S. Lontzek (2017): "The Social Cost of Carbon with Economic and Climate Risks," Working Paper 18113, Hoover Institution, Stanford, CA.

Cai, Y., T. M. Lenton, and T. S. Lontzek (2016): "Risk of multiple interacting tipping points should encourage rapid CO2 emission reduction," *Nature Climate Change*, 520–525.

Cai, Y. and T. S. Lontzek (2019): "The social cost of carbon with economic and climate risks," *Journal of Political Economy*, 127, 2684–2734.

Chen, H., S. Joslin, and N.-K. Tran (2012): "Rare disasters and risk sharing with heterogeneous beliefs," *The Review of Financial Studies*, 25, 2189–2224.

Choi, D., Z. Gao, and W. Jiang (2020): "Attention to Global Warming," *The Review of Financial Studies*, 33, 1112–1145.

Daniel, K. D., R. B. Litterman, and G. Wagner (2016): "Applying asset pricing theory to calibrate the price of climate risk," Tech. rep., National Bureau of Economic Research.

Engle, R. F., S. Giglio, B. Kelly, H. Lee, and J. Stroebel (2020): "Hedging Climate Change News," *The Review of Financial Studies*, 33, 1184–1216.

Epstein, L. and S. E. Zin (1989): "Substitution, risk aversion, and the temporal behavior of consumption and asset returns: A theoretical framework," *Econometrica*, 57, 937–969.

Gabaix, X. (2012): " Variable Rare Disasters: An Exactly Solved Framework for Ten Puzzles in Macro-Finance *," *The Quarterly Journal of Economics*, 127, 645–700.

Gibson Brandon, R., S. Glossner, P. Krueger, P. Matos, and T. Steffen (2022): "Do responsible investors invest responsibly?" *Review of Finance*, 26, 1389–1432.

Giglio, S., B. Kelly, and J. Stroebel (2021a): "Climate Finance," *Annual Review of Financial Economics*, 13, 15–36.

Giglio, S., M. Maggiori, K. Rao, J. Stroebel, and A. Weber (2021b): "Climate change and long-run discount rates: Evidence from real estate," *The Review of Financial Studies*, 34, 3527–3571.

Global Sustainable Investment Alliance (2020): "Global Sustainable Investment Review," http://www.gsi-alliance.org/wp-content/uploads/2021/08/GSIR-20201.pdf.

Hsu, P.-H., K. Li, and C.-Y. Tsou (2023): "The Pollution Premium," *Journal of Finance*, forthcoming.

Huij, J., D. Laurs, P. A. Stork, and R. C. Zwinkels (2021): "Carbon Beta: A Market-Based Measure of Climate Risk," *Available at SSRN*.

Hulme, M. (2009): *Why We Disagree about Climate Change: Understanding Controversy, Inaction and Opportunity*, Cambridge University Press.

IPCC (2014): "Impacts, adaptation and vulnerability," *Part A: global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental Panel on Climate Change*, 1132.

Kriegler, E., J. W. Hall, H. Held, R. Dawson, and H. J. Schellnhuber (2009): "Imprecise probability assessment of tipping points in the climate system," *Proceedings of the national Academy of Sciences*, 106, 5041–5046.

Lemoine, D. and C. Traeger (2014): "Watch your step: optimal policy in a tipping climate," *American Economic Journal: Economic Policy*, 6, 137–166.

Lenton, T. M., H. Held, E. Kriegler, J. W. Hall, W. Lucht, S. Rahmstorf, and H. J. Schellnhuber (2008): "Tipping Elements in the Earth's Climate System," *Proceedings of the National Academy of Sciences*, 105, 1786–1793.

Lontzek, T. S., Y. Cai, K. L. Judd, and T. M. Lenton (2015): "Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy," *Nature Climate Change*, 441–444.

MacDougall, A. H., N. C. Swart, and R. Knutti (2017): "The uncertainty in the transient climate response to cumulative CO2 emissions arising from the uncertainty in physical climate parameters," *Journal of Climate*, 30, 813–827.

Matthews, H. D., N. P. Gillett, P. A. Stott, and K. Zickfeld (2009): "The proportionality of global warming to cumulative carbon emissions," *Nature*, 459, 829.

Nauels, A., M. Meinshausen, M. Mengel, K. Lorbacher, and T. M. L. Wigley (2017): "Synthesizing long-term sea level rise projections – the MAGICC sea level model v2.0," *Geoscientific Model Development*, 10, 2495–2524.

OECD (2022): *Climate Tipping Points*, OECD.

Pástor, L., R. F. Stambaugh, and L. A. Taylor (2021): "Sustainable investing in equilibrium," *Journal of Financial Economics*, 142, 550–571.

——— (2022): "Dissecting green returns," *Journal of Financial Economics*, 146, 403–424.

Pohl, W., K. Schmedders, and O. Wilms (2018): "Higher Order Effects in Asset Pricing Models with Long-Run Risks," *The Journal of Finance*, 73, 1061–1111.

——— (2021): "Asset pricing with heterogeneous agents and long-run risk," *Journal of Financial Economics*, 140, 941–964.

——— (2023): "Existence Conditions for Asset Pricing Models with Recursive Utility," Working paper.

Principles of Responsible Investment (2021): "Annual Report of the UN Principles of Responsible Investment," `https://www.unpri.org/annual-report-2021`.

Saad, L. (2017): "Global warming concern at three-decade high in US," *Gallup poll social series*.

UNFCCC (2015): "Paris agreement," in *Report of the Conference of the Parties to the United Nations Framework Convention on Climate Change (21st Session, 2015: Paris). Retrieved December*, HeinOnline, vol. 4, 2017.

van der Beck, P. (2022): "Flow-Driven ESG Returns," Working paper.

van der Ploeg, F. and A. de Zeeuw (2018): "Climate tipping and economic growth: Precautionary capital and the price of carbon," *Journal of the European Economic Association*, 16, 1577–1617.

Wachter, J. A. (2013): "Can Time-Varying Risk of Rare Disasters Explain Aggregate Stock Market Volatility?" *Journal of Finance*, 68, 987–1035.

Weil, P. (1989): "The equity premium puzzle and the risk-free rate puzzle," *Journal of monetary economics*, 24, 401–421.

Zickfeld, K., A. Levermann, M. G. Morgan, T. Kuhlbrodt, S. Rahmstorf, and D. W. Keith (2007): "Expert judgements on the response of the Atlantic meridional overturning circulation to climate change," *Climatic Change*, 82, 235–265.

A Appendix

A.1 Additional Figures and Tables

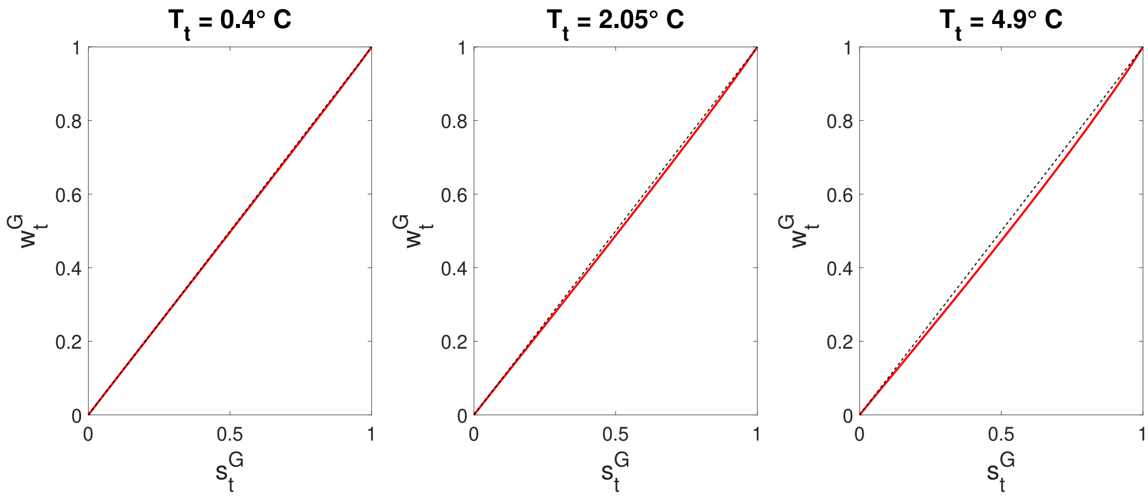


Figure 17: The wealth share, w_t^G, of the green investor as a function of her consumption share, s_t^G, for different temperature states. The dashed lines mark the 45 degree line. Model parameters are calibrated using values reported in Table 1.

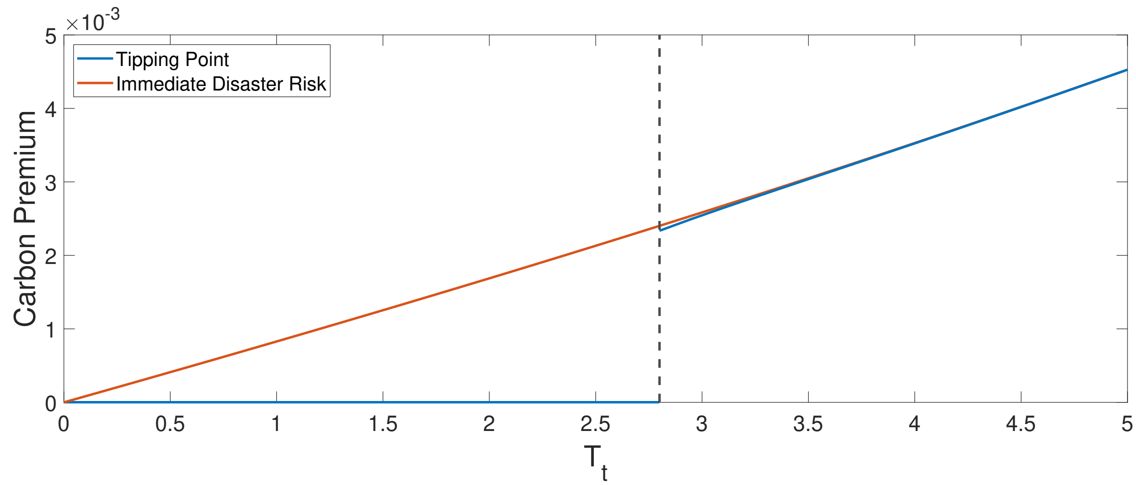


Figure 18: The expected return of the brown stock minus the expected return of the green stock as a function of temperature, T_t, for $w_t^G = 0.5$ for CRRA preferences with $\gamma = 1/\psi = 2$. Results are shown for the case with immediate disaster risk and for the case with the distant tipping threshold for the beliefs of the green investor. The vertical dashed line marks the tipping threshold.

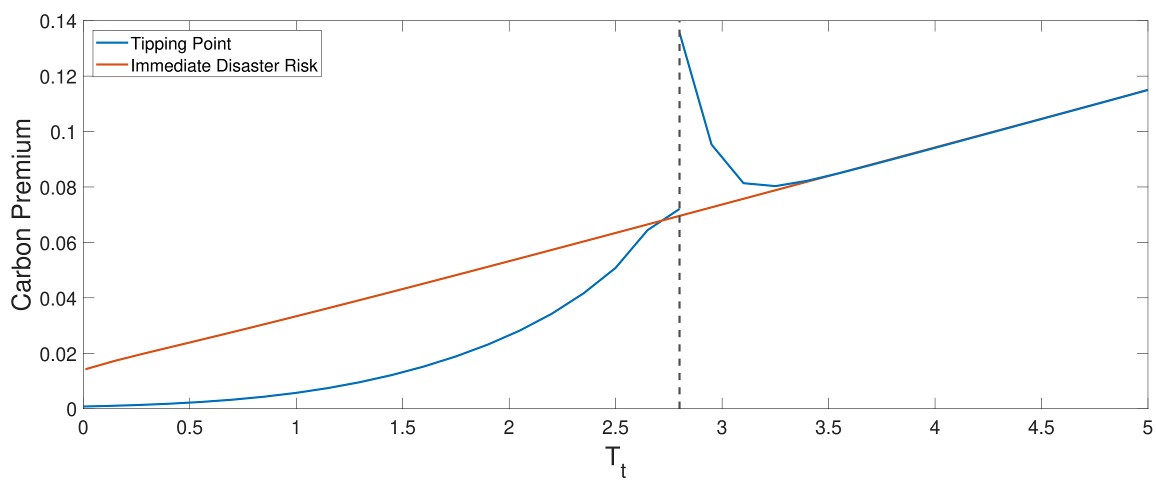


Figure 19: The expected return of the brown stock minus the expected return of the green stock as a function of temperature, T_t, for $w_t^G = 0.5$ for Epstein–Zin preferences with $\gamma = 8$ and $\psi = 1.5$. Results are shown for the case with immediate disaster risk and for the case with the distant tipping threshold for the beliefs of the green investor. The vertical dashed line marks the tipping threshold.

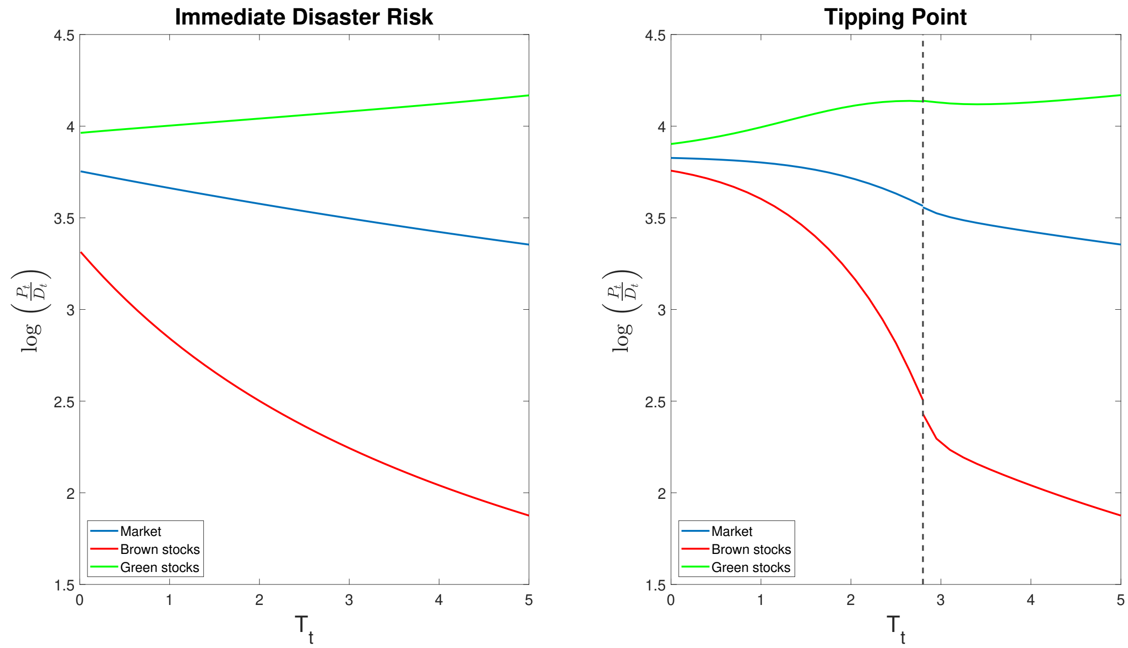


Figure 20: The log price–dividend ratios for the green and the brown stock and for the market portfolio as a function of temperature, T_t, for $w_t^G = 0.5$. Results are shown for the case with immediate disaster risk and for the case with the distant tipping threshold. The vertical dashed line in the right panel marks the tipping threshold.

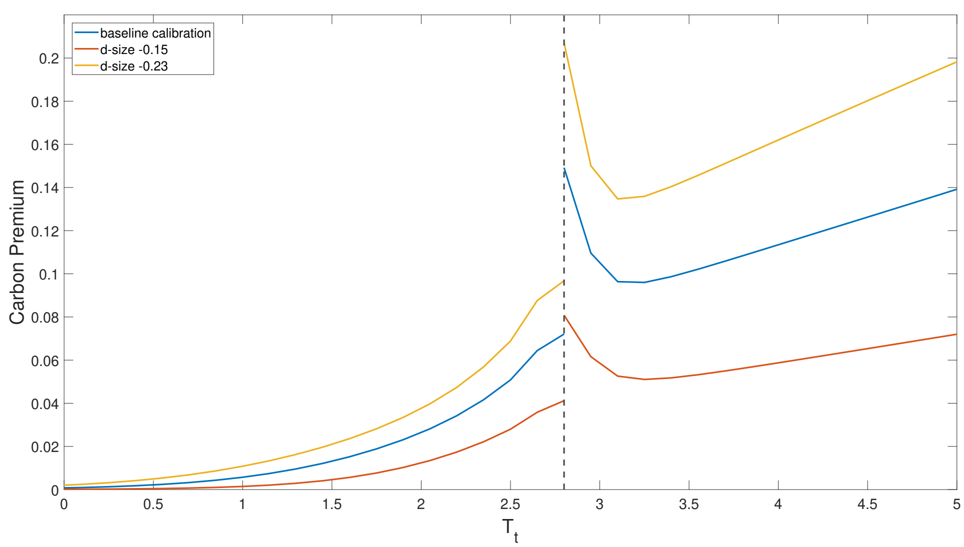


Figure 21: The expected return of the brown stock minus the expected return of the green stock for the beliefs of the brown investor as a function of temperature, T_t, for $w_t^G = 0.5$. The blue line depicts the case of our benchmark model with parameters provided in Table 1, especially $d = -0.2$. The red line assumes a lower disaster impact of $d = -0.15$. The yellow line assumes a higher disaster impact of $d = -0.23$. The vertical dashed line marks the tipping threshold.

B Derivations of the Welfare Cost of Carbon

The welfare cost of carbon (WCC) is defined as the ratio of two marginal values:

$$WCC_t = -\frac{\frac{\partial V_t}{\partial E_t}}{\frac{\partial V_t}{\partial C_t}}. \tag{17}$$

For Epstein–Zin preferences, the value function is a function of the aggregate wealth–consumption ratio, $Z_t \equiv \frac{W_t}{C_t}$:

$$\frac{V_t}{C_t} = [(1-\delta)Z_t]^{\frac{\psi}{\psi-1}},$$

where $Z_t \equiv \frac{W_t}{C_t}$. Using this relationship, the two derivatives in equation (17) yield

$$\begin{aligned} \frac{\partial V_t}{\partial E_t} &= \frac{\partial V_t}{\partial Z_t}\frac{\partial Z_t}{\partial E_t} = \frac{\psi}{\psi-1}(1-\delta)^{\frac{\psi}{\psi-1}} Z_t^{\frac{\frac{1}{\psi}}{1-\frac{1}{\psi}}} \frac{\partial Z_t}{\partial E_t}, \\ \frac{\partial V_t}{\partial C_t} &= [(1-\delta)Z_t]^{\frac{\psi}{\psi-1}}. \end{aligned}$$

Hence, the WCC depends on the elasticity of Z_t to emissions:

$$WCC_t = \frac{\psi}{\psi-1}\frac{-\partial Z_t}{\partial E_t}\frac{C_t}{Z_t}. \tag{18}$$

As $\frac{\partial log Z_t}{\partial E_t} = \frac{1}{Z_t}\frac{\partial Z_t}{\partial E_t}$, this is equivalent to

$$WCC_t = \frac{\psi}{\psi-1}\frac{-\partial log Z_t}{\partial E_t}C_t. \tag{19}$$

Dividing and multiplying by ∂T_t yields equation (16).