Climate Finance*

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Abstract

We review the literature studying interactions between climate change and financial markets. We first discuss various approaches to incorporating climate risk in macro-finance models. We then review the empirical literature that explores the pricing of climate risks across a large number of asset classes including real estate, equities, and fixed income securities. In this context, we also discuss how investors can use these assets to construct portfolios that hedge against climate risk. We conclude by proposing several promising directions for future research in climate finance.

Keywords: Climate Change, Climate Risk, Physical Risk, Transition Risk, ESG

1 INTRODUCTION

Climate change is one of the defining challenges of our time, with the potential to impact the health and well-being of nearly every person on the planet. In addition, climate change poses a large aggregate risk to the economy and the financial system

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(see, e.g., Litterman et al., 2020). The tools of financial economics, designed for valuing and managing risky future outcomes, can therefore help society assess and respond to climate change risk.

Starting with the seminal work of Nobel Laureate William Nordhaus in the 1970s, researchers have studied the interactions between climate change and the economy. Fossil fuels are a critical input to production, so economic growth increases greenhouse gas emissions. Those emissions induce climate change, and climate change has a potentially large negative feedback effect on future economic activity. However, many important aspects of climate change economics that are financial in nature — such as the pricing and hedging of risks stemming from climate change, the awareness and attitudes of investors towards these risks, and the effects of climate risks on investment decisions — have received less attention in the literature. Indeed, it is only recently that researchers in financial economics have begun to explore these questions. This burst of research activity constitutes a new and quickly growing field that we refer to as "Climate Finance." In this review article, we summarize some of its theoretical and empirical contributions. We are optimistic that this body of work will grow in size and influence, and that climate finance will contribute to efforts across the physical and social sciences to address the challenges of climate change.

Why study climate change through the lens of financial economics? First, risk and risk preferences play an important role in dictating the optimal policy response to climate change. Second, financial markets are a primary vehicle for mitigating and hedging climate risk. They *mitigate* climate risk by facilitating the flow of investment capital toward "green" projects, and away from "brown" industries and firms, as we transition to an environmentally sustainable economy. Examples of the climate risk-mitigating role played by financial markets include financial innovation in "green bonds" and a ramp up in "climate-aware" mutual funds. Financial markets also provide a venue for *hedging* climate risk. Indeed, one of the most fundamental functions of financial markets is the sharing and transferring of risks. While climate risk is an aggregate risk, the heterogeneity in exposure to climate change across different firms and regions provides valuable risk-sharing opportunities. Likewise, heterogeneity in adaptability and risk tolerance makes some investors better suited to bear this risk than others.

Our review of the current literature is organized into two parts. In the first section, we discuss efforts to incorporate climate risk into macro-finance models. The pioneering work of Nordhaus (1977) paved the way for thinking about the interaction of the physical process of climate change with the real economy. Early papers in this literature — such as Nordhaus (1977, 1991, 1992) — focused on optimal climate change mitigation, and worked in deterministic settings. As such, these papers did not directly speak to the ways in which climate change affects asset prices and risk premia. Subsequent work extends these models to incorporate different aspects of risk and uncertainty about climate change and its link to the economy. These attributes include the stochastic nature of physical and economic processes as well as uncertainty about models of these processes (see, for example, the work by Kolstad, 1992, Manne et al., 1992, Nordhaus, 1994, Kelly & Kolstad, 1999, Nordhaus & Popp, 1997, Weitzman, 2001, 2009, Lemoine & Traeger, 2012, Golosov et al., 2014). Much of this literature has focused on the way risks and uncertainties affect optimal mitigation policies and the "social cost of carbon." More recently, the financial economics literature has explored the implications of these models for the prices and returns of financial assets.

In the second part of this review article, we discuss the empirical literature that explores the pricing of climate risk across a large number of asset classes. This literature considers the price effects of at least two broad categories of climate related risk factors: physical climate risk and transition risk. Physical climate risk includes risks of the direct impairment of productive assets resulting from climate change; transition risk includes risks to cash flows arising from a possible transition to a low-carbon economy. A central element of the research designs in these papers is that assets are differentially exposed to these climate risk factors: for example, houses located near the sea are more exposed to physical climate risks, while coal companies are more exposed to transition risks. Many papers then combine the differential exposure of assets within an asset class with time-varying attention paid to climate risk in order to understand how this type of risk is priced in asset markets. We review research that documents climate-related asset price effects in equity markets, bond markets, housing markets, and mortgage markets. We also discuss recent work that shows how one can use financial assets to construct portfolios that hedge climate change risks.

2 CLIMATE RISK AND ASSET PRICES: THEORY

To introduce climate change risk into an economic model, the researcher must take a stand on the main sources of uncertainty associated with the processes of climate change and the economy. Possible sources include: uncertainty about the future path of economic activity; uncertainty about the future evolution of the climate; and uncertainty about the various components of the model itself (e.g., the model parameters that capture the interaction between the climate and the real economy).

Each source of uncertainty has a different effect on equilibrium prices and risk premia.

To organize the discussion, we begin by providing a stylized framework that helps highlight the distinction between the effects of uncertainty about the future path of economic activity and uncertainty about the evolution of the climate process. As we show, this distinction has radically different implications for asset prices and risk premia. The model we present here is a simplified version of the one introduced in Giglio et al. (2020). Like all integrated models of climate change and the economy, our model specifies both the dynamics of the economy and the physical climate processes. In the interest of parsimony, both processes are highly stylized versions of those considered in the physical sciences. Given our interest in asset prices, we also specify the preferences of investors. We assume a representative-agent Lucas-tree economy and directly specify the dynamics of equilibrium consumption growth as well as the dynamics of climate change:

$$\Delta c_{t+1} = \mu + x_t + J_{t+1}, \tag{1}$$

$$x_{t+1} = \mu_x + \rho x_t + \phi J_{t+1}, \tag{2}$$

$$\lambda_{t+1} = \mu_\lambda + \alpha \lambda_t + \nu x_t + \chi J_{t+1}. \tag{3}$$

Equations 1 and 2 describe the evolution of aggregate consumption growth, Δc_t. J_t is the only shock in this economy; we discuss a number of interpretations of it in greater detail below. J_t directly affects consumption growth, but it also potentially affects the other variables in the system. x_t represents time-varying expected consumption growth, whose persistence is ρ and whose innovations are also driven by J_t. The parameter ϕ captures the way the shock J_t affects the future path of consumption growth, and therefore plays an important role in capturing the dynamics of consumption and, ultimately, the term structure of risk and risk premia. The last equation represents the dynamics in the conditional distribution of J_t. In any given period, J_{t+1} could take one of two values: $-\xi \in (0, 1)$ with probability λ_t, or 0 with probability $(1 - \lambda_t)$. This probability itself is time-varying, according to the dynamics presented in equation 3: in addition to an autoregressive term, it depends on lagged measures of economic activity (x_t), as well as on the current shock to J_{t+1}. Note that in this simplified framework, there is no uncertainty about the model or its parameters: so risk in this economy is entirely due to the shock J_{t+1}.

While this model is very stylized, it can help us compare and contrast two popular ways in which the literature has modeled climate risks. The first approach emphasizes uncertainty about the path of climate change as a direct source of risk for the economy. The second approach starts from the observation that the evolution of the climate and its damages is tightly linked to economic activity; in this approach, uncertainty about climate damages primarily stems from uncertainty about the future path of economic activity. Of course, in practice both channels are likely to be at play at the same time. We review each channel within the framework of our one-shock model.

Uncertainty about the path of climate change. We begin by studying the class of models in which the main source of uncertainty is about the future path of climate change. The most representative set of papers in this area thinks about climate risks in terms of a relatively low-probability catastrophic event that could dramatically impact the economy: a "climate disaster" (Barro, 2013, Weitzman, 2012, 2014, Wagner & Weitzman, 2015). Such a climate disaster is often motivated by reference to a climate "tipping point." In the model above, this view coincides with interpreting J_t as the realization of the climate disaster. The parameter λ_t then captures the conditional probability of the climate disaster, and ξ is the size of the disaster. The occurrence of the climate disaster also affects the future path of the economy, since it directly affects expected consumption growth x_t. Specifically, when $\phi > 0$, the occurrence of the climate shock reduces not only consumption immediately, but also future expected consumption growth (as in Bansal et al., 2016). When instead $\phi < 0$, there is partial mean reversion after a climate shock. The latter case has an especially interesting interpretation when modeling climate change: it captures the ability of the economy to adapt to climate change and rebuild some of the lost output at a relatively faster pace (see the emerging literature on adaptation to climate change, e.g., Brohé & Greenstone, 2007, Deschênes & Greenstone, 2011, Desmet & Rossi-Hansberg, 2015, Burke & Emerick, 2016, Barreca et al., 2016). Through the parameter χ, a climate disaster realization also affects future climate risks λ_t. Finally, the model allows for feedback effects between climate change and the economy. Climate risk affects the economy (when the climate disaster occurs), and economic activity affects climate risk through the effect of x_t on λ_t (modulated through the parameter α): when economic activity is high, climate risk increases. But when the climate shock materializes, consumption is low. In this model, there is no additional source of uncertainty about the path of economic activity beyond what is due to the climate shock.

Uncertainty about the path of the economy. As the early literature in climate economics points out, economic activity is itself a driver of climate change, so uncertainty about economic growth generates uncertainty about climate change. In this vein, the typical model embeds chains of events of the following form: the economy experiences a positive growth shock, pollution increases alongside output, the increase in CO_2 emissions accelerates climate change, which in turn accelerates climate-related damages on the economy (Nordhaus, 1977, 1991, 1992). In short, higher growth today associates with larger negative effects on future growth through the climate feedback channel. Conversely, negative shocks to economic activity (as recently experienced during the COVID-19 crisis) instead results in less pollution and less climate-related economic damage.

This model view can be represented in the one-shock model above by interpreting J_t as a shock to economic activity. A standard specification for climate change damages (e.g., Nordhaus & Boyer (2000) and Nordhaus (2008)) posits that they scale up with consumption. Suppose first that climate damages are a constant fraction of consumption, that is, they are $Q_t = \tau C_t$. Then, equations 1 and 2 represent the dynamics of net consumption (that is, aggregate consumption net of the climate change damages), J_t is a standard shock to economic activity, and equation 3 captures the time-varying distribution of economic activity. As discussed in Giglio et al. (2020), the case in which the climate-related output tax varies over time ($Q_t = \tau_t C_t$, with τ_t time-varying) is also nested in these equations by appropriately changing the dynamics of x_t.

Asset pricing implications. The discussion above highlights that equations 1–3 nest two common paradigms for embedding climate risks in economic models: uncertainty about climate disasters versus uncertainty about economic activity and its climate feedback effects. Once the physical processes of consumption, climate change, and climate damages are determined, the model is completed by choosing a utility function for the representative agent. This implies a stochastic discount factor for the economy, which in turn implies equilibrium asset prices. From here, this toy model can be enriched in many dimensions, for example by introducing heterogeneity, production, governmental climate policies, and realistic information sets for agents inside the model.

We first review a number of asset pricing implications of the two models presented above. The conclusions in this section are derived under power utility, as in Giglio et al. (2020). Before focusing on the central differences between the two modeling approaches, let us begin by pointing out a common implication. Whether uncertainty is directly about the climate or indirectly about climate through economic activity and feedback effects, realized climate damages have negative effects on the sectors of the economy exposed to that risk. Put differently, in both models, an asset with positive exposure to climate risk will decline in value when an adverse climate shock occurs, whatever the origin of that shock.

The two modeling paradigms, however, have starkly different implications for risk premia associated with climate damages. We discuss implications for both the level and the term structure of discount rates. A number of other forces that are not easily captured by our stylized model – such as alternative preference specifications and model uncertainty – can also affect risk premia, and we discuss these forces in more detail below.

When the uncertainty emanates directly from the climate process itself (e.g., in climate disaster models), climate damage tends to be unexpectedly high in times when consumption is low because climate disaster realizations are a primary driver of reduced consumption. Assets that are positively exposed to climate risk — that is, assets with low payoffs when climate damages are high — thus tend to require positive risk premia. On the other hand, assets that are negatively exposed to climate risk — such as marginal mitigation and hedging investments that pay off primarily when climate damages are realized — will have negative risk premia since these assets provide an insurance against bad (high marginal utility) states of the world. This has important implications for the appropriate discount rates used to value mitigating investments. For example, consider an investment that reduces CO_2 emissions by one ton today, the value of which is often referred to as the "social cost of carbon." In climate disaster models, the social cost of carbon is relatively high, because payoffs to investments that mitigate climate damages are discounted at rates lower than the risk-free rate.

On the other hand, if the main source of uncertainty is instead about the path of the economy, the climate risk premium has the opposite sign. In these models, climate damages are assumed to be larger when the economy is performing better. An investment that mitigates climate damages tends to pay off in times when consumption is high and marginal utility is low. Therefore, these investments carry positive risk premia and should be discounted at rates above the risk-free rate. In these models, the associated social cost of carbon is then relatively low. The low value of climate mitigation investments reflects the agent's unwillingness to pay for mitigation because it pays off in good times when marginal utility is low. Lemoine (2015) explains this channel as follows: "Under conventional damage specifications, the consumption losses due to climate change increase in the level of consumption. As a result, emission reductions increase future consumption by a larger amount when future consumption is otherwise high. This mechanical correlation between future consumption and the future consumption benefits of emission reductions makes emission reductions seem like an especially risky investment and therefore works to reduce the policymaker's willingness to pay for emission reductions."

In addition to the *sign* of the risk premium, the stylized model also also allows us to explore how the *term structure of risk premia* is affected by different assumptions about the term structure of the riskiness of cash flows. Consider an investment that can mitigate the effects of climate change at some point in the future. As we discussed above, this investment commands a negative risk premium if uncertainty stems directly from the climate path, and a positive risk premium if uncertainty stems from the path of economic activity. But how do these premia vary along the term structure (i.e., along the horizon at which the benefits of the investment materialize)? The answer depends on the dynamics shocks in the model.

First, we assume that shocks to expected growth are persistent, $\rho > 0$, as in most dynamic macro-finance models. Next, if $\phi > 0$, there are long-run risks in consumption, since today's shock J also affects consumption growth in the future in the same direction. In that case, long-term assets are *more* exposed to climate shocks than short term assets. Long-term discount rates are then larger (in absolute value) than short-term discount rates. If the primary source of uncertainty is about the climate path, risk premia for climate mitigation investments are negative and become even more negative at longer horizons. If the primary uncertainty is about the path of economic activity, discount rates are positive in the short term and become increasingly positive with the horizon.

Alternatively, if $\phi < 0$, then the economy recovers quickly from a negative shock J, growing faster than average during the recovery. In that case, long-term assets benefit from a recovery in a way that short-maturity assets do not. Because of this, the future is less risky, and risk premia revert toward zero as horizon increases. If uncertainty is about the climate path, risk premia for climate mitigation starts negative but increase with the horizon. If uncertainty is about the path of economic activity, risk premia are positive at short horizons but decrease with the horizon.

In our stylized model with power utility, the level and term structure of discount rates are only driven by different assumptions about the term structure of the cash flow risk. As a result, empirical evidence on the term structure of discount rates of assets exposed to climate risk allows researchers to discipline the cash flow processes in equations 1–3. In particular, recent advances have been made in estimating the term structure of discount rates for equities (Binsbergen et al., 2012, Van Binsbergen & Koijen, 2017, van Binsbergen et al., 2013) and real estate (Giglio et al., 2015, 2020), both of which are asset classes that are exposed to climate risk (see the next section). For both asset classes, researchers have found positive risk premia that decline with the horizon. A central insight from Giglio et al. (2020) is that these patterns speak in favor of a version of our model along the "climate disaster" lines, where the primary source of uncertainty is the path of climate change, combined with partial mean reversion of the economy following a climate shock ($\phi < 0$), perhaps because of an ability of the economy to adapt to the new climate.

To sum up, the debate around the term structure of discount rates for valuing investments to mitigate climate change (and its effects on the social cost of carbon) can in large part be traced to different assumptions about the nature of the shocks that mitigation investments are hedging, and about the dynamics of the economy and the climate in response to those shocks. While this two-dimensional distinction does not fully span the variety of models that have been written in the literature, it helps to understand what has lead the literature to reach different (sometimes opposite) conclusions.

So far we have focused on discussing the asset pricing implications of climate change that result from different specifications of the shocks and of the dynamics of the processes. However, researchers have explored additional forces that also affect risk premia and their term structures, such as preferences and uncertainty. As highlighted by a recent literature, drawing meaningful conclusions on the level and term structure of risk premia for climate investments requires taking a stand on the model in its entirety (see Gollier & Weitzman, 2010, Traeger, 2013, Arrow et al., 2013). We next discuss in turn how preferences and uncertainty affect climate risk premia.

Preferences. Preferences for time and risk naturally play an important role in determining discount rates and their term structure.

First, it is important to establish the rate of *pure time preference*. Stern (2007) took the view that ethical considerations should dictate this rate, and suggested using a pure time preference coefficient of effectively zero, giving the same weight to all generations. Most of the literature, such as Nordhaus (2007) and Weitzman (2007), has instead argued for using rates of pure time preference that are greater than zero, consistent with observed savings and investment behavior (see also the discussion in Arrow, 1995).

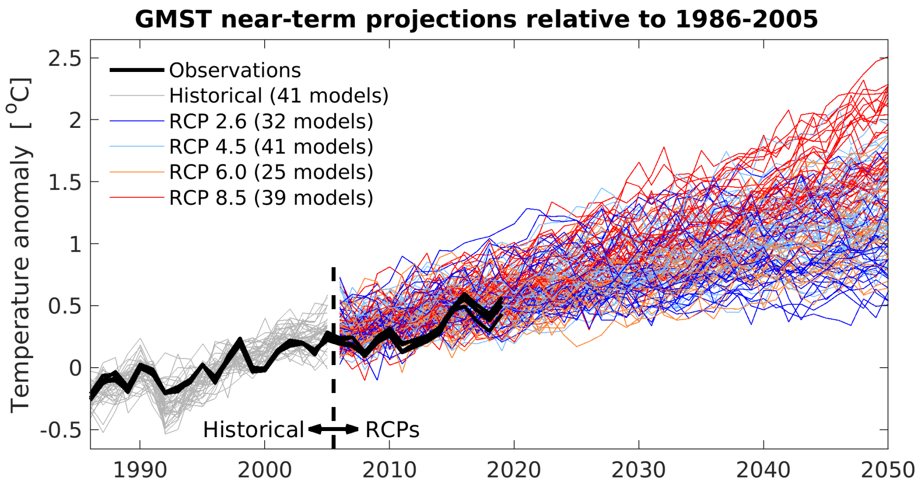
In addition, the climate finance literature has explored a number of alternative *risk preferences*. The most prominent alternative to power utility is Epstein–Zin utility (see, for example, the work of Gollier, 2002, Crost & Traeger, 2014). An Epstein–Zin investor's marginal utility depends not only on the one-period innovation in consumption growth (as in the power utility case that we described above) but also on *news* about consumption growth at future horizons. This specification of preferences has two main consequences for thinking about climate risks (for suitable parameterizations that induce a preference for early resolution of uncertainty): first, it affects the *level* of climate risk premia, because it amplifies the utility consequences of climate shocks if they have long-term implications for the agent's consumption growth (as they do, for example, in Bansal et al., 2019). Second, they affect the term structure of discount rates, as well as the optimal timing of mitigation investments. For example, Daniel et al. (2019) show that Epstein–Zin preferences increase the value of mitigating climate change early, and result in declining paths of CO_2 prices over time, as uncertainty gets resolved.

Model Uncertainty. The vast majority of asset pricing theory is formulated under the assumption of rational expectations, so that investors inside the model know the exact probability laws that govern their decision making environment. The illustrative model introduced above is an example of this modeling approach. But in the context of climate change (and likely more generally), rational expectations endow investors with an unrealistic understanding of their environment. As Hansen (2014) emphasizes, "it is often not clear what information should be presumed on the part of economic agents, how they should use it, and how much confidence they have in that use." Put differently, in rational expectations models, investors face the uncertainty about stochastic realizations from a *known* probability law. In reality, investors also wrestle with *ambiguity*, or uncertainty about the true probability law. Nowhere could this be truer than in economic models of climate risk. Is it implausible that economic agents know with any degree of certainty the precise nature or severity of climate risks that are facing them, a topic of substantial disagreement even within the scientific community. As Lemoine (2020) aptly notes,

> "Uncertainty is fundamental to climate change. Today's greenhouse gas emissions will affect the climate for centuries. The emission price that internalizes the resulting damages depends on the uncertain degree to which emissions generate warming, on the uncertain channels through which warming will impact consumption and the environment, on the uncertain future evolution of greenhouse gas stocks, and on uncertain future growth in productivity and consumption."

Recent climate-economic theory begins to confront ambiguity in climate economic models using tools from the theory of decision under uncertainty. Brock & Hansen (2018) and Heal & Millner (2013) lay out the general argument for, and technical approaches to, featuring model uncertainty in climate economic models. Heal & Millner (2013) catalogs the sources of ambiguity as "scientific uncertainty" (e.g., the effect of atmospheric CO_2 concentrations on surface temperatures) versus "socio-economic uncertainty" (e.g., even if we knew the model for the climate effects of CO_2, we remain uncertain about how societies react to these effects). Surveying predictions from a wide range of climate research and meta-analyses, Brock & Hansen (2018) illustrate wide heterogeneity in forecast distributions among leading climate

Figure 1: Temperature Forecasts From Various Climate Models



Source: Climate Lab Book (`http://www.climate-lab-book.ac.uk/`).

models. As an example, Figure 1 shows the divergence in forecasted temperature anomalies across several models and across parameter values within those models.

In models of ambiguity, investors typically assign probability weights to models in a Bayesian fashion based on a combination of their prior model weights and the data they have observed. Investors make savings and consumption decisions based on the compound uncertainty they face based on their posterior weights over models and the stochasticity within each model. Preferences interact with ambiguity through recursive preferences or, more directly, through robust or ambiguity averse preferences. Brock & Hansen (2018) outline a range of potential modeling choices for the specific forms that model uncertainty might take and for the preference or decision theoretic constructs that agents in the model use to make savings and consumption choices in the face of uncertainty.

Lemoine (2020) argues that accounting for model uncertainty leads to higher estimates of the social cost of carbon than would otherwise prevail. In models with recursive preferences, uncertainty (especially with regards to economic damages arising from temperature increase) raises the social cost of carbon by an order of magnitude relative to a model with the same preference structure but no ambiguity. Parameters that govern climate-related economic damages are random variables when approached from a model uncertainty viewpoint. Uncertainty thus introduces a new channel that impacts asset prices in the form of covariance between model parameters and agents' consumption. This induces precautionary savings and risk premia effects in addition to those resulting from stochastic shocks in standard unambiguous models. Viewing damage uncertainty as a compound lottery, when the agent "draws" an especially adverse damage parameter, carbon mitigation becomes especially valuable and raises the social cost of carbon (as long as relative risk aversion is greater than one, as commonly assumed in calibrations of macro and finance models).

In the face of model uncertainty, Bayesian economic agents gradually update their beliefs about their environment based on the arrival of new data. Since Bayesian posteriors follow a martingale, these updates constitute permanent shocks from the perspective of the learner. As Johannes et al. (2016) and others point out, these belief update shocks are especially risky for agents with recursive preferences and, as a result, risk premia are magnified relative to baseline models with no ambiguity or with non-recursive utility. This "learning as a long-run risk" perspective motivates the measurement of climate risk through news arrival in the empirical analysis of Engle et al. (2020) discussed in Section 3. The persistent effects of belief updating leads model uncertainty to accumulate over time, partially offsetting the effects of discounting on damages in the distant future. This mechanism is at the core of the large increase in the social cost of carbon in Lemoine (2020).[1]

Once we acknowledge that agents in a climate model face ambiguity, it is natural to consider decision theoretic frameworks beyond subjective expected utility in order to accommodate the well documented human tendency of ambiguity aversion (Ellsberg, 1961). As a leading example, Barnett et al. (2020) analyze the social cost of carbon under model uncertainty while accounting for ambiguity aversion. In their setup, ambiguity takes the form of multiple potential models of the impact of carbon emissions on temperature and economic damages caused by high temperatures. Agents make decisions amid this ambiguity based on the recursive smooth ambiguity aversion preferences of Hansen & Miao (2018). While the comparative statics in Lemoine (2020) analyze incremental carbon costs associated with model uncertainty in an expected utility framework, Barnett et al. (2020) analyze the additional incremental effects of ambiguity aversion on the social cost of carbon. Holding fixed the extent of model uncertainty, they compare model calibrations with ambiguity averse investors versus a model with ambiguity neutrality. Ambiguity aversion magnifies

[1] A similar model analyzed by Dietz et al. (2018) calibrates a comparatively small cost of carbon, arguing that "the positive effect on the climate beta [covariance of consumption and the marginal social cost of emissions] of uncertainty about exogenous, emissions-neutral technological progress overwhelms the negative effect on the climate beta of uncertainty about the carbon-climate-response." Lemoine (2020) chalks this difference up to the larger model uncertainty used in his calibration compared to that of Dietz et al. (2018).

the cost of carbon by roughly 60% to 70% in current value terms relative to the baseline scenario with model uncertainty but ambiguity neutrality.[2]

3 CLIMATE RISK AND ASSET MARKETS: EMPIRICAL EVIDENCE

In recent years, the finance literature has made substantial progress in understanding the effects of climate change on asset prices across a number of asset classes. This research effort has the immediate benefit of helping us quantify the forces that link the climate and the economy, and therefore allows us obtain a better understanding of the underlying structural relationships discussed in the previous section. In addition, we will show that understanding the empirical relationship between climate change and asset prices has the benefit of giving us implementable indications on how to use financial markets to hedge climate risks.

For researchers interested in understanding the effects of climate change on asset prices, it is important to note that there are actually several different categories of climate risks potentially priced in asset markets, and that these different risks often do not materialize at the same time. Broadly speaking, climate risks can be divided into physical risks and transition risks. The *physical risks* of climate change are those that result directly from the effects of changes in the climate on economic activity. For example, the threat of damage from rising sea levels to firms' production facilities close to the sea, and the associated destruction of real estate values, would be considered a physical climate risk. *Transition risks* cover a wide range of effects on firms' operations and business models that come from a possible transition to a low-carbon economy. One example of a transition risk is the possible introduction of a carbon tax that might leave fossil fuel companies with stranded assets that are no longer profitable to operate. In addition to such regulatory risks, transition risks also include technological advances and changing consumer preferences away from high-carbon activities. While realizations of physical and transition risks need not occur at the same time, they are often correlated, and might even move in opposite directions. For example, the introduction of a carbon tax — a realization of negative transition

[2] Barnett (2017) also pursues this line of research to understand asset prices and production when agents have both recursive preferences and aversion to uncertainty about the climate model. He analyzes a dynamic general equilibrium model where production involves a mix of cheap, polluting fossil fuels and expensive, clean green energy. Accounting for aversion to climate model misspecification increases the market price of climate risk in the model by as much as an order of magnitude relative to a model with no ambiguity aversion.

risk — might reduce the likelihood of future negative realizations of physical climate risks.

Different assets may be positively or negatively exposed to these types of climate risks; in other words, realizations of both physical and transition risks will have winners and losers in asset markets. For example, while coal companies would likely suffer from realizations of transition risks, renewable energy companies might benefit. And while climate change will negatively affect the value of coastal real estate, it might also increase the value of farmland in colder regions of the world. Given these different risk categories, and the different exposures of various assets to these risk categories, one of the important common challenges for all approaches to exploring how climate risks affect asset markets is to obtain measures of different assets' *exposures* to both physical and climate risks. Our discussion below will highlight how different researchers have approached this challenge.

A second important challenge to documenting how climate change is priced in asset markets is that the rise in investor attention to climate risk is a fairly recent phenomenon. As a result, while climate risk may be priced in asset markets today, it might not have been 10 or 15 years ago. This reduces the ability of researchers to exploit time series variation in documenting how climate change affects asset prices. In addition, the availability of only a short time series makes it hard to estimate the *climate risk premium*, which, as we saw in the previous section, plays a fundamental role in distinguishing between theories. As a result, our understanding of the pricing of climate risks in financial and non-financial assets is likely to evolve substantially over the coming years, as more time series data become available.

3.1 CLIMATE RISK AND FINANCIAL ASSETS

A number of papers have explored the extent to which climate risks are priced in financial assets. This literature often starts from the observation that a growing number of large institutional investors have declared environmental, social, and corporate governance ("ESG") sustainability an important objective in their portfolio allocation process. Naturally, climate change is a focal issue in ESG investing. For example, Larry Fink of BlackRock wrote in his 2020 letter to CEOs that "our investment conviction is that sustainability- and climate-integrated portfolios can provide better risk-adjusted returns to investors." He concludes that, in response to climate change, "in the near future – and sooner than most anticipate – there will be a significant reallocation of capital." This statement is consistent with the systematic analysis of presented in Krueger et al. (2020). These authors conduct a survey of active investment managers to explore their approaches to managing climate risk.

They find that investors believe that climate change has significant financial implications for portfolio firms, and that considerations of climate risk are important in the investment process. For example, 39% of investors in the survey reported to be working to reduce the carbon footprints in their portfolios. These survey responses are also consistent with findings from Alok et al. (2020), who show that fund managers adjust their portfolios in response to climatic disasters. Pedersen et al. (forthcoming) provide an ESG CAPM framework and outline how investor beliefs and preferences regarding climate change risks (and ESG considerations more broadly) fit in with the factor model paradigm that dominates empirical asset pricing research.

Equity Markets. Given the attention that investors dedicate to climate change, a growing literature explores the pricing of various dimensions of climate risk in equity markets (e.g., Hong et al., 2019). Much of this literature has focused on the effects of regulatory climate risk, where different measures of carbon intensity or environmental friendliness are often used as proxies for regulatory climate risk.[3] For example, Bolton & Kacperczyk (2020) analyze U.S. equity markets, and demonstrate that firms with higher carbon emissions are valued at a discount. Quantitatively, the authors estimate that a one standard deviation increase in emissions across firms is associated with a rise in expected returns of roughly 2% per annum. The authors trace this effect at least in part to exclusionary screening performed by institutional investors to limit the carbon risk in their portfolios. In related work, Hsu et al. (2020) show a similar spread in average returns between high- and low-pollution firms, and link it to uncertainty about environmental policy. Engle et al. (2020) document that stocks of firms with high E-Scores — which the authors argue capture lower exposure to regulatory climate risk — have higher returns during periods with negative news about the future path of climate change. Similarly, Choi et al. (2020) explore global stock market data and find that stocks of carbon-intensive firms underperform during times with abnormally warm weather, a period when investors' attention to climate risks are likely to be particularly high. Barnett (2020) uses an event study analysis to explore financial market impacts of regulatory risk. He finds that increases in the likelihood of future climate policy action lead to decreased equity prices for firms with high exposure to climate policy risk. Similar evidence of the pricing of climate risk can be found in equity options markets. Ilhan et al. (2019) show that the cost of option protection against extreme downside risks is larger for firms with more carbon-intense business models, and particularly so at times when there is an increased public attention to climate risk.

[3] A number of recent papers have attempted to provide new measures of firm-level exposures to climate risk that are based, for example, on the language around climate change used in earnings calls (Sautner et al., 2020, Li et al., 2020).

In addition to climate change affecting firm valuations through the exposure of their business model to various forms of climate risk, investors also appear to reward firm efforts to mitigate these risks. For example, Pérez-González & Yun (2013) study the effects of managerial efforts to mitigate firms' climate risk exposures on those firms' valuations. Based on firm-level weather hedging data (using CBOE weather contracts), they show that climate hedgers have higher valuations, and that this effect is more pronounced for more climate sensitive firms. This is consistent with findings from the survey in Krueger et al. (2020), which highlighted that investors were actively engaging with management — both informally and formally through shareholder proposals — to work with them to reduce their climate risk exposures.

Fixed Income Markets. Climate risks may also affect financial assets beyond equities. Municipal bond markets are a particularly interesting setting for analyzing the financial market implications of climate risk. In particular, when considering the physical risks of climate change, firms may be at risk depending on the location of their production facilities. However, even the most exposed firms usually have the option of relocating their modes of production to other geographies. Municipalities have no such luxury. As a result, one would expect that municipal debt backed by tax revenues from localities more exposed to physical climate risks such as rising sea levels or wildfires would trade at a substantial discount. In evidence along these lines, Painter (2020) shows that at-issuance municipal bond yields are higher for counties with large expected losses due to sea level rise (SLR). Consistent with the hypothesis that such price differences reflect the pricing of climate risk, he finds that this effect is concentrated in long-dated bonds and essentially absent at short maturities over which the likelihood of SLR remains low. In related work, Goldsmith-Pinkham et al. (2019) show via a structural model that this effect of SLR on municipal bond yields is tantamount to a 3–8% reduction in the present value of local government long-run cash flows.

Climate risk may also be priced in other fixed income markets, such as the corporate bond markets studied by Huynh & Xia (2020). These authors first calculate the covariance of each bond's returns with the climate news index constructed by Engle et al. (2020). Bonds with a more positive covariance are those that perform relatively well when bad news about climate change emerges, suggesting they are weakly or even negatively exposed to realizations of climate risk. Consistent with climate risk being priced in corporate bond markets, Huynh & Xia (2020) find that those positive-covariance bonds have lower returns.

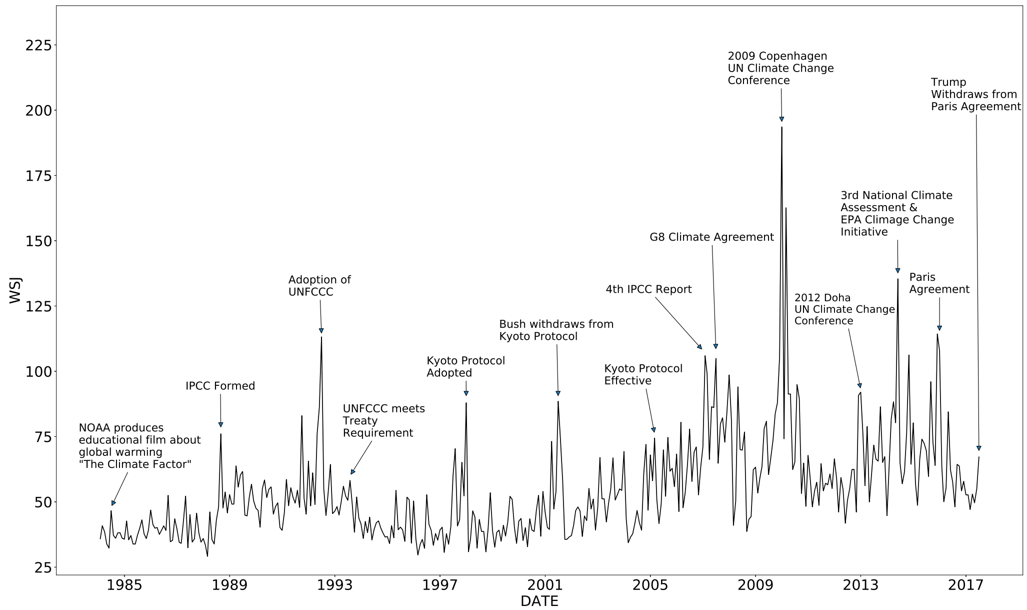
Another class of fixed income assets with valuations that might be affected by climate risk are "green bonds" whose proceeds are expressly linked to environmentally friendly projects (e.g., renewable energies, clean transportation, etc.). Baker et al. (2018) study a sample of more than 2,000 municipal and corporate green bonds and find that green bonds trade at lower yields than bonds with similar attributes that lack a green designation. Quantitatively, after-tax yields at issue for green bonds are roughly 6 basis points below yields paid by otherwise non-green equivalent bonds. The authors attribute these pricing differences to a subset of investors that have a nonpecuniary component of utility, such as a sense of social responsibility from holding green bonds. Realizations of climate risk may move the magnitude of this nonpecuniary valuation component, and will thus affect the valuations of these bonds.

Hedging Climate Risks Using Financial Assets. The research described above shows that climate change is a significant risk factor determining asset prices. This observation then invites the question of how investors can mitigate the risks that climate change poses to their portfolios. This is particularly important since many of the effects of climate change are sufficiently far in the future that neither financial derivatives nor specialized insurance markets are available to directly hedge those long-horizon risks. Instead, investors are largely forced to insure against realizations of climate risk by building hedging portfolios on their own.

Engle et al. (2020) propose an approach to hedging climate risk that combines traditional dynamic trading arguments from financial theory with novel statistical measurements using textual analysis. The paper's first insight follows the Black & Scholes (1973) and Merton (1973) logic that a dynamic strategy to hedge gradually arriving news about future climate change can approximately replicate an infeasible contract that directly pays off in the event of a future climate disaster. The key question, then, is: how to measure such news? To do this, Engle et al. (2020) extract a "climate news" index based on coverage of climate change by *The Wall Street Journal* (WSJ). The index — which is available to other researchers, and which has been used by Huynh & Xia (2020) and others — measures the extent to which WSJ article text overlaps with climate change discourse in authoritative texts published by various governmental and research organizations. The index, shown in Figure 2, displays intuitive variation over time. The level of climate news coverage gradually rises over time and spikes around topical global climate events. In their baseline approach, Engle et al. (2020) interpret rising coverage of climate related topics as the arrival of bad news about future climate change. They validate this approach by complementing their WSJ-based analysis with additional sentiment-based studies of climate coverage in newspapers.

With this measure of the arrival of climate news, Engle et al. (2020) propose an approach to dynamically hedging climate news based on factor mimicking portfolios. Specifically, the authors use relatively easy-to-trade basis assets (U.S. equities) to

Figure 2: Climate Change News Index



Source: Engle et al. (2020).

mimic the WSJ climate news index. Intuitively, the approach is to systematically own or overweight stocks that rise in value when (negative) news about climate change materializes and likewise short or underweight stocks that fall in value on the arriveal of this news. In doing so, the hedge portfolio profits when adverse climate news hits. The authors show how to continually update the hedge portfolio using evolving information about which stocks are most susceptible and which are most resilient to climate risk.

To implement this dynamic hedging strategy, it is necessary to determine which firms increase or decrease in value when there is news around climate change. Engle et al. (2020) solve this problem by proxying for firms' climate risk exposures using "E-Scores" that capture various aspects of how environmentally friendly a firm is. The hedge portfolio would then overweight high-E-Score firms, and underweight low-E-Score firms, with the relative weights updated dynamically as more data on the relationship between E-Scores, climate news, and asset prices is obtained. While it is straightforward to construct such a hedge with the benefit of hindsight, the true test of a hedge portfolio is its ability to profit in adverse conditions on an out-of-sample basis. Indeed, Engle et al. (2020) find an out-of-sample correlation of 20% to 30% between the return of the hedge portfolio and innovations in the WSJ climate change news index. In summary, the paper provides a rigorous methodology for constructing portfolios to hedge against climate risks that are otherwise difficult to insure.

It is worth pointing out an additional connection between this empirical approach and the theories discussed in the previous section. If uncertainty about future climate damages (for example, about the model parameters) is resolved slowly over time, then the news about the future path of the economy will itself represent a risk factor for the investor. A portfolio that hedge the news about future climate, like the one built by Engle et al. (2020), would then be useful not only to dynamically hedge the long-term realization of the damages from climate change, but also to hedge the risks represented by the arrival of information over time (resolution of model uncertainty). This provides an additional advantage of this hedging portfolio (one that would be particularly valuable for investors, like Epstein–Zin investors, that are especially averse to such news shocks).

Finally, mimicking portfolios are closely related to risk premia. As is well known from the asset pricing literature, the risk premium of any nontradable risk (like climate change risk) is the expected excess return of the corresponding hedging portfolio.[4] Once the hedging portfolio for climate risks is built, therefore, one could estimate the climate risk premium by looking at the time-series average return of this portfolio. As highlighted above, however, this exercise is difficult with a short time series. For example, suppose that the true climate risk premium is positive, as many of the models reviewed in the previous section imply. The climate-hedging portfolio should then have a negative risk premium: its average return should be, in the long run, below the risk-free rate. However, if one computes the average return of this hedging portfolio over the last 10-15 years, one might as well find a positive average return, because this short time period is dominated by the realization of a series of bad news about climate change (see Figure 2). This would then lead to estimating the wrong sign for the climate risk premium. Given the short time series available, it is important to keep these caveats in mind when interpreting the historical average returns of climate-exposed portfolios.

3.2 CLIMATE RISK AND HOUSING AND MORTGAGE MARKETS

A growing literature has started to explore the effects of climate change on real estate valuations, and through this channel, on the mortgage market. This focus on real estate is hardly surprising. Indeed, since the value of real estate is tightly linked to

[4]The hedging portfolio can be constructed either directly, via mimicking-portfolio regressions, or indirectly, for example using two step cross-sectional regressions.

the value of the land it is built on, it is natural to suspect that physical climate risk factors, such as rising sea levels and wildfires, might directly affect real estate prices. Take rising sea levels as an example: Hauer et al. (2016) estimates that a 1.8 meter sea level rise by the year 2100 would affect about 13.1 million Americans. Similarly, Zillow economist Krishna Rao (2017) calculates that a six feet sea level rise would put 1.9 million homes worth about $882 billion at risk of flooding, with about half the losses coming from Florida alone. While many of these damages might only arise some decades in the future, the low long-run discount rates for real estate discussed in the previous section mean that present-day real estate prices might already be significantly affected by climate risk.

To explore whether or not climate change risk is priced in real estate today, one would ideally want to compare the valuations of two otherwise identical properties that are differentially exposed to physical climate risk factors such as rising sea levels, flooding, hurricanes, or wildfires. The challenge with this empirical exercise is that all houses are, by nature, a unique combination of aspects of location and structure (Kurlat & Stroebel, 2015, Piazzesi et al., 2020), which complicates the search for comparable units that might be differentially exposed to climate risk. More problematic still, some of the locational or structural aspects that contribute to the value of a particular property might correlate with the property's exposure to climate risk. To give a concrete example: properties with beach access are likely to be more exposed to rising sea levels than properties that are located further inland. And, since beach access is a valuable amenity, beach front properties will usually trade at a premium relative to other properties. This does not mean, however, that climate risk is not priced. Instead, it means that the particular location of the property has both a positive amenity value, which increases the flow utility from the property, and is associated with higher climate risk, which affects the realization and valuation of future cash flows. While hedonic regressions allow researchers to control for observable differences in quality features of properties, such as the property's size, many important location features are hard to measure and therefore difficult to completely control for in a regression.

Many of the researchers studying whether climate risk is priced in real estate markets therefore exploit additional sources of variation, often time-series variation in climate risk, beyond the across-property variation in climate risk exposures. The identifying assumption in these analyses is the following: as long as the amenity value of beach access does not change when climate risk changes, differential price changes of more-exposed and less-exposed properties can be informative about the pricing of climate risk in housing markets. However, such an analysis presents a second challenge: true climate risk is a relatively slow-moving object that does not provide much of the high-frequency time-series variation required to identify how it is priced using the approach just described. Researchers have therefore tried to exploit time-series variation in the *attention* to climate risk in the housing market. Indeed, even though true climate risk might not change much from year to year, the extent to which housing market participants focus on these risks changes much more frequently, and one would thus expect the pricing implications of climate risk to be particularly strong when households pay more attention to these risks

A recent paper using a research design along these lines is Giglio et al. (2020). They explore the pricing of the risk of rising sea levels in four coastal U.S. states — Florida, New Jersey, North Carolina and South Carolina — that are particularly exposed to this physical climate risk factor. To measure different properties' exposure to climate risk, the authors geo-code the addresses of all properties bought and sold in these states between 2008 and 2017. They then map the property locations to information provided by the National Oceanic and Atmospheric Administration (NOAA) that indicates which regions will be flooded should sea levels rise by six feet or more. The authors document substantial variation in exposure to climate risk across properties in the same narrow geography. This variation is driven, for example, by differences in elevation, and allows the authors to compare the pricing of climate risk while holding local housing market conditions fixed.

To identify the pricing of climate risk, Giglio et al. (2020) also construct a measure of attention paid to this risk in housing markets. To construct this measure, which varies across both time and space, the authors analyze the textual descriptions of properties in the universe of for-sale and for-rent property listings from Zillow, a major online real estate listings service. The resulting "Climate Attention Index" is constructed by calculating the proportion of for-sale listings with property descriptions that contain climate risk-related words and phrases such as "hurricanes", "FEMA", "floodplain", and "flood risk."Most of the flagged listings include descriptions that highlight that a specific property is less exposed to climate risk (e.g., "Not in a flood zone, it's high and dry!"). This is unsurprising: if you are selling a house that is not exposed to climate risk, this is something worth highlighting in a property listing, in particular in areas and at times when potential buyers pay more attention to these risks. In terms of spatial variation, more attention to climate risk is paid in coastal regions, which have a higher average exposure to these risks. In the time series, attention to climate risk increases after salient natural disasters. For example, the Climate Attention Index in New Jersey increases substantially between 2011 and 2013, around the time of Hurricane Sandy, which rendered 20,000 homes in the state uninhabitable.

Using these data, Giglio et al. (2020) show that while properties in a flood zone generally trade at a premium compared to otherwise similar properties (likely because of positive amenities such as beach access), this premium compresses in periods with elevated attention paid to climate risk. Quantitatively, a doubling in the Climate Attention Index (i.e., a doubling in the share of listings that mention climate risk-related words) is associated with a relative 2.4% decline in the transaction prices of properties in the flood zone.

One possible concern with these results is that they might not just capture the pricing of future climate change risk. Instead, these estimates might also pick up changes in the flow-utility of climate risk-exposed properties that could be correlated with climate risk attention. For example, as discussed above, it appears to be the case that climate risk attention rises after hurricanes; if those hurricanes also have a particularly strong direct effect on the utility of living in properties located in flood zones, this might explain the relative price decline of these properties. Giglio et al. (2020) rule out such a story, by showing that the relative *rents* of properties more exposed to climate risk do not decline when attention to climate risk increases. Since any decline in the flow-utility from exposed properties that is correlated with increases in climate risk attention would also affect these rental units, this finding emphasizes that the relationship between climate risk attention, climate risk exposure, and price is driven by changes in the expected realization and valuation of future cash flows (rents).

A number of other papers exploit related research designs to explore the pricing of climate risk in real estate markets. Bernstein et al. (2019) also explore the relationship between house prices and sea level rise (SLR). They find that houses that are exposed to sea level rise sell for a discount compared with observably equivalent unexposed properties. The authors are able to control for the distance from the beach, which allows them to alleviate some concerns around differential amenity values of these properties. Quantitatively, properties that will be inundated after one foot of global average SLR sell at a 14.7% discount, properties inundated with two to three feet of SLR sell at a 13.8% discount, and properties inundated with six feet of SLR sell at a discount of 4.4%. Baldauf et al. (2020) present related evidence suggesting that the extent to which physical climate risk is priced in housing markets depends on whether the local population believes in climate change. Bakkensen & Barrage (2017) explore a similar point, highlighting that when individuals who do not believe in climate change disproportionately sort to purchase more exposed properties, this will reduce the extent to which climate change risk is priced in housing markets.[5]

[5] Using similar data but a different identification method, based on cross-sectional differences in relative sea level rise due to vertical land motion, Murfin & Spiegel (2018) find instead a much smaller effect of climate change exposure on house prices, highlighting the importance of the iden-

A related set of papers has explored the effect of hurricanes on house prices, arguing that a recent hurricane makes future costs of climate change more salient to individuals, even in cases where the Hurricane did not affect a particular property. Ortega & Taspinar (2018) show that following Hurricane Sandy there was a significant and permanent relative price decline of New York City properties in flood zones, even if they were not damaged by Sandy. Gibson et al. (2017) also find that increasing salience of climate risk following hurricanes reduces the relative valuation of more exposed properties in the New York housing market. Eichholtz et al. (2019) find similar results in the commercial real estate market. The authors study transactions in three cities, New York, Boston, and Chicago, before and after the shift in the salience of flood risk caused by Hurricane Sandy. They find that properties exposed to flood risk experience slower price appreciation after the storm than equivalent unexposed properties. As the previous papers, Eichholtz et al. (2019) conclude that the price effect is persistent and not driven by physical damage incurred from Hurricane Sandy.

While rising sea levels are a first-order concern for coastal home owners, they are not the only channel through which climate change poses a physical risk for real estate values. Another salient risk of climate change is the increasing danger of wildfires in many states. For example, Corelogic (2019) found that nearly 776,000 homes with an associated reconstruction cost value of more than $221 billion were at extreme risk of wildfire damage. Many of the most at-risk properties are in California MSAs, but properties in Texas and Colorado are also potentially at risk. Garnache & Guilfoos (2019) explore whether such wildfire risk is priced, and find that the price of homes drops when these home are designated to be in a wildfire risk zone (see also McCoy & Walsh, 2018).

Since most residential real estate is purchased with a mortgage, climate risk will also affect the valuations of these mortgages. Consistent with this, recent research has shown that realizations of wildfire risk and flooding lead to increased mortgage default (Issler et al., 2019). Similarly, recent evidence provided by Ouazad & Kahn (2019) suggests that perceived climate risk affects banks' decisions to securitize originated mortgages (see also Keenan & Bradt, 2020). This suggests that the federal government, through the default-risk guarantees that Fannie Mae and Freddie Mac provide to agency-insured MBS, may be directly exposed to the effects of climate risks in real estate markets.

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tification assumptions for the conclusions in this branch of research.

4 CLIMATE FINANCE: A RESEARCH AGENDA

Climate change will be a first-order issue facing our society for many years to come. Researchers in financial economics have only recently turned their attention to exploring the many ways in which climate change will affect financial markets. Much progress has been made on both modeling the relationship between climate, the economy, and asset prices as well as on documenting the many ways in which climate risk is already priced in financial markets. But much work remains to be done.

On the modeling side, advances in computational power will allow researchers to model the various feedback loops between climate change and the real economy with increasing sophistication. While the basic economic mechanisms of these models will be similar to those discussed in this review, such modeling advances will provide new and improved quantifications of important objects such as the social cost of carbon.

On the empirical side, there is substantial scope for improvements of the measures of climate risk exposure in different asset classes, and in particular for equity assets. Over the coming years, increased disclosure by firms — whether mandated by regulators or demanded by large investors — will provide new opportunities to measure firms' exposure to various types of climate risks. In the absence of new data disclosed directly by firms, more creative use of already existing data — such as satellite imagery or text from 10-K statements or earnings calls — can be processed to improve climate risk exposure measures. Similarly, more sophisticated sentiment analysis can improve our measures of negative climate news, as well as our ability to separately identify news about physical and transition risk. Taken together, these improvements will improve our ability to construct increasingly more effective climate hedge portfolios.

Another important question is to explore the extent to which climate risk, through its effect on asset prices, may affect financial stability. The answer to this question depends, to a large extent, on the degree of concentration of these risks in the portfolios of financial institutions and investors. Measuring this concentration is an important and valuable research agenda. To do this, we require better measures of asset-level risk exposures, which could then be aggregated to the portfolio level. These numbers would allow financial institutions to better manage their climate risk exposures, and regulators to ensure that these risks do not pose a threat to financial stability.

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