Finance and Economics Discussion Series

Federal Reserve Board, Washington, D.C.
ISSN 1936-2854 (Print)
ISSN 2767-3898 (Online)

Climate Change and Financial Policy: A Literature Review

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2022-048

Please cite this paper as:
Dennis, Benjamin N. (2022). "Climate Change and Financial Policy: A Literature Review," Finance and Economics Discussion Series 2022-048. Washington: Board of Governors of the Federal Reserve System, https://doi.org/10.17016/FEDS.2022.048.

Climate change and financial policy: A literature survey

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July 29, 2022

[1]I thank Katherine Arnold, Joseph Cox, Benjamin Kay, Elizabeth Kiser, Mathias Kruttli, Andreas Rapp, and Nicholas Tabor for helpful discussions and comments. The views expressed in this paper are not those of the Federal Reserve Board and are the sole responsibility of the author, including all errors and omissions.

Abstract

This article reviews the rapidly proliferating economic literature on climate change and financial policy. We find: (1) enduring challenges in estimating the statistical properties of a changed climate; (2) emerging evidence of financial markets pricing in climate-related risks; and (3) a range of significant institutional distortions preventing such pricing from being complete. Finally, we argue that geographic regions may be an especially fruitful unit of analysis for understanding the financial impact of climate change.

Contents

1 Introduction

This literature survey addresses the implications of climate change research for policymakers, most specifically those at central banks. At least since Mark Carney began to place emphasis on climate change as Governor of the Bank of England, financial system vulnerability to climate change has been a concern of central banks, and policymakers have grappled with the appropriate role for monetary, financial stability, and banking supervisory and regulatory policy (Carney, (2015) [53]). The basic framework advanced by Carney considers two classes of risk: 1) physical risk—that is, physical damage caused by severe climate events or chronic worsening of conditions as with sea level risk—and 2) transition risk, or the risk to certain sectors of the economy as the structure of economic activity necessarily becomes less carbon intensive.[1] In this framework, central banks must manage risks to the financial system that result from physical climate vulnerabilities as well as from policy imperatives.

This literature review is organized around three fundamental questions with which policymakers must grapple as illustrated in Figure 1.

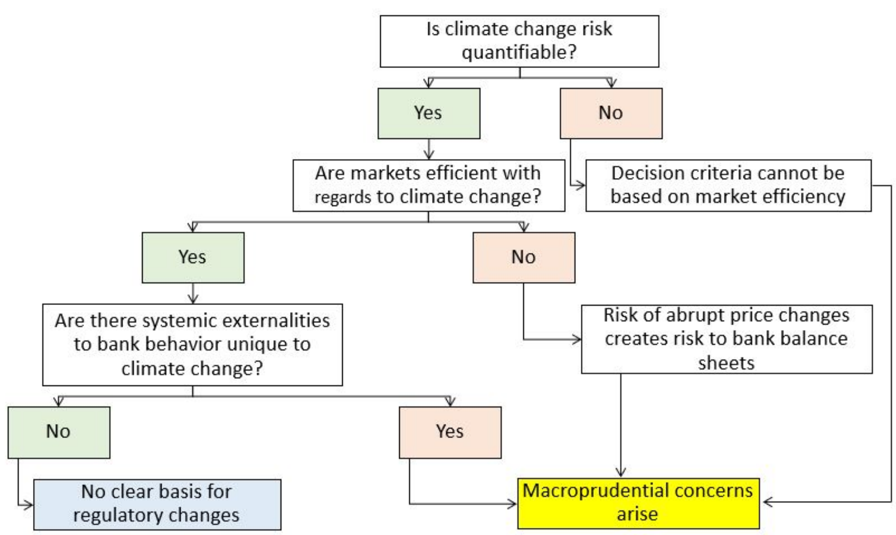

Figure 1: Fundamental climate questions

[1]Carney also addresses 'liability risk,' arising from claims of those harmed from climate change.

The first is whether, and to what extent, climate risk is quantifiable. Perhaps most famously described by Knight (1921), [131]), radical (or "Knightian") uncertainty—defined by Bewley (1988) [31] as, 'randomness with an unknown distribution'—has been recognized as a challenge for economic decision-making. Unsurprisingly, radical uncertainty does not easily translate into clear tools for risk management. Von Neuman and Morgenstern (1953) [190] demonstrated the advances that could be made when uncertainty can be represented by quantifiable risk. The burgeoning literature on continuous-time finance (see, e.g., Merton, (1992) [147]) ushered in the development of derivative assets and the hedging and risk-management tools that define modern financial markets. These tools are built on the ability to transform financial risks into stationary or otherwise well-behaved functions whose (relative) behavior can be coaxed to yield tractable policy targets that are legible in terms of discoverable parameter values. Often, these targets—for example, credit limits or minimum liquidity thresholds—take on precise values based on careful analysis of historical data. Yet, the limitations of relying on history to contain all the facts needed to protect against future shocks are well known, and they are particularly true for climate change. Section (2) of this paper therefore examines the literature on how to address uncertainty in climate models, and the implications for use of common tools in financial risk management.

The second key question, which we address in Section (3), is whether current market prices for goods and assets are efficient with respect to potential physical and transitional climate shocks. That is, have market participants rationally integrated all currently known information about climate risks into market prices? There are multiple dimensions to this question, and the literature on asset price bubbles is possibly closest in helping to frame the issues involved. However, unlike a bubble, in which the question is whether prices are rising too quickly, the question with climate change is whether certain asset prices, such as coastal real estate, are adjusting downwards quickly enough. Factors stressed by Shiller (2016) [181] among others—such as beliefs (animal spirits) and magical thinking—as well as institutional factors that misalign the burden of risky behavior across market participants are all potentially relevant.

Section (4) turns to the final question, whether climate change imposes specific externalities of its own within the financial system. These externalities can most easily be seen in the macro implications for insurers or widespread climate damage resulting from global shocks. By altering the nature of shocks towards systemic as opposed to idiosyncratic events, much of the load-bearing capacity of risk management tools and institutions may require a macro-prudential approach attuned to the specific threat of climate change.

The examination of the literature that follows suggests that, even though this research is still in its early stages, we have a good sense of how to answer these questions. It remains difficult, if not impossible, to identify a reliable probability distribution of climate events in a warmed world. Economists have developed different approaches to this dilemma, which can result in enormous differences in outcomes, often driven by emergent and unintuitive properties of the models themselves. More promising methods, such as agent-based modeling, are gradually coming within reach as the computing power required for them increases. Other cost/benefit-oriented approaches work with less specific assumptions of climate-related economic costs, generating tractable guidance for general economic policy but not climate-related financial risk. Disputes over discount rates compound the difficulties further.

Studies of financial markets face similar challenges, although with more reliable local results. Most suggest that, while ESG-adaptive equities display some reduced risk premia, the prices of economically specific assets (like real estate) do not fully reflect climate-related financial risks. Agents appear to respond differently to climate-related information "news"; their ex ante beliefs, their ability to exit a market, their ability to mitigate risk, and their access to information can all affect their behavior. In addition, agents' responses may not be durable or complete. However, literature on this point is less complete, relying heavily on assumptions about sectoral carbon intensity and using physical variables to proxy the intensity of transition-related financial risks. Studies of banks are scant.

However, a more robust body of literature documents the institutional distortions that keep investors from pricing climate-related risks completely. These distortions include the short time horizon of large institutional investors, which can impair monitoring activities and create moral hazard; principal-agent problems between such investors and their agents, which ultimately reduce returns; network effects, which limit the exposure of any one investor to climate risks without appreciably reducing funding to a climate-exposed sector; and the effect of fiscal transfers, which may reduce adaptive behavior in the wake of a climate shock. Such distortions can have secondary effects, such as a substitution to more fully insured assets, with a less direct relationship to climate change. Banks, which seem to have over-performed in the wake of climate events, may be particularly susceptible to these dynamics.

These institutional factors suggest that researchers should place a special focus on the geographic region rather than focusing exclusively on the investor, the consumer, or the financial intermediary. Different regions represent different portfolios of assets—the physical infrastructure, real estate, firms, and people, which allow it to produce, collaborate, and compete. Each element of this portfolio may have different exposure to climate change. A region's buildings may be more exposed to sea-level rise or more frequent hurricanes, and its bridges and highways may have a higher baseline level of decay. Its firms may be in industries likely to struggle in a world experiencing climate change—and those firms, and their employees, may be more able to migrate elsewhere as conditions deteriorate. Above all, different regions may bring different financial resources to those challenges from their tax base to their credit rating, to their eligibility for intergovernmental transfers. These resources will allow them to reduce their exposure to climate-related risks or prevent them from doing so. This, in turn, creates a feedback effect on the value of the region's portfolio. The economic story of climate change—and indeed, the financial on—may be less a story of investors and financial markets than a story of states, cities, and other local governments.

2 Is climate change risk quantifiable?

There is a growing literature on climate-related uncertainty in economic decision-making. Much of this literature focuses on the social cost of carbon (SCC), but there are clear implications for the efficiency of financial markets. In this section, we survey literature on the probability distribution of climate risk; sources of uncertainty, including modeling uncertainty and ambiguity; and extensions to cost-benefit analysis and policy evaluation.

2.1 The probability distribution of climate outcomes

Pindyck (2021) [164] argues that climate change is characterized by a double layer of uncertainty including (i) the degree of "climate sensitivity" and (ii) the relationship between economic outcomes (and by extension, asset values) and climate phenomena. Climate sensitivity is the degree to which the temperature will change for a given amount of carbon in the atmosphere, and this sensitivity is far more difficult to estimate than the extent of carbon in the atmosphere. This is because there are complex and potentially tightly-coupled feedback effects between an ever growing list of factors that govern this relationship.[2]

Regarding the link between climate change and economic outcomes, direct impacts could in principle be positive or negative, although the scale and scope of structural change could be unprecedented. Climate change, by forcing adaptation, will likely lead to innovation and an upgrading of existing infrastructure, buildings, and equipment. Migration will likely lead to a reallocation of the population across the globe, and new practices commensurate with sustainability. Against this optimistic set of outcomes, we must reckon with the destruction of capital, loss of homes, barriers (implicit, explicit, and pecuniary) to migration, stresses on communities, heightened inequality, belief structures that question climate change, resistance to change, and loss of GDP. Peters et al. (2017) [162] provide an approach to integrate technological change and adaptation into a nested structure of indicators designed to assess global emissions pathways.

2.1.1 The DICE Model approach

This complex social, political and economic process is expressed as a *damage function* in the Dynamic Integrated Climate-Economy (DICE) model, the integrated assessment model (IAM) approach used by most economists to quantify the impact of climate change (see Nordhaus, 2017 [155], for the most recent iteration). The damage function relates temperature rise to reduced economic output using an arbitrary function that is designed to be Hicks-neutral, leaving the optimal mix of capital and labor unchanged. The damage function acts as a tax on output:

$$Q(t) = \Omega \cdot A(t)K(t)^{\alpha}L(t)^{1-\alpha}. \tag{1}$$

where $Q(t)$ is output at time t, $\Omega(t)$ is the damage function, or the fraction of output destroyed by climate damage at time t, $A(t)$ is technology, $K(t)$ is the capital stock, $L(t)$ is labor force, and α is the Cobb-Douglas production parameter (the share contribution of capital to output).

[2] For example, it has only recently been recognized that soot from climate-induced wildfires may land on glaciers, reducing their albedo and increasing the amount of solar energy absorbed by the earth.

The damage function in the most recent iteration of the DICE model (DICE-2016R2) is given as:

$$\Omega(t) \quad = \quad [1 - D(t)] = 1 - \Psi_t T(1) - \Psi_2 T(t)^2. \tag{2}$$

where $D(t)$ is quadratic in $T(t)$, the globally averaged change in temperature, and the Ψ parameters are determined by fitting the quadratic to data from existing damage studies.[3] Given that the damage function is arbitrary (polynomials of other degrees are not ruled out in principle) and that data are necessary limited, it is not surprising that the damage function is one of the most controversial aspects of the DICE model (see, e.g., Botzen and van den Bergh, 2012 [42]).[4]

2.1.2 The Macro-empirical approach

An alternative approach is to look at historical relationships between changes in temperature (and other climate variables) and economic output. Schenkler and Roberts (2009) [173] and Dell, Jones, and Olken (2014) [71] both estimate the effect of temperature on economic output to shed light on the likely impact of a two degree Celsius increase in temperature. Schenkler and Roberts use U.S. county-level yields for corn, soybeans, and cotton to investigate the effects of temperature distributions both within each day and across days. They find that crop yields increase with temperature up to a threshold temperature, but that once the threshold is crossed, yields implode. This approach, which quantifies one specific microeconomic vector through which temperature directly affects GDP, stands in contrast to the approach taken by Dell et al., which focuses on years with high temperatures in less-developed countries as an identification strategy.[5] Addoum, Ng, and

[3]The damage function has changed significantly since early versions of the DICE model. Initially, the damage function was given as:

$$\Omega(t) \quad = \quad \frac{D(t)}{1 + D(t)} \tag{3}$$

to ensure that damages never exceeded output. This formulation was dropped when it became clear that projected damages did not lead this ratio to approach unity.

[4]For example, Nordhaus (2017) [155] uses 27 studies that contained 36 usable damage estimates as data points with ad hoc adjustments to account for omitted sectors and non-market and catastrophic damages.

[5]For other papers on the link between macro growth and temperature, see Burke, Hsiang, and Miguel (2015) [48], Burke, Davis, and Diffenbaugh (2018) [47], Colacito,

Ortiz-Bobea (2019) [3] instead use panel data from the United States to look at the impact of location-specific transitory temperature shocks on establishment sales and productivity. They find no effect on sales and productivity on average.

Kiley (2021) [127] moves beyond average effects of climate change to look at how fluctuations in temperature affect the distribution of growth, including the tail risk of a severe contraction in GDP. Using quantile regressions, Kiley finds the impact of temperature on the lower decile of the growth distribution is 50 percent larger (in absolute value) than the effect on mean growth. Consequently, he concludes that growth-at-risk due to climate-induced higher temperatures is large.

While researchers can use historical episodic temperature fluctuations to avoid modeling the various interactions that underly a damage function, extrapolating the results is tricky. First, it is unclear how much adaptation will result from a one-time weather shock. In principle, the empirical design could include a learning function that allows agents to update their assumptions about the distribution and severity of future temperature shocks. With a gradual rise in temperature, agents would likely broaden the range of actions they might take, including migration, investment, and output mix. Second, survivorship bias in these and similar studies risks the possibility that firms have either fallen out of the dataset (by failing because of the shock) or that firms would have entered the market but for the shock. Both types of firms potentially end up missing from the analysis. Third, historical data might not account for threshold effects.

2.1.3 Allowing for fat-tailed distributions

Threshold effects skew the probability distribution of climate outcomes. In his review of the 2007 Stern Review of the Economics of Climate Change (Stern, 2007) [186], Weitzman (2007) [195] suggests that the standard risk analysis method of truncating tails of the distribution is incompatible with the thick tail of negative potential climate outcomes.[6] This was also an explicit concern of Mastrandrea et al. (2011) [144], who developed the guidance on how the authors of the Intergovernmental Panel on Climate Change

Hoffman, and Phan (2019) [60], and Desmet et al. (2021) [74].

[6]Truncation is most justified when the economic salience of an outcome drops faster than the probability of that outcome—the opposite of the fat-tailed case of climate change.

(IPCC) Fifth Assessment Report should treat uncertainty.[7] As a result, the likely distribution of climate outcomes is itself subject to a probability distribution. The probability of the shape of the distribution adds an additional element to the standard approach of estimating the *probability of default* (outcome) as a draw from a known distribution and the *loss given default* (severity) as determined by known conditions.[8]

Similarly, Wagner and Weitzman (WW) (2018) [192] emphasize the difference between uncertainty about the expected value of global warming—specifically, Equilibrium Climate Sensitivity (ECS)—and uncertainty about the likelihood of an extreme event. Reviewing the Cox et. al. (2018) [67] results that constrain the ECS to lie within $2.2 - 3.4°$C with a 66% probability, WW point out that the assumed shape of the probability distribution is decisive. Assuming a log-normal or pareto distribution, while preserving every other aspect of Cox et. al.'s analysis, increases the probability of exceeding 4.5°C by over 5 to over 40 times, respectively. WW point out that tail behavior is hard to determine empirically given that it deals with extreme events, but even so a normal distribution tail is unlikely to be accurate. Many physical phenomena follow power-law distributions, and various studies indicate that the ECS has a thick-tailed distribution (e.g., Baker and Roe, 2009 [16]; Roe and Baker, 2007 [170]; Weitzman, 2009 [194]). An important robustness check for future climate modeling will be to determine sensitivity to different probability distributions (e.g., log-normal or pareto).

The impossibility of resolving the shape of the climate distribution due to the rarity of extreme events has unfortunate implications for Bayesian analysis, the obvious alternative approach to uncertainty. The accumulation of data over any reasonable time-frame will likely be inadequate to sufficiently update priors to the true distribution. Although fat tails may reflect feedback effects, we can consider feedback effects to be a distinct additional factor that

[7]The guidance to lead authors of the IPCC assessment report states, "Sound decision-making that anticipates, prepares for, and responds to climate change depends on information about the full range of possible consequences and associated probabilities. Such decisions often include a risk management perspective. Because risk is a function of probability and consequence, information on the tails of the distribution of outcomes can be especially important. Low-probability outcomes can have significant impacts, particularly when characterized by large magnitude, long persistence, broad prevalence, and/or irreversibility. Author teams are therefore encouraged to provide information on the tails of distributions of key variables, reporting quantitative estimates when possible and supplying qualitative assessments and evaluations when appropriate."

[8]Adrian, Covitz, and Liang (2014), [4].

can magnify the likelihood of extreme outcomes.[9] Roe and Baker (2007) [170] explore the role of feedback effects on climate sensitivity in a highly cited study.

2.2 Model uncertainty: Beyond risk

Other sources of uncertainty are important to consider as well. Barnett, Brock, and Hansen (BBH) (2020) [20] explicitly introduce parameters into a dynamic structural model that address the following different elements of uncertainty:

- *Risk – uncertainty within a model*: uncertain outcomes with known probabilities
- *Ambiguity – uncertainty across models*: unknown weights for alternative possible models
- *Misspecification – uncertainty about models*: unknown flaws of approximating models

Even though most risk assessment has developed around the first element, many challenges remain in this area including how to deal with long-term impacts that fall outside of agents' planning horizons and potential behavioral feedback effects such as animal spirits and other indeterminacies.[10] BBH take a standard approach and introduce random draws (shocks or impulses) from assumed distributions for key variables.[11]

In a less standard approach, BBH evaluate uncertainty which climate model is correct given that each model specifies a different set of rules and information sets. BBH define ambiguity as uncertainty over what weights

[9]See Sornette (2006) [184] for a primer on the mathematical techniques used to model physical climate risks, and Bruns et al. (2020) [45] for an application to the role of the ocean in climate change using multi-co-integration techniques.

[10]For example, international finance has a long tradition of precipitous behavior caused by subtle changes in expectations of long-run outcomes as in the literature on central bank sovereign currency crises (see, for example, Krugman (1979) [136] and Flood and Garber (1984) [87]).

[11]BBH assume a simple linear relationship between temperature and accumulated emissions that allows them to use cumulative emissions, and not temperature, as the relevant state variable. There is uncertainty over the true value of climate sensitivity, however, as well as in the functional form of damage function.

should be applied across a given set of models. They propose using a robust Bayesian approach to explore the sensitivity of the weighted outcome to subjective inputs, as in Hansen and Sargent (2007) [104]. Strikingly, this approach becomes restrictive even in a relatively simple dynamic model using the standard assumptions of a representative agent, "AK" technology with exogenous productivity growth, and other common macroeconomic simplifications.[12]

BBH point to the degree of misspecification as a third type of uncertainty. To explore the implications of misspecification, BBH employ distortionary penalties, drawing from robust control theory and the applied probability concept of relative entropy. However, even in this less restrictive approach, misspecification uncertainty must still be well-behaved to avoid degenerate outcomes.

The key contribution of BBH is its demonstration of the large impact of these various types of uncertainty on the results of dynamic programming exercises. The differences are enormous, and they can often be driven by nonintuitive emergent properties of the models. Much remains unknown, however. The treatment of uncertainty, while transparent, remains highly formalized and abstract. The computational penalty for adding complexity is high, and the model can only introduce a limited amount of the full spectrum of uncertainty.

2.3 Agent-based approaches

Another complication to quantification is that analysis of climate impacts must also account for technological change and aggregation, heterogeneity and distributional implications, *inter alia*, as discussed by Farmer et al. (2015) [84]. After reviewing the merits of dynamic stochastic general equilibrium models, Farmer et al. describe how agent-based modeling (ABM) can reconcile all the necessary requirements. As available computational power increases, ABM is becoming increasingly within reach. However, research into ABM fits better into a medium-term research program given the significant amount of work needed to make these models tractable, although initial efforts are appearing.

An example of an early agent-based approach is Lamperti et al. (2017)

[12]See Ait-Sahalia et al. (2021) [6] for another implementation of a probability distribution across possible models.

[141], who use an agent-based IAM composed of heterogeneous firms. They allow for increasing temperature to impact labor productivity, energy efficiency, the capital stock, and firm inventories. Aggregate damage is an emergent property of out-of-equilibrium interactions of these heterogeneous agents who form expectations using bounded rationality. The authors tout the ability of the model to account for many micro and macro empirical regularities in both economic and climate dynamics. Ultimately, the results are heavily influenced by uncertainty involving tipping points and irreversible trajectories that generate intuitive frictions in the allocation of resources. A transition involving the reallocation of resources and demand in which there are frictions can be much more costly than when reallocation is frictionless. As with Daniel, Litterman, and Wagner (2018) [70], discussed below, this model therefore generates much larger climate change impacts than the standard IAMs and likewise implies urgency in addressing global warming.

Lamperti et al. (2021) [140] extend the model to account for the impact of three climate policies on financial stability. A key tenet of economic policy is that n policy targets typically require n policy tools to achieve them. Following their analysis, Lamperti et al. (2021) imply three objective-tool pairs as follows:

1. **Objective**: Improve resilience of the banks to climate shocks – **Tool**: Capital buffer
2. **Objective**: Reduce risk of large price dislocations – **Tool**: Disclosure requirements/credit rating adjustments
3. **Objective**: Promote economic growth by channeling financing towards strong climate-proof sectors – **Tool**: Partial credit guarantees

All three policies combined are necessary and sufficient for achieving these goals. For example, a capital buffer on its own might end up reducing credit to the economy and slowing growth. The partial credit guarantee can counter that chilling effect. However, climate buffers alone are too blunt an instrument to effectively improve resilience without the introduction of enhanced disclosure. Partial credit guarantees also suffer from bluntness in the absence of disclosure, but also do not facilitate a sufficiently rapid evolution of bank balance sheets towards greater resilience.

One interpretation of these results begins with the view that any adjustment to bank balance sheets can be sustained if it is sufficiently gradual (within provisioning capacities). Analogous to automobile brakes, a driver should depress the pedal gently and early enough to achieve the necessary adjustment in velocity. Spreading the braking actions across three separate policy tools (with the attendant sequencing and coordination considerations) is likely to reduce the load any given tool must bear, allowing for less precipitous action being required. For example, the impact of credit downgrades on bank equity will be lessened if banks can point to the fact that they are holding greater capital against those risks.

2.4 Cost-benefit analysis and policy evaluation

Despite uncertainty about climate impacts, policy must still be made. Consequently, a large and rapidly growing literature is dedicated to measuring the SCC.[13] We will not attempt an in-depth review of that literature here, except to note its necessity for US policymaking (US climate policies must undergo cost-benefit analysis), and to note that cost-benefit analysis (which requires the use of an SCC) is a fraught enterprise.[14]

To make decision-making under uncertainty tractable, Daniel, Litterman, and Wagner (DLW, 2018, [70]) allow uncertainty to influence an agent's willingness to independently substitute across time and states of nature using the Epstein-Zin (EZ) class of utility functions. EZ preferences are not amenable to analytical solutions, so DLW do two things to reduce computational requirements. First, uncertainty about the ensuing direction of climate change is resolved at five discrete dates, with 2015 being the first and 2400 the last. Second, uncertainty is binomial at each of these dates, with a possible "up" or "down" state. The path of uncertainty into the future is therefore a sequential outcome of five up-or-down states, e.g., "uduud" or "ddddu". They find that, rather than a small near-term cost of carbon as implied by the DICE model, their model implies a high initial cost of carbon that declines only gradually. This turns the familiar metaphor of "policymaker as supertanker captain" on its head. Rather than taking small and measured initial policy corrections, the policymaker should engage in urgent and bold action

[13]The most comprehensive effort is being undertaken by the Energy Policy Institute at the University of Chicago.

[14]In 1996, the White House issued an executive order stressing the importance of economic analysis in federal policymaking that led to Office of Management and Budget (OMB) Circular A-4 in 2003. This circular requires cost-benefit estimates for federal agency rulemaking decisions.

at the outset, not least to determine if the policy measures are sufficiently potent.[15]

For policymakers, uncertainty poses two key challenges. When should specific actions be taken, and what is the scope of those actions? The first question relates to the valuation of policy options, while the second relates to the degree of market efficiency in addressing climate risks. Building on the approach that he pioneered with Dixit [77], Pindyck (2000) [165] applies dynamic stochastic programming tools to the problem of global warming. Pindyck's model identifies separate real options values to unrecoverable sunk costs (which makes waiting desirable) and irreversible sunk benefits (which urges immediate action). Waiting may allow for good surprises or better and cheaper solutions to appear but waiting also means a larger cumulative stock of carbon that may cross a critical threshold. Crossing that threshold may lead to runaway climate change depending on the convexity of the (true) damage function.

The integration of these two options values into a tractable model clarifies the stakes, but as Pindyck (Pindyck, 2021 [164]) acknowledges, the necessary simplifications—e.g., assuming efficient markets, the existence of a well-behaved stochastic process—make the exercise an elucidation of principles rather than a means of quantifying costs and benefits. Pindyck (2021) suggests that climate change's fundamental uncertainty cannot feasibly be made precise in any model. This conclusion fits well with that of Kay and King (2020) [124] who argue in favor of a detailed scenarios analysis in lieu of precise but poorly premised quantitative models when developing policy under uncertainty. Alternatively, Pezzey (2018) [163] argues for an approach based on marginal abatement costs found by modeling low-cost pathways to socially-agreed, physical climate targets. This is similar to the "cost effectiveness" approach taken in the development literature, where there is difficulty in specifying the benefits of a policy and hence in defining optimality.[16] In-

[15] The supertanker metaphor cautions that large adjustments to the rudder lead to oversteering and ultimately instability given the lags involved in steering a supertanker. However, advising the captain to make small corrections requires that we understand well the impact of the ships wheel on the rudder, and consequently the impact of the rudder on the ships direction. DLW point out that this is a poor description of managing climate change.

[16] In development, this is primarily for ethical reasons given that the benefit of some development projects (e.g., provision of potable water) would require the delicate issue of quantifying the value of a human life (or alternatively "quality-adjusted life years" (QALY's)). This ignores the various "capabilities" benefits stressed by Amartya Sen (1999)

deed, the IPCC's 3rd Assessment Report made a distinction between full cost-benefit analyses, or *policy optimization models*, and analyses of the cost effectiveness of alternatives of meeting specific targets, referred to as *policy effectiveness models.*[117] Harvey et al. (2018) [105] provide a comprehensive overview of three classes of policies that can be subjected to cost-effectiveness analyses: performance standards, economic signals, and support for research and development. These policy classes are not substitutes for one another, but rather each should be used sequentially in promoting transition to a zero-carbon economy. For this reason, cost-effectiveness analysis is likely to depend heavily on context and, for technological development, the point in the lifecycle a technology has reached.

The outcome of a cost-benefit analysis often depends on the discount rate applied to future costs and benefits. Given the time-scales involved in climate considerations, the choice of discount rate has been heavily debated. Weitzman (1998) argues that far-distant outcomes should be discounted at the *lowest possible* interest rate.[196] Showing that the low discount rate reached in the Stern Review [186] is not unreasonable, Weitzman (2007) [195] points out that "...the choice of appropriate interest rate is itself extraordinarily sensitive to seemingly arcane modeling details like the value of the climate-change investment beta and how the asset-return puzzles are resolved." (p. 715) He goes on to argue that resolving the discount rate puzzle is complicated by the greater importance of uncertainty over risk, stating, "...people are willing to pay high premiums for relatively safe stores of value that might represent 'catastrophe insurance' against out-of-sample or newly evolved rare disasters." (p. 715)

Bauer and Rudebusch (2020) [27] make a distinction between *prescriptive* approaches to the appropriate discount rate, which are based on a normative approach, and *descriptive* approaches, which are based on observed financial market prices. Prescriptive discount rates tend to be about 2 percentage points lower than descriptive rates, which has made it hard to reach consensus on the appropriate rate. However, Bauer and Rudebusch show that the 'descriptive' discount rate is arguably declining and converging to prescriptive levels as various global structural economic drivers bring down the steady-state real interest rate. Consequentially, the case for immediate action on greenhouse gas emissions becomes stronger.

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[176].

3 Are markets efficient with respect to climate change?

Valuations that significantly deviate from fundamental values risk sharp price corrections that could impair the solvency of firms or create financial instability. Yet, considering Section 2, is it even theoretically possible for markets to determine a fundamental price? The difficulty of assessing the fundamental value of assets is only compounded by climate change; especially if severe events occur so infrequently that there is no ability to develop the statistical moments (the variances and covariances of returns) needed for asset pricing.

While the literature on asset pricing and climate change has taken different directions because of this challenge, most studies attempt to show that climate-vulnerable assets are priced at a *relative* discount, and this is taken to imply that markets are integrating climate change into asset values. However, market stability depends not just on the existence of a discount, but whether the discount is sufficiently large. Many of the studies discussed below consider an event that should lead to a realignment of the fundamental value of prices. In some cases, there is movement in prices consistent with what we might expect, while in other cases, prices appear to overreact before returning to close to their original levels. Should we view this dynamic behavior as implying that prices are generally efficient subject to temporary displacements? Or does the resemblance to Minsky-like dynamics of booms and busts (triggered by climate events) imply that the theory of asset price bubbles is a better guide to analysis? We will return to this question below.

To make sense of this literature, it is helpful to talk about the three distinct types of climate risks: (i) anticipated but unrealized physical risk (e.g., flooding based on sea level rise; sometimes referred to as chronic physical risk), (ii) reactions to a severe climate event (or, acute physical risk), and (iii) transition risk.

3.1 Chronic physical risk

3.1.1 Real estate markets

That climate change will lead to a steady increase in damage to certain regions over time is not in dispute.[17] Yet, as in the case of Miami coastal real

[17] See, e.g., First Street Foundation (2020) [86], Resources for the Future (2020) [169], and Southeast Florida Regional Climate Change Compact (2019) [89].

estate, there is no clear evidence that real estate prices (particularly coastal real estate) reflect increasing vulnerability. While there is some potential for adaption, real estate is not mobile and of all asset classes it should most unambiguously reflect the impact of rising climate vulnerability.

Using national data on coastal housing markets, Bernstein, Gustafson, and Lewis (2019) [30] find that vulnerability to sea level rise is not capitalized into the price of owner-occupied homes, although there is a large and significant discount of 7 percent for sea level rise exposure for non-owner occupied residences. Murfin and Spiegel (2020) [153] use a different identification strategy (controlling for elevation as distinct from sea level rise by using differences in subsidence and post-glacial land rebound) with national data and find no evidence that real estate prices are affected by projections of sea level rise. Using a difference-in-difference methodology to examine a temporary detailed disclosure of sea level rise risks to a coastal New Zealand community, Filippova et al. (2020) [85] also find little evidence that homebuyers factor in long-term sea level rise risks. Hino and Burke (2020) [108] echo these findings using a large dataset of home across the United States, estimating that floodplain homes in the United States are currently overvalued by $34 billion.

Non-stationarity

Comparing the use of forward-looking and historical data to assess asset price valuations, Severen et al. (2018) [177] examine the bias that a backward-looking methodology might introduce into asset prices. In applying their empirical correction to agricultural land prices, they find that climate change damages based on historical data may understate climate damages by one- to two-thirds.

Segmented markets

There is evidence that the degree to which climate risk is priced differs across types of buyers. Conyers et al. (2019) [62] find that in Miami Beach there is a high correlation between vulnerability and high income and transiency. Given that the very wealthy and the transient are likely less concerned about climate risk, they view this correlation as a reason to fear sudden price adjustments as the sea level rises. Fu and Nijman (2020) [90], who distinguish between primary and non-primary homes, similarly find that high-income households are associated with smaller climate-related price discounts. This segmenting of buyers into groups with different buying motivations and risk tolerances is a potential distortion that could lead to higher market volatility as sea levels rise. Market segmentation is also supported by Ariza [11], who suggests that foreign investors view Miami condominiums as a desirable store of value. The U.S. dollar exchange rate is highly correlated with prices in this segment of the market, suggesting that Miami condominiums might serve as dollar-based hedge against foreign exchange risk. Some non-coastal climate vulnerable areas also have high non-resident ownership. For example, Butsic et al. (2011) [50] use hedonic estimates to analyze potential home price decreases in ski resort communities.

While transiency—defined as an intention for short-term residence—can weaken the responsiveness of real estate prices given the buyer's shorter horizon, the effect can go in the other direction as well. Bunten and Kahn (2014) [46] consider the importance of heterogeneity and suggest that the willingness-to-pay of the marginal household is much higher than that of the average household. The marginal household, "...may have a comparative advantage in coping with local risk or may have built up city-specific capital (both social capital and local knowledge) such that this household effectively faces a higher migration cost for leaving the city." (p. 3) Their analysis employs a compensating differentials model that evaluates the impact of heterogeneity using cross-city spatial equilibrium (see Albouy et al. (2014) [7] for an analysis of the value of climate amenities; and Semenenko and Yoo (2019) [175] for the extension of real estate returns to various moments of the distribution of temperature measures).

Belief heterogeneity

Then there is the impact of beliefs. A foundational paper in linking beliefs to real estate prices that serves as the basis for leading work in climate impacts is Burnside et al. (2016) [49], which develops a search model in which housing price bubbles emerge from belief structures as agents infect each other with optimism or pessimism. Baldauf et al. (2020) [18] use this structure to explain how a community sorted by climate change skepticism may experience bubbles in which home values exceed climate-adjusted fundamental valuations.[18] They confirm that while sea level rise is some-

[18] The authors draw upon data from the Yale Program on Climate Change Communication (Howe et al., 2015 [111]), which provides estimates of the fraction of the population in a county or city who believe in factual statements about climate change.

what capitalized into home prices in communities that acknowledge climate change, prices in climate-skeptical communities do not reflect vulnerability to sea level rise. Undertaking a similar exercise for demand for flood insurance coverage, Ratnadiwakara and Venugopal (2020) [168] find that a one standard deviation decrease in the fraction of adults who believe global warming is happening leads to a 26 percent decrease in the demand for flood insurance. This finding is corroborated by other evidence of links between beliefs and insurance coverage.

Bakkensen and Barrage (2021) [17] use a household survey to examine the impact of beliefs about climate-driven flood risk stemming on mispricing and price dynamics of coastal real estate. In the absence of immediate experience with a climate event, many agents are skeptical of climate change predictions. As a result, they do not ask for a discount on property subject to climate-linked flooding risk. However, the realization of a flood event typically collapses this heterogeneity and leads to a sharp decrease in the price of vulnerable homes. The authors find direct evidence of this heterogeneity in a survey of households located in the coastal and non-coastal zones of a single community and calculate that coastal housing prices exceed fundamentals by 13 percent under a business as usual (BAU) climate scenario. Tellingly, differences in beliefs were more visible across these two zones than within them, indicating significant self-sorting when controlling for the amenities value of waterfront living. The authors therefore demonstrate the value of intra-county and city data on climate attitudes missed by the more aggregated Yale data collected by Howe et al. [111] (see also, Barrage and Furst (2019) [21]). Integrating parameters from their housing survey data with the Yale data, Bakkensen and Barrage project property overvaluation in other cities—finding, for example, a 50 percent overvaluation in Charleston, South Carolina.

Salience

Gibson et al. (2019) [96] examine how beliefs might change in response to various policies or events by examining property transactions in New York City from 2003 to 2017. Using Arrow-Pratt risk aversion and value-at-risk concepts to differentiate changes in beliefs, Gibson et al. examine the impact of increased flood insurance premiums, new floodplain maps, and Hurricane Sandy. All these events led to price decreases, but changes to floodplain maps had the largest impact by far, with agents increasing their estimate of flooding by twice the amount of increase due to Hurricane Sandy. Notably, this increased estimate of risk was still only half of the risk estimated by FEMA. Surprisingly, insurance reform had the smallest impact on beliefs. Among the various factors for which the authors control, they do not find that prices fell because panicking homeowners rushed to place their homes on the market, nor do they find much influence on their reduced-form price results from differences across populations in education, duration of residence, or similar factors.

Giglio et al. (2018) [97] examine the presence of terms including hurricanes or flood zones in property listings to construct a 'climate attention index'. They then analyze how real estate prices are affected by their climate attention index finding that drawing attention to climate risks affects prices. Treuer (2018) [188] recruited various Miami residents to take part in an immersive simulation experiment designed to elicit their awareness and attitudes towards flood risk by portraying fictional events playing out over 35 years. He found that relatively low initial levels of concern gave way to heightened concern and increasing willingness to migrate out of the area if climate change effects worsened.

Botzen et al. (2015) [41] undertake an analysis of how well individual perceptions of climate tail risks align with objective indicators of those risks for floodplain residents in New York City.[19] A key finding is that even though the probability of tail risks (equivalent to PD) is overestimated, potential damage (equivalent to LGD) is underestimated, leading individuals to refrain from investing in protection. With an empirical strategy designed to highlight the presence of various behavioral biases, the authors arrive at several findings: (i) awareness of both probability and potential damage is weakly positively correlated with objective estimates of risks, (ii) direct flood experience has a strong positive relation to this awareness, (iii) awareness and perceptions of flood probability and damage decrease if individuals think that their flood probability is below their threshold level of concern, and (iv) a high level of trust in local authorities reduces perceptions of flood damage (see also Seigrist and Gutscher, 2006 [182]). Their findings call into question whether policies designed to raise awareness and promote accurate information would be effective in helping markets move towards fundamental valuations. By contrast, Muller and Hopkins (2019) [152] find that public flood awareness

[19]Mase et al. (2017) [143] consider these issues for midwestern farmers facing climate risk.

activities heighten the impact that non-local climate shocks (hurricanes and tropical storms) have on real estate prices in high flood risk areas.

However, Brenkert-Smith et al. (2015) [44] show that the correlation between climate change skepticism and efforts at mitigation can be positive in some cases. Working from a survey of Colorado residents living at the wildland-urban interface, they find that disbelief in climate change may nonetheless coexist with strong traits towards self-sufficiency and the impulse to improve and protect one's property. By contrast, belief in anthropogenic climate change is associated with support for climate mitigation policies, but they find no clear association between belief in climate change and direct mitigation actions taken to protect one's property. Taking this bias toward self-sufficiency into account, local resiliency might be underestimated.

3.1.2 Equity markets

Consistent with studies of the impact of flood risk on home values, several studies argue that carbon emission risk is at least partially being priced into equity values. For example, Bolton and Kacperczyk (2019) [39] find that stocks of U.S. firms with higher total CO_2 emissions generate greater returns. This extra return is not dependent on firm size, book-to-market ratios, or other typical factors influencing returns, so they interpret their finding as evidence that shareholders require compensation for this form of climate exposure, but there are many other reasons why these returns might be relatively high. Indeed, the argument that some penalty accrues to high carbon emitters (and flood vulnerable properties) should imply that these firms face higher capital costs, but there is no evidence that this is true.

If we accept the premise that the higher returns identified by Bolton and Kacperczyk represent an equity penalty, a key question is whether the penalty is large enough to capture the entire risk. Hsu, Li, and Tsou (2019) [112] calibrate a general equilibrium asset pricing model to compare the actual pollution premium with its predicted value if firms face transition risk. While future climate regulation will negatively affect the stock price of all firms, the model predicts it will affect high-emission firms' valuations the most. Their empirical method uses a high-minus-low portfolio strategy (or a long-short strategy) to obtain a high-emission pollution premium of around 5.5 percent per annum. As with Bolton and Kacperczyk (2019) [39], they show that these results are robust to a host of fixed effects and other known predictors of premiums. The calibrated quantitative model generates a comparable premium of 4.7 percent, which they argue shows that markets are broadly efficient in the terms of the size of the premium. Some additional results address various other lines of inquiry. In addition, they confirm that some other predicted associations also hold, including that firm-level emissions negatively and significantly predict future profitability; a higher likelihood of shifts in policy regime leads to an even higher pollution premium, and higher emission firms face a higher likelihood of climate litigation.

We now turn to studies that focus more exclusively on the impact of severe weather events and price reactions.

3.2 Acute physical risk

One recurrent theme of the literature on acute physical risk is the tendency of prices to strongly react to a climate shock only to revert towards the original valuation over time. It is tempting to think of the initial price movement as an overreaction, but it is also possible that, as the salience of the climate shock fades, prices lose touch with climate risk and a bubble-like divergence between the price and the (climate-) fundamental value of the asset re-emerges. The non-stationarity of physical climate variables implies that the psychological tendency for reversion to previous asset valuations—which is often based on assumptions that conditions will return to 'normal'—is likely to be misleading. This possibility that price reversion is a divergence away from, and not a convergence toward, the fundamentals is not easily dismissed.

3.2.1 Real estate markets

In a meta-analysis comprising 37 published works and 364 point estimates, Beltran, Maddison, and Elliot (BME, 2018) [28] find that time elapsed since the most recent flood is crucial in understanding the significant heterogeneity in results of the effect of being in a coastal flood plain on home prices. For example, one of the papers included in the meta-analysis, Atreya et al. (2013) [12], found that an initial 25 to 44 percent post-flood home price decrease within a 100-year floodplain disappeared completely within four to nine years depending on the econometric specification.[20] Chandra-Putra and Andrews (2019) [55] find a similar result for Monmouth County, New Jersey.

[20]See also Bin and Landry, 2013 [34]; Bin and Polasky, 2004 [35]; Lamond (2009) [139]; and note the strong contrast with Kousky, 2010 [134].

As an additional consideration, Atreya and Ferraira (2015) [13] argue that the post–flood decline in flooded home values is not solely due to changes in the perception of flood risk (which they call the 'information effect'), but rather actual damage to the homes (the 'inundation effect'). The resulting increase in home values can be attributed to the effect of repairs and restoration. They undertake an analysis that suggests that the entirety of price declines can be explained by damage to homes and that there are no significant price updates to homes that were located in the floodplain but were not affected by flooding. This apparent lack of updating of beliefs should be a matter of concern for policymakers if true. However, Eichholtz et al. (2019) [78] inject a note of caution. In their examination of post-Hurricane Sandy real estate trends in New York, Boston, and Chicago, they find slower price appreciation for properties vulnerable to flooding. Crucially, they show that the price effect is not driven by flood damage and that it is persistent and does not reflect a temporary overreaction that is later reversed. Gallagher and Hartley (2017) [91] complicate the 'inundation effect' hypothesis further in their examination of the impact of Hurricane Katrina on household credit. They find that total household debt declined as homeowners used flood insurance to repay their mortgages as opposed to paying for reconstruction. However, the paying down of mortgage debt may not be by choice. As Gallagher and Hartley point out, lenders must agree on how insurance payments are dispensed, and they may (inappropriately) pressure homeowners to use insurance payments for mortgage reductions.

As a broader caution for researchers studying the effect of flooding on home values, BME [28] point out that (i) there is significant statistical evidence of publication bias, especially for coastal studies, and (ii) many coastal studies included in their meta-analysis did not adequately control for the amenities value of living close to the coast.

3.2.2 Equity markets

Alok, Kumar, and Wermers (2019) [9] find evidence that asset prices similarly rebound after falling initially in response to the impact of a severe climate shock. Identifying salience bias as the key mechanism, they argue that direct experience with the event by fund managers within 100 miles of the disaster zone leads these managers to underweight disaster zone stocks relative to their fundamental value. Fund managers farther than 100 miles from the zone maintain steadier valuations to which prices tend to converge in the ensuing two years after the event. Alok et al. demonstrate that a long–short strategy that exploits the overreaction of local fund managers generates a significant DGTW-adjusted return over the ensuing two years. In a similar vein, Choi et al. (2020) [58] show that retail investors sell carbon-intensive firm stocks during warm weather events, even when returns on those stocks are unlikely to be affected. The divergence between fundamentals and collective beliefs introduces a type of 'climate animal spirits' in which loose associations with severe weather events can translate into coordinated price shocks.

However, not all studies find that agents react sharply to climate news. Addoum et al. (2019) [3] explore whether and how quickly sell-side analysts integrate the impact of extreme temperature events on company earnings into their earnings forecasts. They first establish that over 40 percent of firms will face changes in earnings should they experience an extreme temperature event, with some firms gaining even as others are harmed. In principle, sell-side analysts could respond by making intra-quarter adjustments to earnings forecasts in response to extreme events. However, Addoum et al. find no evidence of this, even though many affected firms' forecasts are adjusted for the temperature shock by the end of the financial quarter.

Kruttli, Roth Tran, and Watugala (KRW, 2021) [137] undertake an analysis of extreme weather uncertainty that takes advantage of uncertainty in the track of hurricanes to separate out incidence uncertainty—or the probability of getting hit, which can be read from predicted storm paths released by NOAA—from the impact uncertainty, which is uncertainty of how severe the shock will be once hit.[21] To measure risk, KRW use the implied volatility of stock options. At the inception of a hurricane in the Atlantic, and when its path is still uncertain, many public companies will lie within the forecast landfall range, and this has a measurable impact on implied volatility. Once the hurricane makes landfall, incidence uncertainty disappears, and impact uncertainty is all that remains. Taking the difference between the two allows for incidence uncertainty to be calculated. KRW confirm that idiosyncratic risk increases once it becomes known that a company is in the path of a hurricane.

KRW use this framework to explore the baseline efficiency of markets in evaluating climate risk prior to the realization of hurricanes by focusing on the volatility risk premia (VRP), which is the difference between the option-

[21] These are analogous to financial risk frameworks that emphasize probability of default separate from loss-given-default.

implied volatility and the subsequent realized volatility of the underlying stock over the remaining life of the option. If markets are efficient, the VRP should not differ significantly between hurricane-affected and non-affected firms. However, KRW show that the VRP is significantly lower for hurricane-affected firms than for non-affected firms, implying that realized volatility is much higher than anticipated under the contracts. Yet KRW also uncover evidence that this inefficiency may not persist, finding that the underreaction of option prices becomes smaller after Hurricane Sandy in 2012.

Moreover, the design of new portfolios designed to hedge climate risks may also lead to improved market efficiency. Engle et al. (2019) [82] discuss how these temporary price discrepancies can lead to opportunities to hedge risk. They build a hedging portfolio using textual analysis of newspapers to identify innovations in climate change views as a proxy for climate vulnerability. This portfolio construct is shown to be a successful hedge of climate risk using various out-of-sample performance tests.

3.2.3 Banks

Sharp reaction and reversion also appear in bank pricing of loans to firms that are highly vulnerable to severe weather events (e.g., hurricanes, wildfires, or floods) as examined by Correa et al. (2021) [64]. The authors find that in the wake of a severe weather event, banks initially raise lending rates to borrowers vulnerable to a similar event (consistent with a salience bias), but rates tend to converge again over time. The authors interpret the increase in lending rates as an "updating" of beliefs, suggesting a Bayesian process at work. But it is hard to understand why such updating would be subject to decay. Nonetheless, there is something unique about climate versus non-climate related disasters. Borrowers with indirect exposure to *non-climate* disasters (which the authors identify as earthquakes, tornadoes, and winter weather), do not experience interest rate adjustments, presumably because of greater stationarity in the frequency of these events.

3.3 Transition Risk

Climate-related transition risk is a part of the structural transformation that households and firms contend with on a regular basis. Firms and even entire industries rise and fall according to technological developments, shifts in relative productivity growth, and the dictates of income elasticities of demand.

What distinguishes concerns about climate-related risks is the potential scale, scope, and rapidity of the foreseen structural economic changes. Given the degree to which countries must reduce emissions to achieve net-zero targets, the scale of adjustment is enormous. Moreover, most industries are directly or indirectly reliant on carbon-emitting production techniques, so the scope of industries affected is large as well. However, it is the rapidity with which changes must be made to prevent global temperature from exceeding targets set by COP26 that has generated the most concern about the financial system's ability to handle transition risk and about whether prices accurately reflect these risks.[22]

3.3.1 Equity markets

One influential application of the potential of market efficiency to accurately gauge climate risk is Bansal, Kiku, and Ochoa (BKO, 2016) [19], who develop a model based on infinitely lived rational agents to assess how long-term climate risk should be capitalized into asset prices. Building on Epstein-Zin preferences, which allow for both state-contingent and intertemporal risk aversion, they demonstrate that an increase in current emissions should impact asset prices through two channels: (i) the impact of temperature fluctuations on future consumption (the cash-flow channel) and (ii) the impact of temperature on future risk (the discount-rate channel).[23] The model allows for calculation of a "temperature beta," that is, the change in asset returns for a temperature shock. A temperature risk premium can be calculated by combining the temperature beta with the (negative) market price of temperature risk.

There are a few implications of this modeling approach. First, given that agents are assumed to rationally anticipate climate disasters, these disasters have no effect on the ex-ante mean of log consumption growth, only its variation. Second, the distribution of future consumption growth is negatively skewed and fat-tailed given the nature of climate risks. The model is thus inherently nonlinear and numerical methods are required for its solution. Third, most of the calculated risk premium is compensation for a broad range of long-run risks, with only a modest fraction due to climate risks. Fourth,

[22] See CFCMA-NGFS (2021) [59]. Blackrock (2016) [37] provides a compelling case that climate transition risk, among other risks, has yet to be fully priced into asset values.

[23] See Karp and Rezai (2017) [123] for an overlapping generations (OLG) modeling approach.

because agents are infinitely lived dynasties, they do not suffer from Carney's *tragedy of the horizon*.[24]

To apply the model empirically, BKO measure the impact of temperature on GDP by using forward-looking equity prices, rather than historical growth rates (as in Dell et al., 2012, [72]; note the similarity to the approach taken by Severen et al. (2018) [177]). The authors make use of sectoral differences in climate exposure to estimate the price of temperature risks primarily by considering the ease with which production could take place in hot and humid environments. Sectoral portfolios assumed to have a high sensitivity to climate include mining, oil and gas extraction, construction, transportation, and utilities. Those with a low sensitivity include manufacturing, wholesale, retail trade, services, and communications.[25] Data are sampled at an annual frequency and span the period 1934–2014.

Sectoral temperature betas are estimated by regressing excess portfolio returns on temperature variations while controlling for market and economic growth risks:

$$r_{i,t}^{e} \;=\; \bar{r}_i + \beta_{\Delta T,i}\left(\Delta \bar{T}_t^{K}\right) + \beta_{M,i}\left(r_{M,t}^{e}\right) + \beta_{C,i}\left(\varphi_{c,t}\right) + u_{i,t}.$$

where $r_{i,t}^{e}$ is the excess return of portfolio i, $\bar{r}_i$ is the risk-free interest rate, $\Delta \bar{T}_t^{K}$ is the de-meaned change in K-year moving-average trend in temperature, $r_{M,t}^{e}$ is the excess return of the market portfolio, and $\varphi_{c,t}$ is the innovation in a smoothed aggregate consumption growth that proxies for variations in macroeconomic growth. Both the market beta, $\beta_{M,i}$, and the consumption beta, $\beta_{C,i}$, are well-known elements of the consumption-based CAPM framework. What is novel here is the temperature beta, $\beta_{\Delta T,i}$. A shock to temperature generates a persistent effect on the ability of a portfolio-specific investment to produce a (consumption-based) return that should be immediately reflected in the excess return of the portfolio. By allowing for different horizons for K (from 1 to 10 years), BKO separate out short-run fluctuations from low-frequency changes (where the average temperature over ten years is used) to capture these persistent effects.

[24] In a 2015 speech, Mark Carney, the governor of the Bank of England, pointed out that we cannot rely on current actors, whose decision horizons are likely to be unaffected by climate change, to act commensurate with the interests of future generations on climate issues. See Carney (2015) [53].

[25] This focus on the supply side and the ease of production in hotter climates is important, but omits the important role that certain sectors will play in adapation. As difficult as it may become to *produce* construction and utilities, demand for these sectors' output will surely rise sharply as the climate changes.

Pankrantz, Bauer, and Derwall (PBD, 2019) [158] demonstrate that extremely high temperature events negatively affect both revenues and operating income in ways that market analysts did not anticipate. PBD test analysts' understanding of the implications of extreme heat for specific firms by reviewing whether revenue and income forecasts were adequately updated in response to severe heat events (prior to earnings announcements). PBD point out that "exogenous year-to-year changes in firms' heat exposure should not be systematically related to announcement returns if investors incorporate information on temperatures in their expectations on performance prior to the announcement." (p.6) Yet they do find that the announcement of returns matter, becoming increasingly negative when firms are exposed to larger extreme heat events. PBD interpret this as a sign of market inefficiency, although it is important to note that this finding relates primarily to non-U.S. firms and not the United States, for which they find no effect of abnormal temperatures on sales and productivity.

Hong, Li, and Xu (2016) [110] also find evidence of market inefficiency using international data. Focusing on the impact of drought on food production, they show that a portfolio that shorted food-sector stocks in drought-stricken countries and was long in food-sector stocks in drought-free countries would have produced a 9.2 percent annualized return from 1985 to 2015. The authors provide evidence that climate surprises are driving this premium by noting that the premium was larger for drought-affected countries where there was not much history of droughts prior to 1980.

Kumar, Xin, and Zhang (2019) [138] find that stock returns are sensitive to abnormal temperature changes. Long–short portfolios return a statistically-significant, risk-adjusted 3.6 premium for the most sensitive firms, but only if the lag between portfolio formation and estimating climate sensitivity is short (less than two months). High-frequency arbitrage opportunities appear responsible for the abnormal returns, but these opportunities disappear within a few months. Climate sensitivity is also shown to predict lower future firm profits, demonstrating that fundamentals are affected. On balance, the authors argue that their empirical exercise demonstrates mispricing, albeit only in the short run.

Other studies support the hypothesis that investors price in at least some transition risk. El Ghoul et al. (2016) [79] find that manufacturing firms across 30 countries that invest in corporate environmental responsibility have a lower cost of equity capital. Chava (2014) [56] finds that stocks associated with hazardous chemicals, substantial emissions, and climate change concerns have a higher cost of equity and debt capital, where the implied cost of capital is imputed from analysts' earnings estimates. Moreover, these firms have lower institutional ownership, and loan syndicates are less likely to provide them with funding. Ginglinger and Moreau (2021) [98], using data that measure forward-looking physical climate risk at the firm level, find a similar result. Firms facing greater climate risk have lower leverage due to both a reduction in their optimal leverage (a demand-side effect) and a reduced willingness on the part of lenders to fund them (a supply-side effect).

3.3.2 Banks

Ivanov et al. (2020) [121] look at the efficiency with which banks price lending in the presence of transition risk using a discontinuity in the embedded free-permit threshold of the federal Waxman-Markey cap-and-trade bill and the geographic restrictions inherent in the California cap-and-trade bill. The discrepancy between these bills leaves certain firms vulnerable to transition risk that banks have seemingly identified, resulting in those firms facing shorter loan maturities, lower access to permanent forms of bank financing, higher interest rates, and greater dependence on shadow banks in their lending syndicates.

3.3.3 Municipal bond markets

Painter (2020) [157] looks instead at the municipal bond (muni) market, which helps to control for the fact that, unlike corporations, cities cannot relocate away from physical climate risk. Painter uses heterogeneity in term structure of munis to estimate the pricing of climate risk. Long-term bonds issued by climate-vulnerable municipalities should face higher issuance costs than those issued by non-affected municipalities, but not for short-dated bonds. Painter finds that a 1 percent increase in climate risk leads to an increase of 23.4 basis points in issuing long-term bonds, adding up to an increase in annualized issuance costs of $1.7 million for the average county. No such premium is found to exist for short-term bonds, consistent with the motivating hypothesis.

By contrast, Goldsmith-Pinkham et al. (2021) [99] find that this risk-adjusted premium is substantially reduced when adjusting for the implied volatility in municipal cash flows.[26] They find that a 1 standard deviation

[26] Goldsmith-Pinkham et al. discuss the complicated chain of causation that municipal

(approximately 10 percentage point) increase in the fraction of properties less than six feet above sea level is associated with a 5 basis point increase in municipal bond spreads (equivalent to 9 percent of the average spread in the sample). Using a credit risk model, the authors determine that their figures are consistent with a 2 to 5 percent reduction in the present value of municipalities' underlying cash flows, a proportional increase of 1 to 3 percent in the volatility of cash flows, or some combination of the two. Accordingly, they find that Painter's estimated elasticity of long-term bond yields is likely significantly overstated and that municipal bond markets have not been as responsive to sea level rise risk. Furthermore, they conclude that adaptation measures to reduce sea level rise (SLR) risk can benefit investors and reduce municipal borrowing costs today in contrast to Painter, where adaptation measures would only have very long-term effects.

3.3.4 Investor preferences

Considering the practical and non-pecuniary benefits of supporting climate-forward investments, Environmental, Social, and Governance (ESG) criteria have been designed to inform climate-conscious investors. Although in principle ESG preferences can be applied to all assets, it is easiest to evaluate their impact on corporate bonds. In equilibrium, idiosyncratic investor demand for a given type of bond should increase its price relative to a given stream of coupon payments. As a result, risk-adjusted returns should be lower. If investors have a preference for ESG-adaptive activities, we expect that they would pay a premium, or "greenium," to purchase bonds that finance these activities for a given stream of coupon payments.[27] The issuing firm, on the other hand, is able to issue a green bond at a lower yield relative

bondholders must evaluate in pricing bonds in the case of sea level rise. Such investors know that sea level rise will reduce home values and therefore local real estate taxes. The time horizon over which that will occur is uncertain not only due to the science, but due to forward-looking behavior by coastal residents which could bring the real estate losses forward in time. There is also the question of how highly the municipal government will prioritize bond repayments relative to other expenditures, and whether sea level rise will complicate the orderly flow of repayments by increasing the volatility of government revenues. The challenges to the analyst are even more daunting and include disentangling the sea level rise risk from time-varying economic risk; translating estimated changes in credit spreads back into changes in revenues available to fund the bonds.

[27]Note that the greenium measures the yield spread between a conventional bond and a green bond *for the same issuer* and as such controls for transition risk.

to its conventional debt, leading to an interest rate saving.

Lau et al. (2022) [142] develop a theoretical model to relate the size of a bond's greenium to investor preferences, issuing cost differentials, and inherent benefits of issuing a green bond (including reputational effects). Using a triplet-based matching strategy to compare conventional and green bonds, they estimate the greenium for both individual bonds and for green bonds overall (considering market liquidity and volatility). Their results confirm a robust greenium, but also that the greenium is small on average, equal to about 1 basis point. Their results also show that the greenium varies by sector and by whether a third party certifies the greenness of the bond. The higher greenium when a third party is involved suggests that investors discount bonds suspected of being associated with "greenwashing." See their Table 5 for a comparison of greenium estimates in the literature.

Likewise, Pastor et al. (2021) [160] frame the investor decision as choosing portfolio weights across the risk-free asset, the market portfolio, and the ESG portfolio based on risk tolerance and ESG preferences. Greater ESG preference leads to a lower financial return, but this is compensated for ESG-motivated investors by the hedonic value of conforming to their ESG preferences. However, this is only true in equilibrium.

There are two forces that could influence the relative returns to ESG-adaptive bonds during a transition to a new climate-conscious equilibrium. First, climate sensitivity—that ESG scores partially estimate/characterize—could become an important determinant of risk-adjusted profitability. Consider a transitional process of learning about the true risk characteristics of ESG- and non-ESG-adaptive activities/firms, with successive events revealing that ESG-adaptive activities/firms are better investments than previously understood. Based purely on efficiency criteria, investors will respond by shifting their portfolios towards ESG-adaptive assets (including green bonds), generating temporarily higher returns due to the ensuing asset price appreciation. However, a large scale shift in portfolios towards ESG-adaptive assets could also result purely from a change in average preferences, with the same transitory effect of price appreciation driving higher ESG returns.

Alessi et al. (2021) [8] extend the greenium concept to equities and present evidence that shares in green companies trade at a value consistent with a negative risk premium relative to brown companies, that is, green firms are priced higher. Alessi et al. use an expanded approach to define green firms. First, they attempt to neutralize the impact of greenwashing by requiring that firms labeled as green are sufficiently transparent. Second, they rate firms relative to their peers. In this way, a steel firm can be green if it is sufficiently less carbon intensive than other steel firms.

Pedersen et al. (2021) [161] clarify the forces at work in the greenium by developing an efficient frontier for ESG investing, demonstrating with a CAPM framework that investors face a tradeoff between ESG-adherence and risk-adjusted return as measured by the Sharpe ratio (SR). In principle, fully-informed investors would all agree on the ESG-SR frontier but would choose different "ESG-efficient" portfolios based on their preference for ESG. Higher ESG preferences on this efficient frontier inevitable require lower returns, consistent with our earlier intuition. Pedersen et al. allow for the existence of three kinds of investors: uninformed (who do not admit ESG scores into their information set), informed but unmotivated (who use ESG scores but do not otherwise prefer ESG-adaptive shares), and motivated (who are willing to trade off returns for higher ESG scores).

The presence of a large share of uninformed investors creates an inefficiency. In the case where high-ESG scores predict high future profits, high returns for ESG-motivated investors are possible if there are many uninformed investors who do not make use of (or ignore) the information set embedded in ESG scores. These high returns are eliminated as the share of uninformed investors declines towards zero, even if they are only replaced by informed yet unmotivated investors. Support for the reduced risk of ESG-adaptive stocks is growing. For example, Hoepner et al. (2020) [109] use a lower partial moment analysis and find that engagement on ESG issues benefits shareholders by reducing a firm's downside risk (see also, Sharfman and Fernando (2008) [178]; Shen et al. (2019) [179]; and Jagannathan et al. (2017) [122]).

Evidence in a shift in preferences towards ESG stocks comes from Gibson et al. (2020) [95], who construct a sustainability footprint measure for institutional investment managers by matching stock-level environmental and social scores to portfolio holdings as reported in SEC 13F filings. Using the methodology proposed by Koijen and Yogo (2019) [133], Gibson et al. find that risk-adjusted returns for institutional investment managers are higher for firms that score more highly on environmental factors, as expected, providing evidence that this performance is due to rising investor demand for sustainable investment opportunities.

3.4 The climate-fundamental price level

We return now to the key question raised at the beginning of this section: is there a climate-fundamental price level, and do markets tend to converge to it? Quantitative methods of deriving a fundamental risk-adjusted price are unlikely to proxy well for uncertainty, given that uncertainty does not have a well-behaved distribution with known moments. The interpretation of the reversion of prices to original levels post-shock is clearly dependent on how we view the fundamental price level. For example, in the wake of a hurricane, Alok et al. (2019) [9] suggest that local fund managers overreact but eventually come to adopt more reasonable valuations in line with distant fund managers. This is the fundamental implication of framing experiences with climate change using "salience bias," that is, the behavioral trait that direct experience with a recent rare event leads us to overstate the risk of that experience happening again.

In this framing, we might view climate events as draws from a fixed distribution where the severity of events remains relatively stable across the distribution. If the distribution is well known, prices averaged across a certain minimum number of years should be stable around their fundamental values. Experience with a tail event will not alter the true distribution, so the initial distortion introduced by salience bias should abate over time. Hence, post-climate-event price shocks are movements away from equilibrium within this framework, not towards it. This overshooting dynamic is compatible with a gradually changing distribution so long as the rate of change is sufficiently slow.

Yet it is also possible that the distribution is changing rapidly or is subject to discrete phase transitions. In this case, large price dislocations may represent a correct revaluation of the value of the underlying assets. That this downward price adjustment does not last may reflect the difficulty of fully comprehending the scope of change underway. One intriguing possibility is to link post-shock rebounds to the experience of repeated bubbles in housing and equity markets, whose collapses have been famously characterized as Minsky moments. Shiller (2016) [181] has documented the many behavioral phenomena that lead to a form of amnesia about past lessons. For climate outcomes, this 'bubble' framing is perhaps best developed in the coastal real estate literature, despite the difficulty of distinguishing between behavioral biases that prevent learning about the true value of these assets (as in Botzen et al., 2015, [41]) and distortions that incentivize accumulation of assets vulnerable to climate change (such as subsidized flood insurance).

We turn now to the impact of these distortions on financial markets, including factors such as the short horizons employed by credit risk and sell-side equity analysts, the lack of disclosure of climate risks, the ability to pass along risk due to the relative indifference to climate risk pricing by banks and corporate bond markets, among other behavioral distortions.

4 Institutional distortions and other externalities

Turning to the third question addressed by this literature review, we examine the literature on distortions to financial institution behavior, which can lead to mispricing and other vulnerabilities independent of the price efficiency considerations discussed above. These distortions are decisive drivers of market outcomes, and they matter for both system-wide as well as local financial-sector vulnerability to climate change. The non-exhaustive list of potential distortions discussed below include the time horizon problem, principle-agent problems, network effects, load-bearing capacity thresholds, locational/jurisdictional heterogeneity, the effect of the government backstop, and the intersection of climate change and inequality. Each of these items is ripe for research and each plays a significant role in how the financial system is responding to climate change.

4.1 Time horizon

Carney's 2015 [53] speech referred to one of the most widely cited concerns about market distortions, which is that financial institutions have decisional time horizons that are too short to adequately accommodate climate change. This theme is taken up in Naqvi et al. (2017) [154], which highlights the 1- to 5-year horizons of sell-side equity and credit risk analysts and the ensuing implications for financial risk management in detail. Their analysis points to a lack of demand by investors for long-term analysis. Many investors have short-time horizons themselves, and so are content not to commission or purchase complicated analyses of non-linear long-term trends.

Unfortunately, this constrained perspective can create significant risk for pensions and insurance companies that ultimately rely on long-term investments. Naqvi et al. (2017) [154] suggest that two-thirds of the net present value of long-term institutional investors' assets are based on cashflows at least five years out. To emphasize the point that a large portion of these risks are detectable (and not unforeseeable "black swans"), they point out how puzzling it is that analysts did not anticipate the impact of the emissions scandal on Volkswagen shares, even though there were adequate telltale signs that the crisis was brewing. More to the point, they discuss how the lofty 2011 valuation of Peabody Energy (a major supplier of coal) at $18 billion was incompatible with the transparent risks of a rising supply of natural gas due to advances in fracking technology and greater climate policy restrictions on coal. These predictable trends matured, and Peabody's valuation dropped to a mere $38 million by 2016.

4.2 Principal-agent problems

Institutions may also lack the incentive to reflect shareholder wishes to move towards more sustainable practices and to better guard against climate risks. Krueger et al. (2019) [135] conduct a survey of institutional investors, arguably the strongest external force on individual firms' incentives to take climate into account. Although there is undoubtedly bias in terms of the investors that responded, the survey does span a significant number of large investors and is informative about the actions that engaged investors take.

The survey results indicate a concern with climate risk, with 40 percent of respondents anticipating a higher degree of climate change than the median IPCC estimate. Moreover, many respondents do not see climate change as a distant issue, but rather believe that climate is impacting financial performance already. However, investors did not seem to be responding in similar ways to these risks, with slightly over one-third of respondents respectively engaged in analysis of portfolio firms' carbon footprints and evaluation of stranded asset risks. While respondents indicated that they did not believe asset prices fully reflected climate risk, they also did not feel that asset prices were severely overvalued echoing the curious lack of demand for longer term climate risk analysis cited by Naqvi et al. (2017) [154].[28] Indeed, concerns fi-

[28] The inability of institutional investors to accurately assess climate risk also stems from imperfect information. Monasterolo et al. (2017) [149] propose improving knowledge of climate risk by introducing two complementary indices: (i) a "GHG exposure" index, which measures the exposure of a given investor's portfolio to climate transition risk, and (ii) a "GHG holding" index, which measures the market share of each financial actor weighted by its contribution to GHG emissions.

nancial institutions may be underestimating their exposure to climate-related risks are taken up in many additional studies (Daniel et al., 2016 [70]; Farid et al., 2016 [83]; Battiston et al., 2017 [25]; Batten et al., 2018 [24]; Dafermos et al., 2018 [69]).

Many institutional investors in Krueger et al.'s survey engaged with firms in their portfolio on climate issues (over four-fifths of respondents), with many holding discussions with management that included specific requests for action. In addition, respondents submitted shareholder proposals and voted against management on specific issues during shareholder meetings. Only one-fourth of respondents indicated that their engagement led to a successful resolution of the issue. When the engagement did not lead to resolution, most investors appeared to drop the matter, with many choosing to hedge the risk instead. Very few chose divestment. Larger firms tended to engage more broadly and consistently, which raises the possibility of a free rider problem.

Dimson et al. (2015) [76] also explore whether attentiveness and engagement lead to improved outcomes by examining a large set of ESG engagements with U.S. companies from 1999 to 2009. In cases where the firms responded positively to the engagements, they achieved subsequent positive abnormal returns. Unsuccessful engagements corresponded to zero subsequent abnormal returns.

4.3 Network effects and other spillovers

The heterogeneity in institutional investor approaches to climate risk may partially reflect an inadequate appreciation of network effects combined with a lack of standardized climate risk metrics. The papers surveyed above use multiple means to identify portfolio exposures to various kinds of climate risk, but Battiston et al. (2017) [25] introduce standard value-at-risk (VaR) tools in conjunction with a network-based approach, the DebtRank algorithm, designed to capture indirect systemic effects as well.[29] The DebtRank algorithm focuses on feedback centrality and measures the impact of a climate shock to one or more financial institutions on their counterparties throughout the network.[30] Specifically, the method portrays institutions as nodes

[29]By contrast, Dietz et al. (2016) [75] undertake a value-at-risk (VaR) exercise based on a version of the DICE model.

[30]See Battiston et al., 2012 [26]; feedback centrality is linked to the concept of recursive centrality measures such as eigenvector centrality and Google's PageRank algorithm.

and lending relationships (weighted by the amount of outstanding debt) as directed edges within a network. The DebtRank of node i is given as R_i, a number that measures the fraction of the total economic value in the network that would be affected by the distress or default of node i. Battiston et al. proceed by reclassifying NACERev2 sectors (at the four digit level) into climate-policy relevant sectors based on their contribution to CO2 emissions. Direct exposure to climate risks can then be calculated by measuring a portfolio's exposure to these sectors and calculating the climate VaR. Indirect exposures are then calculated by using the DebtRank algorithm.

Battiston et al. (2017) find that, while direct exposure of top European Union banks to the fossil fuel sector is small at around 1 percent of average bank capital, the combined exposures of equity portfolios to climate risk intensive sectors is large at around 45 percent for investment funds and 47 percent for pension funds. The network effects tend to amplify risk through the exposures that financial investors have to one another and this in turn might lead to systematic mispricing.

Spillovers can also take the form of reallocation of credit across geographic regions in response to a local climate-related disaster. This reallocation can be seen in the vital role that banks play in reconstruction. Bos, Li, and Sanders (2018) [40] find that total loans, and real estate loans in particular, significantly increase after natural disasters, apparently funded by a reduction in holdings of government bonds. Based on their empirical results, they develop and calibrate a model that allows them to quantify the impact of climate change on banks' balance sheets.

Are all types of banks equally responsive to the needs of affected areas? Some evidence suggests that community and local banks may play an especially important role. Cortés (2014) [65] found that local lenders (those with more than 65 percent of their deposits from the affected area) increase lending in the wake of a natural disaster, particularly supporting employment growth at young and/or small firms. He (2018) [106] found a reallocation of lending among borrowers with a strong connection to a bank from those not affected by natural disasters to those who suffered losses. This reduction in credit to unaffected borrowers came at a cost, leading those firms to suffer reduced credit, output losses, and decreases in the value of their equity (particularly if they do not have other creditor relationships to call upon). The author finds that one dollar of additional lending to disaster-affected firms is associated with an 11.5 cent decline to unaffected firms. Koetter, Noth, and Rehbein (2019) [132] show a similar increase in lending to connected borrowers took place in the wake of the 2013 Elbe River flooding in Germany, with no evidence of higher insolvency risk or loan impairment rates, and no rent-skimming from more desperate, disaster-affected firms.

This is a clear spillover channel that is deserving of more investigation, and it is important to better understand the motivations of banks to undertake this behavior. As Cortés (2014) [65] points out, government regulators encourage lending after a natural disaster, often offering guidance on how to do so while still observing sound banking practices (p.3). Barth et al. (2019) [22] demonstrate that such behavior is profitable, although not so much as to indicate profiteering. They find that lending into a disaster-affected region increases a bank's return on assets and net interest margins. Although banks raise deposit rates in the wake of a disaster, they raise lending rates even more. The additional deposits brought in by the higher rates are augmented by deposits brought in from branches outside of the affected communities as well as brokered deposits.

The emphasis on local banks is not to say larger institutions are immune from climate-related risk, however. At least three reasons underline the concern for larger institutions. First, climate shocks may be correlated across regions and sectors and therefore may come to comprise a much larger share of a large institution's balance sheet (e.g., through a heat wave affecting multiple U.S. states simultaneously or a climate/transitional policy shock to a broad sectoral category). Second, a climate shock to a single region or sector may spill over to other metropolitan regions and sectors through demand or supply shocks or through shared fiscal constraints that mean, under certain conditions, that extra spending on mitigation and adaptation crowds out important spending and investment elsewhere. For example, in a review of the impact of the Canterbury earthquakes (not a climate shock, but similar in effect) in New Zealand, Parker and Steenkamp (2012) [159] review the evidence on spillovers and find that although goods exports and manufacturing held up, there was nonetheless significant outmigration and a decline in service sectors (retail, accommodation, and hospitality) a year out.

Third, interlinkages within the financial system may lead to market functioning risks or other macroprudential concerns. For some markets, it is easy to see how a reevaluation of inherent risks might lead to a discrete price dislocation. Suppose a coastal city, whose credit rating has been downgraded due to rising climate risks, is ultimately forced to default on municipal bond repayments due to a steady erosion of tax revenue and rising refinancing costs. Despite the evidence in Painter (2020) [157], municipal bond markets might not have fully priced in default risk. What might have been unthinkable to municipal bond holders—that is, the possibility of a municipal default—might now be considered a viable risk for all cities facing a similar predicament, with municipal bond prices falling quickly as contagion ensues. The implications of such a recalibration on the local economy could potentially lead to a negative spiral, with dynamics that can be analyzed as in Inman (1983) [116], Inman (1995) [115]) , Cornaggia et al. (2017) [63], and Adelino et al. (2017) [1]. Morris et al. (2020) examine the impact of transition risk to counties reliant on coal revenues and estimate that around one-fifth of their budgets could be lost as the industry is phased out. They point out that municipal bonds have not priced this risk but that as the impact on budgets becomes increasingly clear it is likely that refinancing costs could increase sharply.

4.4 Load-bearing capacity thresholds

Systemic risk may result when financial actors misgauge the load-bearing capacity of counterparties to handle their obligations in the event of a climate shock. Pozsar (2014) [166], in a different context, highlighted the need to flow-of-funds analysis to be complemented by a flow-of-risk analysis to see where risk ends up pooling in the financial system. The load-bearing capacity of insurers and local and federal governments are addressed below, but the critical roles played by investment funds and government-sponsored entities (GSEs) deserve special attention.

Ouazad and Kahn (2021) [156] find, for example, that the GSEs may act as *de facto* insurers due to their willingness to purchase securitized conforming mortgages without updating their risk models beyond FEMA-flood plain designations. Examining 15 different billion dollar natural disasters, Ouazad and Khan show that "...the difference in approval rates for conforming loans and jumbo loans increases by up to 7.3 percentage points [and] the probability of securitization increases by up to 19.3 percentage points."(p.4) They go on to show that the bunching of mortgages just below the conforming loan limit is likely due to adverse selection as opposed to any greater inherent safety in these loans. Based on results from their quasi-experimental analysis, Ouazad and Khan present model results that show a contraction in mortgage credit in areas struck by natural disasters in the absence of GSE purchases.

Based on these results, unless government-sponsored entities GSEs improve their screening of conforming mortgages for updated climate risk, they will continue to accumulate climate risk in their portfolios. Should a correction to the value of these securities occur as climate change factors into valuations, the GSE's financial health could in turn potentially threaten entities that rely on portfolios of their *agency* bonds. However, the withdrawal from purchasing these mortgages by GSEs would also have consequences. Following from Ouazad and Khan's analysis, mortgage availability would fall in vulnerable areas, which would in turn lead to a reduction in the value of the affected housing stock.

Keenan and Brandt (2020) [**?**], coining the term "underwaterwriting," provide evidence that concentrated local lenders, engaging in adverse selection made possible by local soft information, securitize and sell flood-vulnerable mortgages to institutional investors. They argue that these climate risks, particularly flooding and sea level rise, should be reflected in accounting rules for forward-looking credit losses.

Garbarino and Guin (2020) [92], examining a severe flood event in England in 2013–14, find additional evidence of the distortionary effect of public insurance programs using a panel of almost 120,000 properties and 40,000 mortgage refinancing transactions with three treatment groups (long floods of 50 days or more; short floods of less than 50 days; and increased risk, but no flooding) and a control group. Lenders did not adjust their valuation of properties in the wake of local price declines, nor did they alter loan pricing or the size of loans granted. This is puzzling given studies such as Cerqueiro et al. 2016, [54] that document the important role that collateral plays in the setting of bank loan contracts. While the absence of revaluation might make sense if the overall probability distribution of flooding remains unchanged, this is unlikely to be the case.

An additional confounding effect noted by Garbarino and Guin [92] is that borrowers with low credit risk moved into high flood risk areas, implying that high flooding risk might have been offset in part by the lower credit risk of the borrower (see, e.g., Graff-Zivin, Liao, and Panassie, 2020, [101], for evidence of post-hurricane demographic transition). Nonetheless, this self-selection in combination with public flood insurance programs implies a subsidy that increasingly benefits high income households.

Garbarino and Guin highlight several important lines of inquiry for understand the role of acute climate events on bank lending. First, to the extent that loan-to-value (LTV) ratios constrain bank lending due to risk-based regulatory capital ratios, distortions in valuations can lead to sub-optimal outcomes. Rather than an ever-inflating valuation driving a bubble (as in Ben-David (2011) [29]; and Agarwal et al. (2015) [5]), it is the persistence of existing valuation despite reasons for that valuation to decline (also a bubble of sorts) that cause distortions in LTV ratios. Consequently, valuation bias can paradoxically relax credit constraints relative to demand as supported by studies that show that small banks reallocate lending to areas affected by natural disasters (see, e.g., Cortes and Strahan (2017) [66] and Koetter et al. (forthcoming) [132]).

If home valuations are left untouched while other loan categories face higher risks, banks (particularly those with low capitalization) will likely shift lending towards real estate. That this reallocation occurs because of the need to manage risk-based capital ratios is documented by Schüwer et al. (2019) [174]. Second, although it is possible for banks to offset risk of climate disasters by tapping into specialist knowledge available to local banks or insurers (e.g., Garmaise and Moskowitz (2009) [93] and Chavaz (2016) [57]), they do not seem to be doing so, at least not yet. Consequently, it is not surprising that Klomp (2014) [130] finds that natural disasters increase the likelihood of a bank's default using data for more than 160 countries.

Does this lack of responsiveness of bank pricing of climate risk carry over to other areas of the financial system? It could be that the unique distortionary presence of GSEs in the mortgage market, which allows banks to offload risk, makes that segmented market unique. After all, banks do seem to react to increased risk as seen in the bunching occurring just under the conforming threshold. Delis et al. (2021) [73] look at whether banks adjust loan pricing to fossil fuel firms using syndicated loan data. They find that loan pricing went up significantly in 2015 for fossil fuel firms exposed to transition risk. This effect increased for longer-maturity loans.

Despite these distortions, Blickle et al. (2021) [38] argue that, over the past quarter century, bank performance has been largely unaffected by weather disasters. In keeping with Cortés (2014) [65] and He (2018) [106], they find increased lending in the wake of a natural disaster, as loan demand rises. For larger banks, this increased demand not only offsets losses but raises profits as well. Local banks face higher stability impacts, but not significantly damaging to threaten their solvency. Blickle et al. find that federal funding through FEMA does not seem to drive their results, even though such assistance is substantial when given.

This finding that losses caused by climate-event-driven defaults are more than offset by demand-driven increases in lending income places emphasis on the resiliency of default rates and the success in bank risk mitigation strategies. One interpretation of the relative unimportance of FEMA assistance to Blickle et al.'s results is that insurance and/or forbearance may play a large role in limiting defaults and that banks have been successful in diversifying risk by securitizing loans or using other strategies. As the authors point out, chronic physical and transition risks might need additional analysis. Chronic risks potentially imply structural changes in the ability of banks to limit default risk if they affect insurance availability and ability to securitize loans. If banks do not have sufficient time to adjust their lending and asset holdings in response to these changes, losses may be large relative to the historical patterns evaluated in the paper.

4.5 Locational/jurisdictional heterogeneity

Another important consideration for the financial implications of climate change is identifying the appropriate unit of analysis. For example, many studies have focused on national implications, but individual financial institutions have differing geographical and sectoral footprints. It is a trivial observation to state that large banks have relatively little to fear from severe weather events in each area because that area makes up only a small portion of their overall exposure. In the absence of sophisticated diversification strategies, smaller local institutions are likely more vulnerable to regional climate shocks.

An advantage to focusing on regions is that they are subject to distinct physical and transitional risks that may not be shared with other regions. In addition, they differ in terms of engineering options for adaptation, local fiscal and institutional capacity, and political economy; all of which will affect their ability to adapt to climate change. We take each of these issues in turn. Engineering options for adaptation exist and are likely economically feasible for certain geologies and conditions, as described for sea level rise in Goodell, 2017, [100]. For New York City, the construction of a sea wall around lower Manhattan, however expensive, would protect the city from flooding. However, a sea wall will not lead to the same protection for Miami, which is built on porous limestone that allows the sea to seep in under the city (Ariza, 2020, [11]). A Miami wall would have to be supplemented with powerful sump pumps to balance the rate of seepage.[31]

[31] See Klima et al. (2012) [129] for other adaptation technologies available to Miami.

Local fiscal capacity to meet climate risks will depend on the relative expense of adaptation measures needed to maintain essential amenities, the cost of financing debt (as discussed in Painter (2020) [157], and Goldsmith-Pinkham et al. (2021), [99]), and the dependence of municipal tax revenues on activities that are robust to realized and expected climate change, as we discuss below. Kim (2020) [128] examines whether investment in adaptation can boost real estate values in a hedonic analysis of two cities, with obvious ramifications for local tax revenue. He finds that the outcome depends on the adaptation, with perception not necessarily correlated with effectiveness.

Institutional capacity will depend on the degree to which authority is invested in parties both able and willing to take meaningful action. As Bierbaum et al. (2013) [33] make clear, the record on climate adaption is mixed at best. Again, Miami presents an interesting case. Miami-Dade County contains 34 distinct municipalities, and the unincorporated part of the county would be one of Florida's largest municipalities were it to become incorporated as a single municipality (Ariza, 2020, [11]).

Uncoordinated actions across municipalities, such as unilaterally building flood barriers, have resulted in flooding in neighboring communities (again, see Ariza for this beggar-thy-neighbor result). Some efforts are underway to resolve these coordination failures as with the Southwest Florida Regional Climate Change Compact, which is a partnership between several counties and municipalities to work collaboratively to address climate risks [185]. One concrete action taken under its aegis is to set predicted levels of sea level rise that local agencies will agree to use for common planning purposes. Vrolijks et al. (2011) [191] compare similar actions to identify and address climate change challenges across ten urban areas around the world.

Finally, differences in the political economy will affect the scope of action available to municipalities. For example, Ariza (2020) [11] discusses the conflicts of interest faced by real estate developers who sit on city councils who could suffer significant losses depending on the public response to visible climate adaption measures. Alternatively, Shi (2019) [180] undertakes case studies to better understand the consequences when metropolitan regions take independent actions out of step with broader polities, concluding, "...scaling up adaptation to the metropolitan region is no panacea for overcoming structural limits to local adaptation in places with weak regional governance institutions."

As part of a series of McKinsey Global Institute climate change case studies focused on concerns at the regional level, Woetzel et al. (2020) [197]

examine a broad range of concerns around climate risk in the Florida coastal real estate market, weaving together many of the themes discussed above.[32] In quantifying potential damages, the report estimates $4.5 billion in annual storm surge damages at the high end by 2050, with the potential for damage from a 1-in-100 extreme weather event reaching $75 billion by that same year. The considerations involved are very region specific. Woetzel et al. point to three categories of risk. Physical characteristics include special vulnerability to storm surge, wind speed, precipitation, and sea level rise; a porous limestone foundation that rules out sea walls; saltwater intrusion into aquifers; and vulnerability to toxic algae blooms and seaweed piles on beaches that reduce the attractiveness of living near coastal waters; Economic characteristics include a heavy dependence on real estate in the local economy (real estate accounts for 22 percent of Florida's GDP); a heavy dependence of local government tax revenue on property taxes (30 percent); and a high degree of homeowner wealth embedded in real estate. Demographic characteristics include around two-thirds of the population living near the coastline; 10 percent of the population located less than 1.5 meters above sea level; 27 percent of housing units located on a 100-year floodplain; and rapid growth in both population and building permits in low-lying areas of the state such as Miami-Dade county.

4.6 The effect of the government backstop

As described above, financial stability is predicated on the notion that all parties in the web of financial transactions have sufficient load-bearing capacity to handle their obligations in the event of shocks. The ultimate shock absorber is exceptional federal government support. In a study of the U.S. federal government's financial support in the wake of natural catastrophes, Cummins et al. (2010) [68] take the existing level of federal government largess in the wake of natural disasters and project the cost of this support considering anticipated increases in natural disasters. Using projections from a leading catastrophe modeling firm and loss data from a propriety database, they estimate that the federal government faces an unfunded disaster liability of between $1.2 and $7.1 trillion in net present value (over 75 years) in the analysis year of 2007. They compare the size of this liability to the projected shortfall of Social Security of $4.9 trillion over the same horizon to put the

[32]See also, Meyer (2014) [148].

size of this liability into context. Two qualifications are in order. First, the natural disasters that they consider include non-climate related events, such as earthquakes, and on that basis this figure overstates climate-related liabilities. Second, estimates of the frequency and severity of acute physical risks have increased significantly since 2007, which would tend to make this figure an underestimate. Whether the ultimate number associated with physical climate risks is within the load-bearing capacity of the federal government is an important question.

4.7 Climate change and inequality

The inevitable migration and social dislocation that will result from climate change raises important inequality concerns. Given that migration, rebuilding, accommodative infrastructure, and the interaction of market prices with restrictions on building all intersect with an enabling environment of credit provision and financial services, it is clear that the nexus between climate change and inequality is enormous. Some early work has begun to tackle these concerns, and Avtar et al. (2021) [15] provide a systematic overview of key issues and literature. For example, Keenan et al. (2018)[126] examine the emergence of *climate gentrification* in Miami-Dade County. They find evidence that, with a rising sea level and increased nuisance flooding, prices are rising faster in areas of higher elevation when controlling for other factors. Given that the highest land in Miami-Dade is farthest from the coast, and therefore has been largely occupied by lower-income households, a shift in demand towards these areas carries with it the prospect of gentrification unless attenuated by government policy. Similarly, Rapaport et al. (2015) [167] consider the special vulnerabilities of senior citizens based on case studies of coastal communities in Nova Scotia and policy actions that might address their concerns. Smiley et al. (2021) [183] show that climate-vulnerable Latinx households were particularly hard hit by Hurricane Harvey. Latinx households tended to be overrepresented in newly vulnerable areas just outside of FEMA 100-year flood plain designation, where the lack of a FEMA floodplain designation meant they were unlikely to be adequately insured.

5 Conclusions and recommendations

We return to the three basic questions posed in the introduction: (i) is uncertainty quantifiable, (ii) are markets efficient with respect to climate risk, and (iii) do financial institutions integrate those prices into economic decisions that are free from distortions? Although the literature is developing rapidly, we already have some compelling answers to these questions.

A large quotient of the uncertainty we face with climate change is of the "radical uncertainty" variety and therefore remains functionally out of scope for quantitative risk analysis. Decisionmaking under radical uncertainty requires flexibility in terms of the tools and approaches policymakers and researchers employ. This is one reason for the current pivot to scenarios analysis in financial regulatory circles, as well as for calls to focus economic analysis on least-cost ways to achieve defined goals rather than to determine what the goals themselves should be (see, e.g., BCBS (2020) [23]). More subtle but vitally important is the question of what uncertainty implies for policy action. One common view is that uncertainty creates an options value for waiting to see how things resolve given that there are sunk costs associated with environmental actions taken now. However, as Pindyck points out, there are also sunk benefits of avoided environmental degradation that can potentially more than offset those sunk costs. Given the impossibility of resolving which of these two is greater, there is a strong case that the insurance value of acting now should dominate. Another implication of uncertainty is that chasing precision in quantitative modeling is unlikely to be fruitful and that medium- to long-range models should best be thought of as parables or consistency checks on our thinking. This implication applies equally to the Holy Grail of much economic analysis on the precise value of the social cost of carbon.

In terms of whether markets are efficient in integrating all currently known information, there is mixed evidence on whether asset prices have become increasingly responsive to climate risk (e.g., insurance rates have been responsive while borrowing costs have not). The bigger question is whether they have become responsive enough. This remains an open question, although there are reasons to doubt that prices adequately reflect such risks, including the opaqueness of local soft knowledge, the spotty availability and delays in locally relevant climate predictions, the obscure flow of risk between financial entities and their attendant load bearing capacity, and the degree to which economic agents will act proactively to circumvent risks in unanticipated ways. Using historical data to condition our expectations of how individuals will react to future events is challenged by the novel nature of climate change and the relatively limited number of climate events covered by historical data. Moreover, survey responses by investors and fund managers indicate that they subjectively feel that asset prices have not fully incorporated climate risks.

Finally, there are many well-recognized distortions in financial markets that are only amplified in the presence of climate risks. Under-policed risk shifting by mortgage lenders to the GSEs is but one example. A good first step and worthy agenda for research is to map out the flow of climate-affected funds and flow of climate risks within the system, matching this to the load-bearing capacity of different entities. It is important to be concrete about how actual institutions function instead of abstracting from such details as is clear when looking at the capacity of city regions to handle climate risks. A bottom-up approach is likely to be a valuable approach that can hopefully lead to meaningful aggregation of risk for national supervisors, regulators, and policymakers.

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