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Climate Stress Testing

Abstract

We explore the design of climate stress tests to assess and manage macro-prudential risks from climate change in the financial sector. We review the climate stress scenarios currently employed by regulators, highlighting the need to (i) consider many transition risks as dynamic policy choices; (ii) better understand and incorporate feedback loops between climate change and the economy; and (iii) further explore "compound risk" scenarios in which climate risks co-occur with other risks. We discuss how the process of mapping climate stress scenarios into financial firm outcomes can incorporate existing evidence on the effects of various climate-related risks on credit and market outcomes. We argue that more research is required to (i) identify channels through which plausible scenarios can lead to meaningful short-run impact on credit risks given typical bank loan maturities; (ii) incorporate bank-lending responses to climate risks; (iii) assess the adequacy of climate risk pricing in financial markets; and (iv) better understand and incorporate the process of expectations formation around the realizations of climate stress tests that can be conducted using publicly available data to complement existing stress testing frameworks.

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Financial market participants and policymakers are becoming increasingly concerned about the potential risks from climate change to economic activity, corporate performance, and asset values (e.g., Krueger et al., 2020; Giglio et al., 2021a; Stroebel and Wurgler, 2021; Hong et al., 2020; Litterman et al., 2021). Such concerns have motivated central banks and regulatory authorities around the world to consider whether climate-related risks might undermine financial stability with adverse consequences for the economy (e.g., Bailey, 2020; Financial Stability Oversight Council, 2021).¹

In this review article, we examine the potential for stress testing to assess and manage climate-related risks to financial stability. We discuss various challenges with the existing approaches and highlight areas with a particular need for future academic research. We then compare and contrast existing stress testing methods with alternative market-based stress tests. While we acknowledge that many parts of the financial system such as insurance companies and asset managers are potentially exposed to climate risks, our analysis focuses on the assessment of climate risks to the banking sector.²

We start by reviewing key aspects of the existing stress-testing toolkit. Stress tests are quantitative assessments of the resilience of individual banks as well as the financial system to severe but plausible realization of adverse economic outcomes such as GDP contractions, increases in unemployment, house price declines, or interest rate movements. Applying this existing toolkit to the analysis of climate risk requires important work in at least two dimensions: the design of scenarios that describe the relevant realizations of "climate risk", and quantitative modeling of the channels through which these risk realizations lead to adverse economic outcomes that can affect banks and potentially financial stability. In the first part of this review, we therefore discuss recent progress and future work in the design of climate risk scenarios and the modeling of bank performance under each scenario.

We discuss climate scenario design by reviewing the types of climate risk that are often thought to affect economic activity: *physical risk* (i.e., the risk to economic activity from physical manifestations of climate change, such as rising sea levels and heat stress including

¹For example, U.S. Treasury Secretary Janet L. Yellen (2021) argued that: "Climate change poses a potential systemic risk to the American economy, and I believe we must seriously look at assessing the risks to the financial system from climate change. This will be an issue regulators will also have to think more about in the years ahead, and we need to ensure that we have appropriate processes and regulations necessary to assess and mitigate this risk." Janet L. Yellen (2023) further warns that: "As climate change intensifies, natural disasters and warming temperatures can lead to declines in asset values that could cascade through the financial system. And a delayed and disorderly transition to a net-zero economy can lead to shocks to the financial system as well." Federal Reserve Vice Chair Brainard (2021), suggested that, "going forward, it will be important to improve our understanding of climate-related financial risks and vulnerabilities."

²We complement and build upon other papers that review climate-related financial stability risks and related topics (e.g., Brunetti et al., 2022; van Dijk M. A., 2020). Most closely related is the work by Cartellier (2022), which also discusses climate stress test methodologies used by central banks and researchers.

wildfires) and *transition risk*, the effects on economic activity from regulatory interventions in response to climate risk (e.g., carbon emission taxes and renewable energy subsidies) or from changes in technologies and preferences. These risks, which can potentially interact, operate at different time horizons and differ substantially both in terms of their implications for overall economic activity as well as the sectoral distribution of any effects.

We then describe recent progress by the Network for Greening the Financial System $(NGFS)^3$ and others to propose various scenarios of physical and transition risk realizations and review how these scenarios have been adopted and adapted for various regulatory exercises around the world. We also describe areas where scenario design would benefit from further academic research.

First, while economics has little to say about the determination of likely physical climate risk realizations, it is important to realize that transition risks arising from carbon taxes and renewable subsidies are dynamic choices made by policymakers who trade off the benefits and costs of various interventions while considering their political feasibility. We thus argue that research that quantitatively studies the relevant political economy considerations would be helpful in defining a range of realistic or plausible transition risk scenarios and their geographic variation. For example, such work would be informative about whether an extreme carbon tax that would dramatically raise energy prices and bankrupt high emissions industries is ever likely to arise in equilibrium, and, even if it does, whether it will be reversed upon adverse economic reactions.

Secondly, we believe that deeper analysis is required to understand the many interactions between climate change and the overall economy, so as to model better the economic environment that will accompany physical climate risk realizations. For example, academic researchers disagree about whether states of the world with substantial climate risk realizations will have high or low GDP, the former implying a possibly negative price on climate risk whereas the latter implies a positive one. Such "compound risk" considerations—which describe the interaction between climate, economic, financial, political, and other risks—appear key to arriving at useful climate stress scenarios.

We also review current approaches to modeling the effects of climate risk realizations in a given scenario on banks, focusing on the effect through banks' loan books (credit risk) and banks' portfolios of financial assets (market risk). We argue that a key aspect of assessing the possible credit risk implications of climate change is an appreciation of the average maturity of banks' exposures to borrowers' ability to repay. To the extent that bank loans have a

³NGFS is a group of central banks, supervisors, and observers committed to "contributing to the development of environment and climate risk management in the financial sector and mobilizing mainstream finance to support the transition toward a sustainable economy" (NGFS, 2019). It was launched at the Paris One Planet Summit in 2017. As of October 2022, the NGFS consists of 121 members and 19 observers.

relatively low average maturity, the probability that climate risk realizations—many of which will only materialize over a medium-term horizon—will result in borrowers' inability to repay over the length of currently outstanding loans is likely small. More probable is a deterioration in the borrower's medium-run repayment ability, for example, due to a reduction in future cash flows. While such a medium-run deterioration is perhaps unlikely to lead to immediate loan losses for banks, it could still affect their profitability and franchise values, for example, by raising required regulatory and/or economic capital. Banks with business models that particularly cater to firms exposed to climate risks (e.g., firms in the oil and gas sector) may see revenue losses if their clients become less profitable and stop investing, though some such losses might be offset by new revenue from financing the green transition. Given these various forces, it would be useful to further understand the precise channels via which climate risk realizations might affect financial stability over the short run (e.g., less than three to five years, which is a typical loan maturity), to specify if and how such effects operate through a credit channel, and to directly incorporate those channels into stress scenarios.

Beyond credit risk, market risk is another channel through which climate change could affect financial stability. In particular, since expectations of longer-term climate risk realizations can already affect asset values today, they can have an immediate effect on banks through a revaluation of financial assets held on bank balance sheets. To highlight this point, we review the evidence on the extent to which climate-related risks already affect prices across a range of asset classes, including equities, fixed income, and real estate.

While this literature has convincingly documented that climate risks are currently priced across a range of asset classes, much less is known about whether they are *adequately* priced. The adequacy of current risk pricing is, however, an important question for assessing the likelihood of potentially substantial short-run asset revaluations as there might be strong learning effects and revisions in the price of risk associated with the inherently evolving nature of climate risk realizations. We argue that to understand the effects of various long-run climate risk scenarios on asset prices today—and therefore to assess banks' market risk—we require a better understanding of the process by which investors update their climate risk beliefs.⁴ If investors fail to accurately update beliefs in response to information about future climate risks across the different scenarios; on the other hand, it could also lead to more substantial revaluation risk in case beliefs eventually move by a substantial amount.⁵

⁴Note that the market risk of bank borrowers could also affect their credit risk via the rollover risk channel, as noted among others by He and Xiong (2012) and Morris and Shin (2016).

⁵Since stress-test scenarios and methodology can be revised by national policymakers relatively frequently compared to internationally agreed capital requirements, stress tests may be particularly well-suited to dynamically adjust to the evolution in the climate risk beliefs of investors.

After discussing the opportunities and challenges of adjusting the standard stress testing toolkit to analyze climate risks, we compare these tools with market-based approaches proposed by academic researchers (e.g., Jung et al., 2023b). Market-based approaches to stress tests study the reaction of bank equity values to movements in aggregate risks (see Acharya et al., 2014), and help address some challenges in regulatory stress tests such as (i) the need for highly standardized but granular (asset-class level) data across institutions, (ii) the use of book values of assets in loan books and hold-to-maturity portfolios even when funding conditions reflect their market values, and (iii) the static nature of regulatory asset-specific risk-weights that determine bank capital requirements even when asset-level risks are evolving quickly. We describe the methodology and summarize the key results of the market-based climate stress test of Jung et al. (2023b), which captures the immediate expected impacts on bank equity values from changes in climate risk along a range of horizons. We propose a range of directions for future research to further develop such market-based approaches as complements to traditional stress testing approaches to managing climate risk.

Lastly, we discuss the possible implications of climate stress tests for macroprudential and microprudential supervision. We highlight that research and policy need to better understand the implications of possible "green capital requirements", which have been proposed by some regulators, on both carbon emissions and financial stability. More broadly, further work is required to better understand what policy, regulatory, and supervisory measures might be appropriate to build resilience against the consequences of climate-related financial risks. This is particularly important since central banks will need to clearly communicate how any proposed policies are justified within their various mandates. However, even if specific interventions might not presently be within central bank mandates, the development of appropriate climate risk scenarios for stress testing purposes is likely to be still valuable. In particular, the design of climate risk scenarios can pave the way for a better understanding of climate-related risks by both bank management and policymakers, for example by establishing uniform standards for bank reporting of climate risk exposures.

1 Central Bank Stress Tests as Risk Management Tools

Central banks frequently conduct stress tests to probe the resilience of the financial system and its components to a wide range of macroeconomic and financial risks. Stress tests are quantitative exercises that assess whether bank capital falls below given regulatory minima under some relatively severe but plausible scenarios.⁶ Stress tests, as employed for bank-level

⁶The Federal Reserve Board of Governors is currently conducting climate *scenario analyses* that are different from climate stress tests. Governor Lael Brainard (2021) clarifies the distinction as follows: "Scenario



Figure 1: Climate Stress Testing flows

Note: RWA: risk-weighted assets. Adapted from Borio et al. (2014) and Baudino and Svoronos (2021)

or regulatory (supervisory or macro-prudential) risk-management purposes, commonly have three components: *scenario*, *model*, and *outcome* (see Figure 1).

The first step of a stress test is to design a set of relatively severe *scenarios* to consider. A scenario is a combination of macroeconomic and financial shocks that are expected to affect the resilience of individual banks as well as the financial system. It describes the severity of the identified shocks, the transmission channels to important outcomes, and the time horizon over which the stress could materialize. To design scenarios, both direct and indirect impacts of shocks are analyzed.

The next step of a stress test involves a set of *models* that explore how the realizations of macro indicators described in a stress scenario affect banks. For each type of risk (e.g., credit risk, market risk, etc.), a granular approach that reflects the structure of different banks' balance sheets and income statements is used to understand how risk realizations would affect each assessed entity. This approach requires detailed exposure information and

analysis is an exploratory exercise that allows banks and supervisors to assess business model resilience to a range of long-run scenarios. It seeks to understand the effects of climate-related risks on a range of financial markets and institutions, as well as the potentially complex dynamics among them. By contrast, traditional stress tests are a regulatory exercise to assess the capital adequacy of banks to specific macroeconomic scenarios and financial market shocks over the short-run." For ease of exposition, we focus throughout the review on climate stress tests, though most of our comments would equally apply to scenario analyses.

other data from the banks used to project losses in the event of a shock based, among other things, on historical data on banks' profitability under various macro conditions.

The result is a set of stress test *outcomes* including bank capital shortfalls, net interest income (NII), pre-provision net revenue (PPNR), and balance sheet (B/S) projections under the stress scenario. In addition to accounting measures, outcomes can also include forward-looking market-based measures. For example, a shock to the viability of firms with loans from a bank could reduce the market capitalization of the bank substantially.

Supervisory stress tests generally focus on individual bank outcomes. For macro-prudential stress tests, additional modeling elements are required to reflect potential feedback loops within the financial system, such as contagion between banks and spillover effects between the real economy and the banking sector.

2 Climate Risks Scenarios

The first step to using stress tests for climate risk management is to determine the set of possible stress scenarios to consider. We begin by reviewing the various channels through which climate change can affect overall economic activity, considering also the horizon over which these channels are operative. We then review recent efforts to turn a qualitative understanding of these channels into quantitative measures that can be used for stress testing. We discuss the development of common stress testing scenarios by the NGFS, as well as various scenarios used by national regulators. We conclude the section with a range of suggestions for further academic research that would be helpful in the development of the next generation of climate risk scenarios.

2.1 Climate-Related Risks to Economic Activity

Climate-related risks to the economy are commonly categorized into two types: *physical* risks and transition risks (e.g., Giglio et al., 2021a; Stroebel and Wurgler, 2021; Baudino and Svoronos, 2021; Financial Stability Board and NGFS, 2022).

Physical risks refer to the effects on economic activity and asset values that come from the direct manifestations of climate change, such as floods, heat waves, and wildfires. For example, sea level rise and coastal flooding can cause economic damage by destroying residential properties and factories in coastal areas. Similarly, heat stress can jeopardize agricultural activities and subsequently devastate crop production, lead to an escalation of energy expenditures, and depress worker productivity. The economic effects of physical risk realizations differ across space and can, in some circumstances, even be positive, for example when

agricultural productivity rises in areas that were previously too cold.

Transition risk instead refers to the economic losses resulting from changes in policies, technologies, or preferences during the transition to a less carbon-intensive economy. The effects of transition risk realizations can differ across industries. For example, consider the introduction of carbon taxes or carbon pricing (as seen in Europe) as an example of a policy transition risk realization. Such risk realizations would reduce the profitability and even the viability of fossil-fuel firms, but improve the profitability of firms producing renewable energies (see the extensive discussion in van Benthem et al., 2022). Technological innovations to reduce carbon emissions can also create both losers and winners. For example, advances in the range of electric vehicles would hurt the sales and profits of internal combustion engine car manufacturers at the expense of firms with a bigger focus on electric vehicles. Similarly, a change in the preferences of consumers, producers, investors, and even employees, might trigger a switch to "greener" products.

Recent research has improved our understanding of financial market participants' perceptions of the relative importance of physical and transition risks over both short- and long-term horizons. These survey results can provide a valuable guide to the design of stress scenarios that are viewed as both plausible and important by market participants. Krueger et al. (2020) find that among investment professionals, regulatory and technological risks are seen as somewhat more important than physical risks. Moreover, most respondents expect that regulatory climate risks are already important today, while physical risks are generally thought to only become important over longer horizons. Stroebel and Wurgler (2021) document that finance academics, professionals, regulators, and policymakers consistently think that regulatory risks are the key climate risk for investors and firms over the next five years, while physical risks are the top risk over the next thirty years. The implied relative importance of different risks from such surveys is consistent with findings from a joint review of the practice of climate scenario analyses by the Financial Stability Board and NGFS (2022). That analysis suggested that almost 90% of the central banks' exercises explored the implications of transition risk, while about 67% analyzed the effects of physical risks.⁷

Physical and transition risks will sometimes move together, and sometimes in opposite directions. Specifically, in the early stages of the transition, these risks can move together, as increasing physical damages cause legislators to implement increasingly forceful regulatory responses. Over a longer time, and to the extent that regulatory interventions are effective in reducing carbon emissions and slowing the process of climate change, long-run physical

⁷This statistic might partly reflect the relative availability and consistency of data and modeling methodologies. For example, granular climate-related information on counterparties, location data, and climaterelated projections are identified as the key data gaps by central banks (Financial Stability Board and NGFS, 2022), and better availability of such data might lead to more stress scenarios that consider physical risks.

risk might decline as a result of the realization of transition risk. Conversely, delays in such policies could reduce transition risks, but increase long-run physical risks. Yet another possibility is that an increasing manifestation of physical risks leads to more adaptation and mitigation responses by private agents that render the incidence of these risks less damaging and thus reduce the need for regulatory action. Climate risk scenarios, therefore, need to consider a range of possible joint evolutions of both physical and transition risks.

2.2 Common Scenario Design

Turning this heuristic understanding of the potential importance of physical and transition risks into quantitative climate risk scenarios involves several challenges. First, unlike other stress scenarios such as housing price declines, no historical precedent exists for either extreme physical or transition risk realizations that would allow a careful calibration of their broader economic effects. Second, many climate risks may only materialize over rather long time horizons, introducing substantial uncertainties around, for example, the extent to which households, firms, and governments will invest in adaptation measures that reduce the economic implications of extreme weather events. Third, it is important to analyze both direct and indirect impacts of climate risk realizations. To analyze the direct impacts, climate impact models need to be developed to quantify the potential losses caused by acute physical events such as floods and hurricanes. To quantify the indirect effects, climate models need to be used to turn scenario narratives, including climate policies and technology changes, into transition pathways such as temperature and carbon trajectories and energy demand and prices. These pathways are further fed into macro models to estimate the impact of the underlying shocks on macro indicators such as GDP, unemployment, and inflation.

While these challenges are yet to be fully addressed, central banks and regulators have taken important first steps in developing a range of climate risk scenarios. Most importantly, the *Network for Greening the Financial System* (NGFS) has played a leading role in the development of a set of climate risk scenarios to serve as a common starting point for different regulators (NGFS, 2020, 2021). Such standardization of the risk scenarios has the benefit of improving the comparability of stress tests across different banks and regulators.

The NGFS published pathways for its first four scenarios in June 2020: *Disorderly*, *Orderly*, *Hot House World*, and *Too Little Too Late* (NGFS, 2020). These scenarios are based on the orderliness of the transition pathway and the achievement of climate targets as shown in the left panel of Figure 2. In June 2021, the NGFS (2021) published the second version of its scenarios, which describes six scenarios across three categories: *Orderly Transition* (Net Zero 2050, Below 2°C), *Disorderly Transition* (Divergent Net Zero, Delayed



Figure 2: Climate Risk Scenarios from NGFS (2020, 2021)

Transition), and *Hot House World* (Nationally Determined Contributions or NDCs, Current Policies), as presented in the right panel of Figure 2. Importantly, the NGFS does not assess the likelihood of each scenario and emphasizes that they should not be viewed as forecasts. Instead, they "aim at exploring the bookends of plausible futures (neither the most probable nor desirable) for financial risk assessment."

The Hot House World scenarios assume that current policies are maintained, resulting in high levels of emissions that lead to global temperature increases in excess of 3° C by 2100. In these scenarios, transition risk is limited, while physical risk is severe. In the two Orderly Transition scenarios, physical and transition risk realizations are relatively mild. For example, Net Zero 2050 is a scenario in which global warming is limited to 1.5 °C and global net zero CO2 emissions are achieved by about 2050. In contrast, the Disorderly Transition scenarios involve higher transition risk realizations due to delayed or divergent policy implementations. For example, the Delayed Transition scenario assumes that annual emissions do not decrease until 2030.

Based on these *scenario narratives*, different models are applied to produce specific *scenario variables* such as the pathways for temperature, carbon emissions, and carbon prices, as well as macro indicators such as the GDP and unemployment. NGFS (2021) outlines three sets of models that are typically employed to map scenario narratives to scenario variables

(see Figure 1). First, to estimate the direct effects of climate risk realizations, *climate impact models* take emission and economic exposure data and generate climate variables such as temperature, and economic variables such as the direct losses from natural disaster events. Second, to estimate the indirect effects of climate risk realizations, *transition pathway models* take climate policies such as constraints from an emissions budget as inputs and generate specific trajectories of carbon prices and temperature. Third, *economic impact models* such as NiGEM and IAMs, take transition pathways as inputs and produces projections of key economic variables such as GDP, unemployment, and inflation.

Different combinations of such models generate a different set of scenario variables. On average, the Net Zero 2050 scenario is expected to cause a 1.97% reduction in world GDP due to chronic physical risk, compared to the baseline scenario. The Delayed Transition scenario is projected to result in a larger GDP decline of 2.86%, while the Current Policies scenario is estimated to cause the greatest average GDP reduction of 5.66%.

2.3 Climate Risk Scenarios in Practice

Many regulators have conducted climate stress tests and scenario analyses, and many more such exercises are planned for the coming years.⁸ While regulators have often employed the NGFS scenarios described in the previous section, others have also developed additional scenarios that focus on aspects that are particularly relevant to the respective economics. Appendix Table 1 reviews the different scenarios chosen by various financial regulators.

Among the regulators working with the NGFS scenarios, some adopt NGFS scenario directly. For example, the Australian Prudential Regulation Authority (2021) used the *Delayed Transition Scenario* and *Current Policies Scenario* without further refinement on the narratives, but carried out Australian-specific modeling to provide macro outputs. Some central banks instead use scenario specifications that are modifications of the NGFS scenarios. For example, the Bank of Canada uses the NGFS *Current Policies, NDCs, Net Zero 2050*, and *Below 2 °C* scenarios, but modifies the time horizon under consideration (Ens and Johnston, 2020). Specifically, while the NGFS scenarios assess emission and temperature reductions by 2050, the Bank of Canada expands the horizon until 2100 and sets the objective to limit global warming to 2°C by 2100. Similarly, the Bank of England (2021b) applies the *Net Zero* 2050, *Delayed Transition*, and *Current Policies* scenarios, but adjusts the temperature goals to be 1.8° C, 1.8° C, and 3.3° C by 2050, respectively. Other central banks use a combination

⁸At least 23 jurisdictions, including the European Union, have conducted a total of 35 scenario analyses and climate stress tests to understand the implications of outcomes for both individuals and aggregate financial systems (Financial Stability Board and NGFS, 2022).

of NGFS and Intergovernmental Panel on Climate Change (IPCC) scenarios.⁹ For instance, the Hong Kong Monetary Authority (2021) directly adopts the IPCC Representative Concentration Pathway¹⁰ (RCP) 8.5 (high emissions scenario) to assess the effect of physical climate risks, and the Orderly Transition and Disorderly Transition scenarios to assess transition risks. Similarly, the Board of Governors of the Federal Reserve System (2023) applies the NGFS Current Policies and Net Zero 2050 scenarios in the transition risk module of their scenario analyses, and the IPCC SSP2-4.5 & RCP4.5 scenario and SSP5-8.5 & RCP8.5 scenario in the physical risk module.¹¹

Some regulators have also developed their own scenarios independently of those provided by the NGFS. For instance, De Nederlandsche Bank focuses on energy transition risks and proposes four scenarios based on two dimensions: government policy and technological developments (Vermeulen et al., 2018). The technology shock scenario assumes that the share of renewable energy in the energy mix doubles due to a technological breakthrough, but there is no policy to mitigate the adverse impact of climate change. The policy shock scenario supposes that the carbon price rises globally by \$100 per ton due to additional policy measures, but there is no technological breakthrough that lowers carbon emissions.

2.4 Scenario Design — Avenues for Future Research

While much progress has been made in recent years to develop the first set of climate risk scenarios, many questions remain. In this section, we discuss avenues for future academic research to improve the design of climate stress scenarios.

Regulatory Transition Risk as a Policy Choice. Climate stress tests should ideally consider scenarios that represent extreme but plausible climate risk realizations. The decision of which physical climate risk scenarios fit this description is largely outside the realm of

⁹IPCC scenarios are designed based on carbon emissions and socioeconomic pathways, and they are developed to assess physical risks. They have been adopted by NGFS in designing the Phase I scenarios. Both the IPCC and the NGFS use Integrated Assessment Models (IAMs) to develop transition pathways. NGFS scenarios, except the Net Zero 2050 scenario, do not have equivalents in IPCC. This is because NGFS focuses on transition pathways, while IPCC focuses on physical risks.

¹⁰Representative Concentration Pathways (RCPs) describe different levels of greenhouse gases and other radiative forcings that might occur in the future. The four RCPs span a broad range of forcing in 2100 (2.6, 4.5, 6.0, and 8.5 watts per meter squared), but do not include any socioeconomic changes to go alongside them (Intergovernmental Panel on Climate Change, 2019).

¹¹Shared Socioeconomic Pathways (SSPs) are complementary to the RCPs, and look at five different ways (SSP1-5) in which the world might evolve (along dimensions such as population, economic growth, education, urbanization, and the rate of technological development) in the absence of climate policy and how different levels of climate change mitigation could be achieved when the mitigation targets of RCPs are combined with this evolution (Intergovernmental Panel on Climate Change, 2019).

economics, and basing it on the best available scientific consensus, such as that produced by the IPCC, seems like the right approach.

On the other hand, regulatory transition risk realizations are unlikely to be primarily and certainly not entirely—driven by exogenous physical processes. Instead, they are the outcome of a decision process by a policymaker that aims to trade off the policy's costs and benefits (see Acharya et al., 2023b). In this light, it is somewhat implausible that policymakers would, for example, ever implement a carbon tax of a magnitude that would jeopardize the short-run debt-servicing abilities of high-emissions firms or dramatically reduce economic activity. While it is tempting on a first pass to treat energy prices as exogenous to a carbon tax, a carbon tax likely raises energy prices in general equilibrium (at least in the short-term until the transition to adequate renewable capacity is complete), and in turn, compresses aggregate demand and reduces economic activity. The resulting energy price volatility can also have important distributional consequences (see Känzig, 2021). Some such considerations likely explain the divergent policy paths adopted by Europe and the United States. Finally, political inclination to tackle climate change may lack time-consistency, or vary over the electoral cycle, especially once the transition to renewable energy has made decent progress. This lack of commitment can induce a countervailing private response via activism of long-term investors or climate-sensitive employees and lead to net-zero commitments by firms (see Acharya et al., 2023a).

We, therefore, believe that it is important to complement the design of *plausible* transition risk scenarios with a more formal exploration of which policies and private responses over time and across states of the world—are likely to be subgame-perfect equilibrium outcomes. Research that combines insights into the relevant political economy considerations with quantitative modeling techniques to explore whether a scenario with a given regulatory intervention is a plausible equilibrium policy outcome has the potential to add substantial value to regulatory practice (see Dunz et al., 2021a).¹²

Feedback Loops between Climate Change and the Economy. A key focus in the design of climate risk scenarios is to assign plausible GDP levels that would coincide with the realizations of various climate risk realizations. While existing models such as NiGEM provide one path to assessing these relationships, more work is required to ensure that the resulting scenarios do indeed accurately capture the various feedback loops between climate risks and economic activity.

One key challenge with determining these co-dependencies is that, unlike for macroe-

¹²Some transition risks, such as risks coming from changes in preferences or technologies, may not be a policy choice. However, regulatory risk is often viewed as the most concerning transition risk (e.g., Stroebel and Wurgler, 2021; Financial Stability Board and NGFS, 2022).

conomic and financial risk factors with in-sample realizations that typify the traditional bank stress tests, extreme physical or regulatory climate risks have not yet occurred, which minimizes the usefulness of statistical techniques to understand the relevant feedback loops. Therefore, understanding the relationship between, for example, climate risk realizations and GDP growth, requires the use of structural economic models.

In existing models, a number of opposing forces are at work (see Giglio et al., 2021a,b, for a detailed discussion). Specifically, a key ingredient in many Dynamic Integrated Climate-Economy (DICE) models along the lines of Nordhaus and Boyer (2000) is that climate change is the byproduct of economic growth; damages from climate change, which are often modeled as a tax on consumption, are thus largest when GDP levels are the highest. In contrast, models along the lines of Weitzman (2012), Weitzman (2014), and Barro (2015) consider the possibility of climate disasters: low-probability catastrophic climate events that could dramatically impact the economy. In those models, states with substantial physical climate risk realizations and low GDP can occur jointly, with low-GDP states directly resulting from realizations of the climate disaster.

Survey evidence mirrors this disagreement about the relationship between climate change and economic activity. Stroebel and Wurgler (2021) find that 32% of their survey respondents believe investments to mitigate climate damages pay off particularly in good economic times, consistent with expecting climate damages to be larger during those good times. 13% of survey respondents believe that investments to mitigate climate damages are more likely to pay off in bad economic times, while 55% of respondents do not see a strong relationship between the payoffs to investments to mitigate climate change and economic conditions.

Given this disagreement in both survey data and across modeling approaches, research that further advances our understanding of the feedback loops between climate change and economic activity can help with the generation of plausible economic pathways in scenarios with large physical climate risk realizations. Such research may also help ascertain if/when the market price of physical climate risk is likely to be negative (DICE models) versus positive (climate disaster models), enabling a better mapping from climate risk into market risk.

Compound Risk. It is widely recognized that multiple risks may be realized at the same time, giving rise to "compound risk." Conceptually, there are at least three distinct cases that can arise. First, the realization of two risks at the same time may be purely due to chance when risks are independent. Second, realizations of multiple risks at the same time may occur because they are both reflections of a common underlying event. Third, and most relevant for systemic risk implications of climate change, compound risk scenarios may result when the realization of one risk subsequently increases the probability of another risk, so that there is a causal ordering or feedback between the risks. For example, the feedback loops between growth and climate risk discussed in the prior section are a potential source of this type of compound risk. But there are other potentially important compound risk channels when considering climate risks. For example, researchers have discussed possible feedback loops whereby increasing climate change raises the probability of pandemic risks (Di Marco et al., 2020).

How should compound risks be modeled in stress test scenarios? We argue that this depends on whether compound risks result from independent or interdependent risk realizations. Specifically, if two risks are largely independent, then it is sensible to design scenarios for each event separately since the probability of two or more tail events at the same time is much smaller than either alone. If the probability of each risk occurring is α , then the probability that one or the other will occur is approximately 2α if α is small. Thus, a risk manager or regulator that can tolerate the α probability of a risk realization of either type may choose to test scenarios with a probability of only $\frac{\alpha}{2}$. As a corollary, the risk manager or regulator should mitigate each risk as appropriate for a probability $\frac{\alpha}{2}$ event.

On the other extreme, if the risks are completely dependent then the scenario should consider their joint realizations with probability α . In addition, the scenarios can be constructed to account for the possible temporal ordering of risk realizations. For example, carbon emissions from economic growth might only cause climate risks with a substantial delay and the effects of regulatory risk realizations on growth may take some time to materialize. As discussed above, improving our understanding of the co-dependence of climate risks and other risks requires substantial econometric and theoretical analysis. For some climate risk realizations (e.g., hurricanes or a higher carbon price), past data can be informative—for example, one could study how large movements in the carbon price in the European Emissions Trading System (ETS) affect outcomes (see Känzig, 2021). For other risk realizations without any in-sample equivalent, theoretical equilibrium modeling is likely to be required.

If the nature of dependence between risks is intermediate, for example, because sometimes climate risk realizations co-occur with economic slowdown but not always, then the statistical analysis of *tail dependence* suggests a possible path forward. Tail dependence is defined as the limit as α goes to zero of the probability that risk 1 (say, economic growth) is in the tail conditional on risk 2 (say, climate risk) being in the tail (Sibuya, 1960; Joe, 1997; McNeil et al., 2015). Importantly, correlation between the two risks is neither necessary nor sufficient for tail dependence. There is substantial literature on estimating the tail dependence between events (Frahm et al., 2005). Once the tail dependence is estimated, one can find the probability that both risks occur. Suppose then that a risk manager seeks the property that a scenario have an overall probability less than or equal to α of a compound risk

occurring. To achieve this property, the risk manager can factor in tail dependence and adjust the probabilities (and thus the threshold quantiles that lead to stress) of individual risks. We believe that estimating tail dependence of climate and other macroeconomic or financial risks is a fertile area for future research, in particular for those climate risk realizations, such as carbon price movements, for which we observe in-sample realizations. Such studies can pave the way for a judicious construction of compound risk scenarios in climate stress tests.

3 Climate Risk and Banks

After a set of scenarios has been selected, the next step of a climate stress test involves understanding how the changes in the climate and macroeconomic variables specified by the scenarios affect banks' financial situations. Both physical and transition climate risks can, in principle, affect banks through multiple channels (see Figure 3), including through their loan books (credit risk) as well as their trading portfolios (market risk). We next discuss several considerations that are important to assess when each of these channels has the potential to affect financial stability via its implications for banks' financial situation (see also Grippa et al., 2019; Bolton et al., 2020; Bank for International Settlements, 2020).

Figure 3: Climate Risk and Risk Channels



Source: Adapted from Grippa et al. (2019) and Bolton et al. (2020)

3.1 Credit Risk Channel through Loan Portfolios

Most directly, climate risk can affect a bank's credit risk through its loan book, with both physical and transition risk realizations potentially reducing borrowers' abilities or willingness to repay outstanding loans.

Any quantitative assessment of the materiality of various climate risks for a bank's loan portfolio requires a comparison of the horizon over which these risks are expected to materialize and the average maturity of banks' loans. Recent work has documented that the average maturity of loans of the U.S. banks at origination is between 3 and 5 years (Blickle et al., 2020; Chodorow-Reich et al., 2022), with the average maturity in the case of European banks being closer to 5 years (Berg et al., 2017).

Physical climate risk realizations have the potential to increase the credit risk exposure of banks by affecting the cash flows of borrowers. As an example, declining house prices due to sea level rise (or the risk of future sea level rise) may induce borrowers to default on their mortgages. Similarly, cash flow shocks from floods and wildfires, for example due to the need to invest in rebuilding, might reduce homeowners' ability to make mortgage payments (see Bailey et al., 2019; Ganong and Noel, 2020). Through both channels, physical climate risk may affect the value of banks' mortgage loans. Any decline in home values due to sea level rise or wildfire risks could also affect local property tax revenues, and consequently the repayment ability of municipalities in locations exposed to climate risks. Physical climate risk can also affect the value of banks' loans through a collateral channel. Islam and Singh (2022) suggest that the value of borrowers' pledgeable collateral, such as land and machinery, and income streams can be negatively affected by abnormally hot temperatures. Furthermore, heat waves can raise energy expenditures and utilities may be unable to pass through the costs of meeting heightened demand to consumers, with negative effects on their financial health (Acharya et al., 2022). Physical climate risk realizations can also disrupt supply chains and production processes, with the potential to affect firms' ability to service and repay their bank loans (see Pankratz and Schiller, 2021). Beyond the effects of physical climate risks on the repayment ability of directly affected borrowers, any decline in economic growth or productivity from realizations of physical climate risks can affect loan performance even among firms and other borrowers not directly affected by the climate risk realizations.¹³

However, to the extent that many of the cash-flow implications of physical climate risk realizations are expected to materialize only at longer horizons (see Stroebel and Wurgler,

¹³See Das et al. (2022) for the financial intermediation channel through which natural disaster shocks transmit to the real economy, and Boustan et al. (2020) for the economic effect of natural disasters in the U.S. at the county level. As a counterpoint, Addoum et al. (2020) do not find evidence that temperature exposures significantly affect establishment-level sales or productivity.

2021), the effects of those risks on banks through their loan books may be limited. Such a hypothesis is consistent with empirical findings in Painter (2020), who documents that sealevel rise exposure is only priced in municipal bonds with maturities in excess of twenty years, and in Acharya et al. (2022), who find that exposure to heat stress is only priced in municipal bonds with maturities greater than ten years. The hypothesis is also aligned with work by Nguyen et al. (2022) that suggests banks only adjust interest rates to sea level rise exposure for mortgages with maturities longer than fifteen years. Acharya et al. (2022) document that exposure to heat stress affects the Moody's KMV's Expected Default Frequency (EDF) of an S&P500 company—an estimate of the company's statistical probability of default—beyond one year; however, the effect at years five and ten is twice that for year two. In light of this evidence, it would be valuable to increase the focus of future climate risk scenarios on the longer-term implications of physical climate risk scenarios.

Transition risk realizations can also affect banks' loan books by increasing their credit risks. For example, a large carbon tax can reduce the profitability of firms in high-emission industries, many of which tend to have high leverage, reducing their ability to repay any outstanding bank loans. Carbon taxes and the associated shift away from high-emission activities can also affect the local tax revenues in locations with a sizable concentration of high-emission industries, such as the oil-producing regions in Texas and North Dakota, or the coal-producing regions of Germany. Through such effects, transition risk realizations can increase the credit risk from any direct loan exposure of banks to those localities.

Jung et al. (2023a) use the Y-14 data to investigate U.S. banks' credit risk exposures to climate policies. Their methodology builds upon sectoral estimates for the U.S. economy based on the general equilibrium models of Jorgenson et al. (2018), Jorgenson et al. (2013), Goulder and Hafstead (2018), and NGFS (2022). Jung et al. (2023a) find that the impact of climate policies on banks' loan portfolios varies significantly across the policies considered in those studies, though they confirm that, in general, banks with larger exposures to high emitting borrowers are more adversely susceptible to the effects of stricter climate policies.

While the effects of physical climate risks on firm and household cash flows are largely expected to come in the more distant future—and mostly beyond the average maturity of banks' loan books—the effects of transition risks on banks' loan books might materialize more quickly. Indeed, carbon taxes could, in principle, be introduced at any moment, though any carbon tax that can lead to a large negative effect on firms' ability to repay their bank loans may not be a plausible scenario to consider given that policymakers are not likely to implement a disruptive policy in the short run, as discussed in Section 2.4.

3.1.1 How are Banks' Lending Activities Responding to Climate Risks?

The preceding discussion argues that banks' current credit risks are primarily affected by physical and transition climate risk realizations that might materialize in the relative short term. To determine banks' possible exposures through a credit risk channel to more distant realizations of climate risks requires taking a dynamic balance sheet approach that allows for the adaptation of financial institutions to changes in climate risk. For example, it is likely that banks' loan exposures to the coal sector will decline over time, in particular along paths in which transition risk realizations become more likely.

Yet, despite the importance of incorporating banks' dynamic lending responses to climate risks, only about 20% of climate stress testing and scenario analysis exercises adopted a dynamic or a hybrid balance sheet approach (Financial Stability Board and NGFS, 2022). To inform future improvements in modeling dynamic risk exposures of banks over the duration of various climate risk scenarios, we next review academic research that focuses on the various ways that banks' lending activities are already affected by climate risk considerations, and how these responses feed back into the exposure of banks to climate risks.

On the physical risk side, Nguyen et al. (2022) show that mortgage lenders charge higher interest rates for mortgages on properties that are exposed to a greater risk of sea level rise. Javadi and Masum (2021) find that firms in locations with higher exposure to drought pay higher spreads on their bank loans. Correa et al. (2020) suggest that after natural disasters that tend to raise the salience of climate risks, banks increase the relative pricing of loans to borrowers with more substantial climate risk exposures. From a stress-testing standpoint, the higher cost of these loans would not lead to any significant impact on banks' credit risk exposure, unless future costs escalate to a point where loan quantities are meaningfully affected. On the other hand, the higher short-run revenues from loans to entities that are more exposed to climate risk realizations can improve the capital adequacy of the banks, and reduce the probability that any future credit losses due to climate risk realizations will constitute a threat to financial stability.

In addition, to fully understand the effects of physical climate risk realization on banks' profitability, it is important to improve our understanding of the effects of these disasters not just on banks' existing loans, but also on future loan demand. For example, Blickle et al. (2021) find that loan losses due to disasters are offset by an increase in loan demand, resulting in insignificant or small effects on bank performance and stability.

On the transition risk side, several papers have documented that banks price climate policy risk exposure. Chava (2014) finds that banks charge higher interest rates on loans granted to firms with poor environmental performance and tend to avoid firms with environmental concerns. Ivanov et al. (2022) document that banks attempt to reduce their transition risk exposure by shortening loan maturities and lowering access to permanent forms of bank financing for high-emission firms. Delis et al. (2019) suggest that banks charge higher loan rates to fossil fuel firms and that this effect increases in loan maturity. Laeven and Popov (2022) and Benincasa et al. (2022) argue that lenders shift their lending to high emissions sectors in those countries with less strict climate policy and environmental regulation. Such price and quantity adjustments can have real implications. Kacperczyk and Peydró (2022) show that firms with a higher carbon footprint previously borrowing from banks that made a commitment to decarbonize subsequently receive less bank credit. Overall, these adjustments to the quantity of lending to high emissions firms will reduce banks' long-run exposure to climate risk realizations through a credit risk channel.

While there is increasing evidence that banks adjust their lending to entities exposed to physical and transition climate risks, more research is required to understand whether this adjustment is adequate from a risk management perspective—not just the private or bank-level risk management perspective but also the supervisory and macroprudential one. Answering these questions requires researchers to propose a model of how climate risks will affect the cash flows of various borrowers, and how that translates into changes in banks' credit risk exposure. While difficult, such detailed work is central to determining the need for possible policy interventions by macroprudential regulators.

3.2 Market Risk Channel through Trading Portfolios

While physical climate risks that materialize in the distant future are unlikely to affect banks' credit risk exposures through cash flow implications for borrowers in their relatively short-maturity loan books, effects of these risks on expected future cash flows can have an immediate effect on the present-day values of financial assets. Similarly, even if carbon taxes and other transition risks that threaten the immediate repayment ability of high-emission firms are unlikely to be implemented. As a result, both physical and transition climate risks can affect banks via the market risk of their trading books, in which they hold a range of financial assets.¹⁴ We next summarize the current state of the academic literature that studies the extent to which climate risk is reflected in the prices of financial assets (see Giglio et al., 2021a, for a complementary review of this literature). We also discuss directions for future research to improve our understanding of these asset pricing effects.

¹⁴We ignore for simplicity the possibility that such market risk can also affect borrowers' credit risk, especially those subject to short-term rollover risk in capital markets.

3.2.1 Climate Risks and Asset Prices: Empirical Evidence

Equity Markets. Researchers are increasingly studying the effects of climate risks on equity markets, with many concluding that climate risks are at least partially incorporated in stock prices. For example, Bolton and Kacperczyk (2022) find higher stock returns for companies with higher carbon emissions in all sectors and across Asia, Europe, and North America. This is consistent with the model of Pástor et al. (2021), which predicts that green assets have lower expected returns, as well as the evidence in Giglio et al. (2023a), who show that the average retail investor expects negative excess returns on ESG investments.¹⁵ It is also consistent with the work of Engle et al. (2020) and Alekseev et al. (2022), who document that stocks with lower climate risk exposures outperform in periods with negative news about climate risks. Faccini et al. (2022) construct news-based risk factors related to physical and transition risk and find that (only) climate policy risks are priced in U.S. stocks, especially after 2012. Choi et al. (2020) document that carbon-intensive firms underperform firms with lower carbon emissions in periods when local temperatures are abnormally high and investors pay particular attention to climate risks. In terms of physical risks, Acharya et al. (2022) conclude that S&P500 corporations with a one standard deviation higher heat stress exposure have a 45 bps higher (un-levered) expected return per annum, with the effect being observed robustly since 2013. Cuculiza et al. (2021) find that sell-side equity analysts incorporate climate news in their earning forecasts, suggesting that stock prices can be sensitive to climate change events via their forecast revisions.¹⁶

Municipal Bond Markets. Due to the geographic concentration of the tax base, municipal bonds are likely to be affected by concerns about physical climate risks. Painter (2020) examines whether the cost of issuing municipal bonds is affected by the issuing government's exposure to sea level rise. He finds that long-term municipal bonds are significantly affected by this measure of physical climate risk exposure. Goldsmith-Pinkham et al. (2022) also find that municipal bond markets have priced a location's sea level rise exposure since at least 2013. Specifically, they document that issuers in locations that are exposed to sea level rise have significantly higher borrowing costs than "close-neighbor" unexposed issuers, with stronger effects for long-maturity bonds. Kyung Auh et al. (2022) document that natural disasters have significantly negative impacts on bond prices for areas affected by natural disasters, with these impacts being relatively gradual as investors tend to under-react at the

¹⁵However, Pástor et al. (2022) highlight that green assets can have higher realized returns over some periods if agents' demands shift unexpectedly in the green direction.

¹⁶In contrast to this literature, Gostlow (2021) constructs physical climate risk factor-mimicking portfolios and documents that the priced portion of physical climate risk is only between 8% - 38% of its total variance. Similarly, Addoum et al. (2023) document that even though firm profitability is influenced by extreme temperatures, stock prices do not immediately react to temperature shocks.

initial stage after the disaster. Acharya et al. (2022) suggest that exposure to heat stress is also priced in municipal credit spreads: a bond whose issuer is located in a county that is exposed to heat damages equal to 1% of GDP has a 15 bps higher credit spread compared to borrowers with no heat risk exposure. This effect is stronger for lower-rated municipalities, longer-maturity bonds, and revenue-only bonds.

Corporate Bond Markets. Seltzer et al. (2022) study the pricing of climate risks in corporate bond markets. They document that changes in transition risk—for example coming from commitments as part of the Paris agreement—have greater effects on bond credit ratings for firms with a worse environmental performance. Huynh and Xia (2021) find that bonds that are more negatively exposed to climate change risk earn higher returns. Moreover, when investors are concerned about climate risk, they are willing to pay higher prices for bonds issued by firms with better environmental performance. Acharya et al. (2022) find that a one-standard-deviation increase in heat stress exposure raises sub-investment grade bond spreads for S&P500 corporates by 40 bps, with little effect for investment-grade bond spreads. The effect is robustly observed since 2013.

Sovereign Bond Markets. Studies of the pricing of climate risk in sovereign bond markets are complicated by the small set of relatively heterogeneous countries available. In this space, de Boyrie and Pavlova (2020) examine the effects of a country's environmental performance on sovereign credit risk using credit default swaps (CDS) spreads for a panel of 50 countries. Their findings suggest that a country with better environmental performance has lower sovereign credit risk, and this relationship is consistent across different maturities.

Real Estate. A large literature has documented that physical climate risks such as sea level rise, floods, and wildfires have an impact on real estate markets, in particular in locations and at times when home buyers are concerned about climate change. For example, Giglio et al. (2021b) create a "climate attention index" to measure households' perceptions of climate risks. They show that during periods of increased climate risk attention, the relative valuation of more exposed properties declines. Bernstein et al. (2019) analyze U.S. housing markets and estimate that coastal homes that are vulnerable to sea level rise are priced at a 6.6% discount relative to similar homes at higher elevations. Baldauf et al. (2020) find that houses located in a flood zone sell for 2.8% less than an identical house located outside a flood zone. Furthermore, the house prices in a flood zone decrease by 1.0% with an increase of 1.0% in the fraction of residents believing that climate change is happening.

These effects of climate risks on real estate values have follow-on implications for mortgage markets. For example, Nguyen et al. (2022) find that mortgage lenders charge higher interest rates for mortgages on properties with higher exposure to sea level rise. Similarly, De Marco and Limodio (2023) document that in counties with a positive exposure during the El Niño event, house prices and mortgage lending decline significantly, respectively, by 1.4% and 11%. Additionally, transition risks such as regulatory risk can also have an impact on real estate and mortgage markets through the pricing of insurance. One commonly studied setting is the National Flood Insurance Program (NFIP). Blickle and Santos (2022) find that mandatory flood insurance reduces mortgage lending because borrowers have to make expensive insurance and mortgage payments and banks may suspect them of being unable to do so. In a related study, Ge et al. (2022) conclude that a \$1 increase in annual flood insurance premiums causes a reduction of \$102 in home prices.

Other asset classes. Climate risks may also affect the valuations of additional financial assets. For example, crypto-assets can be energy-intensive since Distributed Ledger Technologies can require a considerable amount of electricity usage, a key source of carbon emissions (Office of Science and Technology Policy, 2022). Taxes on carbon emissions could thus substantially increase the cost of mining certain crypto assets. It is an interesting question to explore whether crypto assets exposed to transition climate risks trade at a substantial discount.

3.2.2 Climate Risks and Asset Prices: Open Questions for Future Research

We next discuss a range of directions for future research that would help our understanding of how climate risks can affect bank stability through a market risk channel.

Adequacy of Climate Risk Pricing. As reviewed, the academic literature has convincingly shown that climate risks are at least partially priced across a wide range of asset classes. As a result, any changes in perceived physical or transition risks, as well as any realizations from such risks, have the potential to reduce the values of these assets. However, to understand these market risk implications from such a pricing, a more complex question is central: are climate risks *adequately* priced in asset markets? If they are not, and in particular if there is substantial underpricing of climate risks, changes in investor perception or attention to these risks can lead to a further repricing of assets, even if the true underlying probabilities of risk realizations remain unchanged.

Understanding the adequacy of current climate risk pricing is much harder than rejecting the null hypothesis that climate risks are not priced. Such an analysis requires a model of how risk prices and different assets' state-dependent cash flows are affected by climate change.¹⁷ We believe that such analyses are a natural next step for academic research in climate finance.

¹⁷The work in Giglio et al. (2021a) could provide a starting point for exploring the appropriate discount rates to study the extent to which climate risks are adequately reflected in asset prices.

Two pieces of research provide suggestive evidence that climate risks may not yet be adequately priced. First, in the survey by Stroebel and Wurgler (2021), 60% of respondents argued that climate risks were not priced enough in equity markets, and 67% responded that they were not yet sufficiently priced in real estate markets. Essentially no investor believed that these risks were overpriced in these markets.

Second, there is evidence that, at least in real estate markets, there is increasing sorting between the climate beliefs of investors and the climate change exposure of assets. For example, Bakkensen and Barrage (2022) conduct a door-to-door survey and demonstrate that individuals who do not believe in climate change disproportionately tend to reside in high-risk flood zones. Similarly, Bernstein et al. (2020) document that houses threatened by sea level rise are increasingly more likely to be owned by Republicans, who are less likely to be concerned about climate risks. To the extent that the real estate most exposed to physical climate risks is thus increasingly traded between individuals who may not fully believe in climate change, this would lead to a mispricing of climate risks, at least under the beliefs of an investor or regulator who believes the scientific consensus around climate change. A similar sorting may also occur in other asset classes, where investors skeptical of climate change may be the residual holders of the various climate-exposed assets. Improving our understanding of both the extent and the implications of sorting on heterogeneous climate beliefs appears to us to be an important area for future work.

Climate Expectation Formation. As discussed above, the key mechanism that links future climate risk realizations with asset prices (and thus market risk) today works through investor's expectations. Asset prices today will only be lower in a *Hot House World* scenario if investors already anticipate (and price in) large future declines in GDP in such a scenario. Instead, if investors' climate beliefs today were similar across scenarios, the differences in today's asset prices (and thus market risk) across scenarios would be small.

As a result, we believe that researchers need to better understand the process of climate belief formation, and incorporate relevant insights into the economic models that generate the asset pricing outcomes across different scenarios. For example, possible peer effects in belief formation can have substantial implications about plausible paths of equilibrium asset pricing responses to climate change (see Kuchler and Stroebel, 2021; Bailey et al., 2018a,b, 2020). Furthermore, research shows that realizations of extreme weather events today affect beliefs of future climate risks (e.g., Choi et al., 2020; Alekseev et al., 2022), which has the potential to amplify any asset pricing effects of physical climate risk realizations.

3.3 Liquidity Risks

Climate risks can also be a source of liquidity risk through their effect on banks' deposit and funding costs. For example, banks' liquidity buffers can fall due to deposit withdrawals, a sharp increase in lending relative to their stable funding source, or both. The former can happen when households withdraw deposits due to liquidity needs in response to climate risk realizations. Brei et al. (2019) find that following a hurricane strike, banks face deposit withdrawals and experience a negative funding shock. This can be especially concerning since banks' deposits are often geographically concentrated (Kundu et al., 2022). This suggests that a large climate shock can lead to a substantial liquidity shock for local banks. As is well known from the work of Khwaja and Mian (2008), such liquidity shocks can destabilize bank funding and reduce the supply of long-term financing of corporates, with negative effects on the economy. Billings et al. (2022) and Kundu et al. (2022) provide evidence in support for this channel.¹⁸ Dlugosz et al. (2022) point out that bank branches' ability to set deposit rates locally can play an important role. They find that, after a disaster, branches whose deposit rates are set locally offer higher rates and experience greater deposit inflows. Banks' liquidity buffers can also fall due to a sharp increase in lending after natural disasters (Cortés and Strahan, 2017; Chavaz, 2016). The Bank for International Settlements (2021) documents that the Bank of Japan offered record amounts of liquidity to Japanese banks to ensure stability in the markets after the Great East Japan Earthquake in March 2011.

Compared to other channels, the liquidity risk channel of climate risk has been relatively understudied. As a result, we believe that more research on the adjustments of quantities and prices of deposits and loans would be useful to better quantify the effect of physical climate risk realizations on banks' funding costs and liquidity. In addition, we are not aware of any paper that has studied the effect of transition climate risk on banks through the liquidity risk channel. For example, banks with substantial exposure to depositors in oil-producing regions may see an increase in their funding costs when carbon taxes curb economic growth in those regions. It would also be valuable to study the extent to which liquidity shocks due to climate risks might be correlated across banks, which would increase the importance of understanding climate-induced liquidity risks from a financial stability perspective.

¹⁸Billings et al. (2022) shows that banks with high exposures to physical risks on both sides of their balance sheets decrease their loans when natural disasters occur in the areas they serve. Kundu et al. (2022) focus on the effect of banks' deposit exposure to physical risks and the corresponding negative effects of disasters on bank lending. On the other hand, Steindl and Weinrobe (1983) find the opposite effect: an increase in deposits following a disaster.

3.4 Aggregation and Financial Stability Outcomes

Once the climate risk exposures of individual banks are quantified, a macroprudential stress test would then explore how these bank-level risks aggregate to affect financial stability.

While many stress test reports do not disclose specific methods of aggregation, they commonly conclude that climate-related risks do not (yet) pose a significant threat to financial stability. However, this conclusion usually includes caveats regarding the many assumptions behind the analyses. Some reports present quantitative metrics to measure the various aggregate losses under different scenarios. For instance, the European Central Bank (2022a) finds that under a short-term three-year *Disorderly Transition* risk scenario and two separate physical risk scenarios (flood risk and drought and heat risk), the combined credit and market risk losses for the 41 banks that provided projections would amount to around 70 billion Euros, though the ECB cautions that in their excercise there was no economic downturn accompanying the negative climate effects. The Bank of Canada concludes that under its transition risk scenarios, the largest impacts are in the fossil-fuel sectors, where asset values are 80% - 100% below the current policies baseline in 2050 (Ens and Johnston, 2020).

Some reports emphasize a comparison of outcomes from different scenarios. In most cases, an orderly transition involves fewer economic damages than a disorderly transition or no action. The Bank of England (2022) states that banks' projected climate-related credit losses were 30% higher in the *Late Action* scenario than in the *Early Action* scenario. Similarly, the European Central Bank (2022a) highlights that projected loan losses under the *Orderly Transition* scenario are lower than those both under a *Disorderly Transition* scenario and under a *Hot House World* scenario. The Banque de France concludes that in the *Orderly Transition* scenario, the cost of credit risk is estimated to reach 15.8 bps in 2050, while that of the *Sudden Transition* scenario would reach 17.2 bps, which is 8.9% higher than in the *Orderly Transition* scenario (Autorité de Contrôle Prudentiel et de Résolution, 2021).

To advance our understanding of the system-wide implications of climate risk, several studies have developed a network-based climate stress test framework with a financial contagion module that considers the inter-linkage among financial institutions. Battiston et al. (2017) conduct a network-based stress test to explore the extent to which financial actors have direct exposures to the fossil fuel industry as well as indirect exposures through the financial system. They apply their approach to the Euro area and find that while direct exposures via equity holdings to the fossil-fuel sector are small, the combined exposures that include indirect links through counterparties are substantially larger. Roncoroni et al. (2021) extends this framework to consider four rounds of contagion. The first two rounds correspond to the direct and indirect exposures measured by Battiston et al. (2017). The third round explores fire-sale contagion among financial institutions, and the last round includes losses that are too large to be absorbed by banks and are thus transmitted to external creditors. They apply this framework to the Mexican financial system and suggest that stronger market conditions (higher recovery rate, lower asset price volatility, etc.) can support more ambitious climate policies at the same level of risk.

4 Market-Based Approaches to Climate Stress Testing

A key challenge with implementing the "bottom-up" climate stress tests described in the previous sections is the need for extensive asset-level data on climate risk exposures. Financial Stability Board and NGFS (2022) summarizes the main data gaps to include granular climate-related information such as carbon emissions, geographical location data, forward-looking information about transition plans, industry classification codes, and climate-related projections. To overcome some of these challenges, the European Central Bank provides participants with calculations and examples of proxies that can be used to estimate Scope 1, 2, and 3 emissions (Dunz et al., 2021b).¹⁹ In practice, however, current approaches do not fully solve the data issues. For instance, the European Central Bank (2022b) shows that bank models generate sizable discrepancies of emission estimates for the same counterparty.

Yet another challenge is that regulatory stress tests are based on marking of loan books and hold-to-maturity assets at their current book values, whereas many balance-sheets may be trading in markets at lower values (i.e., at market-to-book ratio less than one) and therefore with substantially lower capacity to raise capital than implied by book values.

Finally, capital shortfalls in stress tests are calculated based on risk-weighted assets, with risk weights revised only infrequently, which renders them vulnerable to the "risk that risk will change" and to regulatory arbitrage by financial institutions.²⁰

To overcome some of these challenges, Jung et al. (2023b) develop a market-based climate stress testing methodology. Their "top-down" stress tests are built on a new measure called *CRISK*, which can be constructed at high frequency using only publicly available data on the balance sheets of financial institutions. The methodology involves three steps.

¹⁹Scope 1 covers direct emissions from owned or controlled sources. Scope 2 covers indirect emissions from the generation of purchased electricity, steam, heating and cooling consumed by the reporting company. Scope 3 includes all other indirect emissions that occur in a company's value chain.

 $^{^{20}}$ For example, Acharya et al. (2014) compare the market-based capital shortfall measure, *SRISK*, with the capital shortfall measured by regulatory stress tests during the Eurozone sovereign debt crisis (2009-2011). They find that when capital shortfalls are measured relative to risk-weighted assets, the ranking of financial institutions is not well correlated to the ranking of SRISK, whereas rank correlations increase when required capitalization is a function of total assets. They show this is because risk-weights on assets are static and not representative of evolving risks. Similar considerations due to static risk weights could arise in the context of climate stress tests, creating a valuable complementary role for market-based tests.

The first step is to propose a climate risk factor that can be measured at high frequency using market prices. Jung et al. (2023b)

The second step is to measure banks' stock return sensitivity to the climate risk factor. Following a standard factor model approach, Jung et al. (2023b) regress each financial institution's stock return on the climate risk factor and the aggregate stock market factor. A bank-specific loading on the climate risk factor is called the bank's "climate beta." The climate betas are estimated dynamically, allowing for time-varying state-dependent volatility and correlation, based on the Dynamic Conditional Beta model in Engle (2002, 2009).

The last step computes a measure called CRISK, defined as the bank's expected capital shortfall conditional on climate stress. The capital shortfall is taken as the capital reserves the financial firm needs to hold to meet a prudential capital requirement based on the market value of equity that would ensure healthy intermediation from the firm. The prudential level of market equity capital relative to quasi-market value of assets (the sum of book debt and market equity) can be set as a stress testing parameter, say 8%. To determine the climate stress level, a low (say 1%) quantile of the 6-month return on the climate risk factor is chosen as a plausible stress scenario. The CRISK so computed is a function of the size of the financial institution, its leverage, and its expected equity loss conditional on the climate stress, which is called Long Run Marginal Expected Shortfall (LRMES).²¹

This top-down market-based approach bypasses some of the key challenges in bottomup book-based climate stress tests based on scenarios with deterministic long-run paths for carbon prices and damages. First, it implements a transparent methodology that is straightforward to estimate on an ongoing basis using publicly available data. Second, it can fully incorporate current market expectations, avoiding the need to define a process of the extent to which future risk realizations are incorporated into beliefs and thus asset prices (see the discussion in Section 3.2.2). Third, the CRISK framework estimates a dynamic beta model that allows for variations in how firms, banks, and markets respond to the climate risk over time. The transparency of the methodology and the outcome at the bank level can enhance understanding of the financial stability implications of climate risk for policymakers, financial institutions, and other stakeholders who manage associated risks.

However, while the market-based approach has many advantages, and reduces the need for regulators to have a clear insight into different banks' asset holdings, it relies heavily on financial markets pricing these risks adequately in different banks' stock returns. In other words, CRISK can measure the expected capital shortfall only to the extent that the market

²¹Formally, the CRISK of bank *i* at time *t* is $CRISK_{it} = kD_{it} - (1 - k)W_{it}(1 - LRMES_{it})$ where *k* denotes the prudential level of capital relative to assets, *D* denotes the bank's book value of debt, *W* denotes the market capitalization of the bank.

is pricing the climate risk and does not reflect underpriced or overpriced risks. Since it is hard to imagine why financial markets should have better data on banks' climate risk exposures than banks themselves, we believe that market-based stress tests are a useful complement, but not necessarily a substitute for the type of stress tests described in Sections 2 and 3. Nevertheless, it would be useful to compare the outcomes of regulatory climate stress tests to those of a methodology based on a market-based approach.

There is no past climate episode that can serve as a stress event to test the performance of CRISK. To validate their approach, Jung et al. (2023b) thus use granular data on large U.S. banks' loan portfolios. They first estimate the climate beta of each 3-digit NAICS code industry and then compute the weighted average climate beta for each bank where the weight is the loan size and each loan is assigned the climate beta of the respective industry. They show that the loan-weighted climate betas so constructed for banks are strongly aligned with top-down climate betas based only on market data of stock returns for respective banks (Figure 4). Put differently, the climate betas are higher for banks lending more to firms in industries (such as petroleum refining) that are more sensitive to the climate risk factor.



Figure 4: Bank Climate Beta and Loan Portfolio Climate Beta

Note. Figure shows a binned scatter plot of bank climate beta and loan portfolio climate beta after controlling for the time fixed effect and the bank fixed effect. Quarterly data from 2012:Q2 to 2021:Q4 for listed U.S. banks in the Y-14. A bank's loan portfolio climate beta is constructed by first estimating the climate beta of each 3-digit NAICS code industry and then computing the weighted average climate beta for each bank where the weight is the loan size and each loan is assigned the climate beta of the respective industry.

To arrive at a financial stability output, Jung et al. (2023b) apply the CRISK methodology to large global banks to understand their climate-related risk exposure. They find that climate betas and CRISK substantially increased during 2020 when the COVID outbreak caused energy prices—and thus the revenues of oil companies—to crash towards zero, a market move that has similarities to a disorderly sudden transition risk realization. Using a stress scenario in which the stranded asset factor falls by 50%, the aggregate CRISK of the top four U.S. banks in 2020 increased by 425 billion USD, or by approximately 47% of their market capitalization. This suggests that banks' climate-related capital shortfall could be substantial. Jung et al. (2023b) find that 40% of the increase in CRISK during 2020 was due to increases in climate betas and 40% due to decreases in the equity values of banks.

5 Central Banks and Climate Change

There are substantial differences across regulators in how extensively they consider climaterelated factors in their regulatory decisions. U.S. policymakers emphasize that the Federal Reserves' climate work will be "limited to our existing mandates—particularly those related to the supervision and regulation of financial institutions and the stability of the broader financial system" (Maher, 2022). While the financial stability implications of climate change are being assessed, they do not currently influence U.S. macro-prudential or supervisory regulatory activity. At the International Symposium on Central Bank Independence on January 2023, Jay Powell, Chairman of the U.S. Federal Reserve emphasized that: "Without explicit congressional legislation, it would be inappropriate for us to use our monetary policy or supervisory tools to promote a greener economy or to achieve other climate-based goals. We are not, and will not be, a climate policymaker." The Bank of Japan also stated in 2021 that while they encourage financial institutions to conduct climate stress tests based on different scenarios, they would avoid direct involvement in micro-level resource allocation as much as possible in terms of monetary policy (Kuroda, 2021).

In contrast, the European Central Bank (2022c) announced in 2022 that it would account for climate change in its corporate bond purchases, collateral framework, disclosure requirements, and risk management to reduce climate-related financial risks and promote the transition to a green economy. The Bank of England (2021a) stated that it would decide the capital requirements for banks and building societies based on the results of stress tests. Similarly, the Central Bank of Ireland discussed the possibility of incorporating the output of climate stress tests into the macroprudential policy (Lane, 2019).

Early research has started to explore how to optimally incorporate climate risk considerations into central bank activities (if at all). In a recent theoretical contribution, Oehmke and Opp (2022) study the effects of adjusting capital requirements for firm-lending based on firms' contribution to emissions (e.g., lower capital requirements for "green" firms, or higher capital requirements for high-emissions firms). They highlight that the effects of such policies on overall emissions are subtle. Raising capital requirements for lending to high-emissions firms decreases the relative profitability of making those loans (similar to a substitution effect). In addition, higher capital requirements on "brown" firms crowd out the bank's marginal loan (similar to an income effect). Through this channel, raising capital requirements for brown loans might crowd out green lending if the marginal loan is green. The overall effects on the relative lending to firms with different emissions thus depend on the relative size of the two effects (though it is important to point out that overall emissions are not a component of most regulators' mandates).²² They also highlight that reducing capital requirements for green firms might raise bank leverage and reduce financial stability.

In related work, Dafermos and Nikolaidi (2021) find that green capital requirements can mitigate global warming and moderately reduce financial risks from physical climate change. Nonetheless, they caution that green capital requirements may result in higher risk either by increasing bank leverage (if capital requirements for green loans are lowered) or by reducing economic activity (if capital requirements for brown loans are raised). Lamperti et al. (2021) also highlight that while a range of regulatory interventions such as green capital requirements and carbon-risk adjustment in credit ratings can reduce carbon emissions, the implications for overall financial stability are less clear.

We believe that more research is required to better understand the effects of potential adjustments to capital requirements and other regulatory tools to account for assets' differential climate impact. In particular, any increase in capital requirements of high-emission firms to account for their more substantial transition risk exposure might raise the cost of capital for those firms, and could thus itself constitute a source of transition risk. Before implementing any such policies, it is thus important to better understand their feedback to the broader macroeconomy, for example through their implications for energy prices as well as for banks' marginal and average portfolio responses. To fully appreciate these effects, it is important to consider, among other things, whether green capital requirements will shift the funding of high emissions firms from the regulated banking sector to the unregulated or less-regulated shadow banking sector.

 $^{^{22}}$ If different firms have different climate risk exposures, an adjustment of capital requirements based on the degree of carbon emissions could be justified even without including overall carbon emissions in the regulator's objective function.

6 Concluding Thoughts

In recent years, central banks and regulators have become increasingly interested in understanding the impact of climate risks on financial stability. We discussed the current practice of climate stress tests. We also highlighted directions for future research to improve our modeling of climate stress scenarios and their mapping into economic and financial outcomes. We emphasize that there is much model risk involved in projecting climate change in different scenarios and mapping them into economic damages and bank loan loss or mark-to-market corrections. Hence, it may be prudent to complement the balance-sheet or bottom-up approach of regulatory stress tests with a market-value or top-down approach that has a greater chance of reflecting shifts in market expectations around climate risk and its impact on firms, banks, and the broader economy.

While our discussion of the financial stability implications of climate change has focused on the effects through the banking sector, climate change might also influence financial stability through its implications for non-bank institutions such as insurance companies, mutual funds, and pension funds. Investigating the effects of climate change on other financial institutions, therefore, appears to be an important research direction to be explored.

While possible risks from climate change have become increasingly salient, various physical and regulatory risks related to biodiversity might become similarly important going forward (see the discussion in Giglio et al., 2023b). As our understanding of the possible materiality of such biodiversity risks evolves, regulators may want to consider also including such risks in their stress testing frameworks.

References

- Acharya, Viral, Robert Engle, and Diane Pierret, "Testing macroprudential stress tests: The risk of regulatory risk weights," *Journal of Monetary Economics*, 2014, 65, 36–53.
- Acharya, Viral V., Robert F. Engle, and Olivier Wang, "Incentives to Decarbonize and Innovate: The Role of Net Zero Commitments," 2023.
- _ , _ , Stefano Pastore, and Johannes Stroebel, "Transition Risk and Energy Prices," 2023.
- _, Timothy Johnson, Suresh Sundaresan, and Tuomas Tomunen, "Is Physical Climate Risk Priced? Evidence from Regional Variation in Exposure to Heat Stress," September 2022.
- Addoum, Jawad M, David T Ng, and Ariel Ortiz-Bobea, "Temperature Shocks and Establishment Sales," *The Review of Financial Studies*, March 2020, *33* (3), 1331–1366.
- Addoum, Jawad M., David T. Ng, and Ariel Ortiz-Bobea, "Temperature Shocks and Industry Earnings News," January 2023.
- Alekseev, Georgij, Stefano Giglio, Quinn Maingi, Julia Selgrad, and Johannes Stroebel, "A Quantity-Based Approach to Constructing Climate Risk Hedge Portfolios," December 2022.
- Auh, Jun Kyung, Jaewon Choi, Tatyana Deryugina, and Tim Park, "Natural Disasters and Municipal Bonds," July 2022.
- Australian Prudential Regulation Authority, "Climate Vulnerability Assessment," September 2021.
- Autorité de Contrôle Prudentiel et de Résolution, "A first assessment of financial risks stemming from climate change: The main results of the 2020 climate pilot exercise," May 2021.
- **Bailey, Andrew**, "The time to push ahead on tackling climate change speech by Andrew Bailey," November 2020.
- Bailey, Michael, Drew M Johnston, Martin Koenen, Theresa Kuchler, Dominic Russel, and Johannes Stroebel, "Social Networks Shape Beliefs and Behavior: Evidence from Social Distancing During the COVID-19 Pandemic," Working Paper 28234, National Bureau of Economic Research December 2020.
- -, Eduardo Dávila, Theresa Kuchler, and Johannes Stroebel, "House Price Beliefs And Mortgage Leverage Choice," *The Review of Economic Studies*, November 2019, *86* (6), 2403–2452.
- -, Rachel Cao, Theresa Kuchler, Johannes Stroebel, and Arlene Wong, "Social Connectedness: Measurement, Determinants, and Effects," *Journal of Economic Perspectives*, August 2018, 32 (3), 259–280.
- -, Ruiqing Cao, Theresa Kuchler, and Johannes Stroebel, "The economic effects of social networks: Evidence from the housing market," *Journal of Political Economy*, 2018, 126 (6), 2224–2276.
- Bakkensen, Laura A and Lint Barrage, "Going Underwater? Flood Risk Belief Heterogeneity and Coastal Home Price Dynamics," *The Review of Financial Studies*, August 2022, *35* (8), 3666–3709.
- Baldauf, Markus, Lorenzo Garlappi, and Constantine Yannelis, "Does Climate

Change Affect Real Estate Prices? Only If You Believe In It," *The Review of Financial Studies*, March 2020, 33 (3), 1256–1295.

- Bank for International Settlements, "Climate-related financial risks: a survey on current initiatives," April 2020.
- _, "Climate-related risk drivers and their transmission channels," April 2021.
- **Bank of England**, "The Internal Capital Adequacy Assessment Process (ICAAP) and the Supervisory Review and Evaluation Process (SREP)," December 2021. Supervisory Statement SS31/15.
- _ , "Key elements of the 2021 Biennial Exploratory Scenario: Financial risks from climate change," June 2021.
- _, "Results of the 2021 Climate Biennial Exploratory Scenario (CBES)," May 2022.
- Barro, Robert J, "Environmental protection, rare disasters and discount rates," *Econom*ica, 2015, 82 (325), 1–23.
- Battiston, Stefano, Antoine Mandel, Irene Monasterolo, Franziska Schütze, and Gabriele Visentin, "A climate stress-test of the financial system," *Nature Climate Change*, April 2017, 7 (4), 283–288.
- Baudino, Patrizia and Jean-Philippe Svoronos, "Stress-testing Banks for climate change a comparison of practices," *Bank for International Settlements*, July 2021, *FSI Insights on policy implementation* (No. 34).
- Benincasa, Emanuela, Gazi Kabas, and Steven Ongena, ""There is No Planet B," March 2022.
- Berg, Tobias, Anthony Saunders, Sascha Steffen, and Daniel Streitz, "Mind the Gap: The Difference between U.S. and European Loan Rates," *The Review of Financial Studies*, March 2017, *30* (3), 948–987.
- Bernstein, Asaf, Matthew T. Gustafson, and Ryan Lewis, "Disaster on the horizon: The price effect of sea level rise," *Journal of Financial Economics*, November 2019, 134 (2), 253–272.
- _, Stephen B Billings, Matthew Gustafson, and Ryan Lewis, "Partisan residential sorting on climate change risk," Technical Report, National Bureau of Economic Research 2020.
- Billings, Mary Brooke, Stephen G. Ryan, and Han Yan, "Climate Risk, Population Migration, and Banks' Lending and Deposit-Taking Activities," October 2022.
- Blickle, Kristian and João A. C. Santos, "Unintended Consequences of "Mandatory" Flood Insurance," April 2022.
- _, Quirin Fleckenstein, Sebastian Hillenbrand, and Anthony Saunders, "The myth of the lead arranger's share," *FRB of New York Staff Report*, 2020, (922).
- _, Sarah Ngo Hamerling, and Donald P Morgan, "How Bad Are Weather Disasters for Banks?," FRB of New York Staff Report, 2021, (990).
- **Board of Governors of the Federal Reserve System**, "Pilot Climate Scenario Analysis Exercise Participant Instructions," January 2023.
- Bolton, Patrick and Marcin T. Kacperczyk, "Firm Commitments," June 2022.
- _ , Morgan Despres, Liuz Awazu Pereira Da Silva, Frédéric Samama, and Romain Svartzman, "The green swan: central Banking and financial stability in the age of climate change," *Bank for International Settlements*, January 2020.
- Borio, Claudio, Mathias Drehmann, and Kostas Tsatsaronis, "Stress-testing macro

stress testing: Does it live up to expectations?," *Journal of Financial Stability*, June 2014, 12, 3–15.

- Boustan, Leah Platt, Matthew E Kahn, Paul W Rhode, and Maria Lucia Yanguas, "The effect of natural disasters on economic activity in US counties: A century of data," *Journal of Urban Economics*, 2020, 118, 103257.
- Brainard, Lael, "Building Climate Scenario Analysis on the Foundations of Economic Research," October 2021.
- Brei, Michael, Preeya Mohan, and Eric Strobl, "The impact of natural disasters on the Banking sector: Evidence from hurricane strikes in the Caribbean," *The Quarterly Review of Economics and Finance*, May 2019, 72, 232–239.
- Brunetti, Celso, John Caramichael, Matteo Crosignani, Benjamin Dennis, Gurubala Kotta, Donald P. Morgan, Chaehee Shin, and Ilknur Zer, "Climate-Related Financial Stability Risks for the United States: Methods and Applications," July 2022.
- Cartellier, Fanny, "Climate Stress Testing, an Answer to the Challenge of Assessing Climate- Related Risks to the Financial System?," August 2022.
- Chava, Sudheer, "Environmental Externalities and Cost of Capital," Management Science, 2014, 60 (9), 2223–2247.
- Chavaz, Matthieu, "Dis-Integrating Credit Markets: Diversification, Securitization, and Lending in a Recovery," September 2016.
- Chodorow-Reich, Gabriel, Olivier Darmouni, Stephan Luck, and Matthew Plosser, "Bank liquidity provision across the firm size distribution," *Journal of Financial Economics*, 2022, 144 (3), 908–932.
- Choi, Darwin, Zhenyu Gao, and Wenxi Jiang, "Attention to Global Warming," The Review of Financial Studies, March 2020, 33 (3), 1112–1145.
- Correa, Ricardo, Ai He, Christoph Herpfer, and Ugur Lel, "The rising tide lifts some interest rates: Climate change, natural disasters and loan pricing," *Natural Disasters and Loan Pricing (March 31, 2020)*, 2020.
- Cortés, Kristle Romero and Philip E. Strahan, "Tracing out capital flows: How financially integrated Banks respond to natural disasters," *Journal of Financial Economics*, July 2017, *125* (1), 182–199.
- Cuculiza, Carina, Alok Kumar, Wei Xin, and Chendi Zhang, "Climate Change, Analyst Forecasts, and Market Behavior," February 2021.
- **Dafermos, Yannis and Maria Nikolaidi**, "How can green differentiated capital requirements affect climate risks? A dynamic macrofinancial analysis," *Journal of Financial Stability*, June 2021, 54, 100871.
- Das, Abhiman, Tanmoy Majilla, and Sumit Saurav, "Natural Disasters, Interest Rates Dynamics, and Economic Activities," September 2022.
- de Boyrie, Maria E. and Ivelina Pavlova, "Analysing the link between environmental performance and sovereign credit risk," *Applied Economics*, November 2020, 52 (54), 5949–5966.
- Delis, Manthos D, Kathrin De Greiff, and Steven Ongena, "Being stranded with fossil fuel reserves? Climate policy risk and the pricing of bank loans," *Climate Policy Risk and the Pricing of Bank loans (September 10, 2019). EBRD Working Paper*, 2019, (231).

- Dlugosz, Jennifer, Yong Kyu Gam, Radhakrishnan Gopalan, and Janis Skrastins, "Decision-making delegation in banks," *SSRN Electronic Journal*, 2022.
- Dunz, Nepomuk, Asjad Naqvi, and Irene Monasterolo, "Climate sentiments, transition risk, and financial stability in a stock-flow consistent model," *Journal of Financial Stability*, June 2021, 54, 100872.
- _, Tina Emambakhsh, Tristan Hennig, Michiel Kaijser, Charalampos Kouratzoglou, and Carmelo Salleo, "ECB's Economy-Wide Climate Stress Test," SSRN Electronic Journal, 2021.
- Engle, Robert, "Dynamic Conditional Correlation: A Simple Class of Multivariate Generalized Autoregressive Conditional Heteroskedasticity Models," Journal of Business & Economic Statistics, 2002, 20 (3), 339–350.
- _ , Anticipating Correlations: A New Paradigm for Risk Management, Princeton University Press, 2009.
- Engle, Robert F, Stefano Giglio, Bryan Kelly, Heebum Lee, and Johannes Stroebel, "Hedging Climate Change News," *The Review of Financial Studies*, March 2020, 33 (3), 1184–1216.
- Ens, Erik and Craig M T Johnston, "Scenario Analysis and the Economic and Financial Risks from Climate Change," 2020.
- European Central Bank, "2022 climate risk stress test.," July 2022.
- _, "ECB report on good practices for climate stress testing," December 2022.
- _ , "ECB takes further steps to incorporate climate change into its monetary policy operations," July 2022.
- Faccini, Renato, Rastin Matin, and George S. Skiadopoulos, "Dissecting Climate Risks: Are they Reflected in Stock Prices?," July 2022.
- Financial Stability Board and NGFS, "Climate Scenario Analysis by Jurisdictions: Initial findings and lessons," 2022.
- **Financial Stability Oversight Council**, "FSOC Report on Climate-Related Financial Risk," 2021.
- Frahm, Gabriel, Markus Junker, and Rafael Schmidt, "Estimating the taildependence coefficient: properties and pitfalls," *Insurance: mathematics and Economics*, 2005, 37 (1), 80–100.
- Ganong, Peter and Pascal J. Noel, "Why Do Borrowers Default on Mortgages?," July 2020.
- Ge, Shan, Ammon Lam, and Ryan Lewis, "The Costs of Hedging Disaster Risk and Home Prices: Evidence from Flood Insurance," August 2022.
- Giglio, Stefano, Bryan Kelly, and Johannes Stroebel, "Climate Finance," Annual Review of Financial Economics, 2021, 13 (1), 15–36.
- , Matteo Maggiori, Johannes Stroebel, Stephen Utkus, Joe Tan, and Xiao Xu, "Four Facts About ESG Beliefs and Investor Portfolios," *Working Paper*, 2023.
- _ , _ , Krishna Rao, Johannes Stroebel, and Andreas Weber, "Climate Change and Long-Run Discount Rates: Evidence from Real Estate," *The Review of Financial Studies*, July 2021, 34 (8), 3527–3571.
- -, Theresa Kuchler, Johannes Stroebel, and Xuran Zeng, "Biodiversity Risk," Working Paper, 2023.
- Goldsmith-Pinkham, Paul, Matthew T Gustafson, Ryan C Lewis, and Michael

Schwert, "Sea Level Rise Exposure and Municipal Bond Yields," 2022.

- Gostlow, Glen, "Pricing Physical Climate Risk in the Cross-Section of Returns," June 2021.
- Goulder, Lawrence and Marc Hafstead, Title: Confronting the Climate Challenge: U.S. Policy Options, Columbia University Press, 2018.
- Grippa, Pierpaolo, Jochen Schmittmann, and Felix Suntheim, "Climate Change and Financial Risk," *Finance & Development*, December 2019, 56 (004).
- He, Zhiguo and Wei Xiong, "Rollover Risk and Credit Risk," The Journal of Finance, 2012, 67 (2), 391–430.
- Hong, Harrison, G Andrew Karolyi, and José A Scheinkman, "Climate Finance," *The Review of Financial Studies*, March 2020, *33* (3), 1011–1023.
- Hong Kong Monetary Authority, "Pilot Banking Sector Climate Risk Stress Test," 2021.
- Huynh, Thanh D. and Ying Xia, "Climate Change News Risk and Corporate Bond Returns," Journal of Financial and Quantitative Analysis, September 2021, 56 (6), 1985– 2009.
- Intergovernmental Panel on Climate Change, "Special Report on Climate Change and Land IPCC site," 2019.
- Islam, Emdad and Mandeep Singh, "Information on Hot Stuff: Do Lenders Pay Attention To Climate Risk?," September 2022.
- Ivanov, Ivan, Mathias S. Kruttli, and Sumudu W. Watugala, "Banking on Carbon: Corporate Lending and Cap-and-Trade Policy," August 2022.
- Janet L. Yellen, "Hearing to Consider the Anticipated Nomination of the Honorable Janet L. Yellen to Secretary of the Treasury - The United States Senate Committee on Finance," 2021.
- _ , "Remarks by Secretary of the Treasury Janet L. Yellen at the First Meeting of the FSOC Climate-related Financial Risk Advisory Committee," 2023.
- Javadi, Siamak and Abdullah-Al Masum, "The impact of climate change on the cost of Bank loans," *Journal of Corporate Finance*, August 2021, 69, 102019.
- **Joe, Harry**, *Multivariate Models and Multivariate Dependence Concepts*, CRC Press, May 1997. Google-Books-ID: iJbRZL2QzMAC.
- Jorgenson, Dale W, Richard J Goettle, Mun S Ho, and Peter J Wilcoxen, Double dividend: environmental taxes and fiscal reform in the United States, MIT Press, 2013.
- Jorgenson, Dale W., Richard J. Goettle, Mun S. Ho, and Peter J. Wilcoxen, "The Welfare Consequences of Taxing Carbon," *Climate Change Economics, Vol. 9, No.* 1 (2018), 2018, 9 (1), 1840013:1–39.
- Jung, Hyeyoon, Joao A.C. Santos, and Lee Seltzer, "U.S. Banks' Exposures to Climate Transition Risks," 2023.
- _ , Robert F. Engle, and Richard Berner, "CRISK: Measuring the Climate Risk Exposure of the Financial System," *FRB of New York Staff Report*, 2023.
- Kacperczyk, Marcin T. and José-Luis Peydró, "Carbon Emissions and the Bank-Lending Channel," August 2022.
- Khwaja, Asim Ijaz and Atif Mian, "Tracing the Impact of Bank Liquidity Shocks: Evidence from an Emerging Market," *American Economic Review*, September 2008, 98 (4), 1413–1442.

- Krueger, Philipp, Zacharias Sautner, and Laura T Starks, "The Importance of Climate Risks for Institutional Investors," *The Review of Financial Studies*, March 2020, 33 (3), 1067–1111.
- Kuchler, Theresa and Johannes Stroebel, "Social Finance," Annual Review of Financial Economics, 2021, 13 (1), 37–55.
- Kundu, Shohini, Seongjin Park, and Nishant Vats, "The Geography of Bank Deposits and the Origins of Aggregate Fluctuations," June 2022.
- Kuroda, Haruhiko, "Haruhiko Kuroda: The Bank of Japan's strategy on climate change," August 2021.
- Känzig, Diego R., "The Macroeconomic Effects of Oil Supply News: Evidence from OPEC Announcements," American Economic Review, April 2021, 111 (4), 1092–1125.
- Laeven, Luc and Alexander Popov, "Carbon Taxes and the Geography of Fossil Lending," November 2022.
- Lamperti, Francesco, Valentina Bosetti, Andrea Roventini, Massimo Tavoni, and Tania Treibich, "Three green financial policies to address climate risks," *Journal of Financial Stability*, June 2021, 54, 100875.
- Lane, Philip R., "Climate Change and the Irish Financial System," *Economic Letters*, February 2019. Number: 1/EL/19.
- Litterman, Bob, Leonardo Martinez-Diaz, Jesse M. Keenan, Stephen Moch, David Gillers, and Rostin Behnam, "Managing Climate Risk in the U.S. Financial System," Technical Report, U.S. Commodity Futures Trading Commission July 2021.
- Maher, Dina, "Testimony on Exploring Financial Risks on Banking Posed by Climate Change Federal Reserve Bank of New York," 2022.
- Marco, Filippo De and Nicola Limodio, "Climate, Amenities and Banking: El Niño in the US," January 2023.
- Marco, Moreno Di, Michelle L Baker, Peter Daszak, Paul De Barro, Evan A Eskew, Cecile M Godde, Tom D Harwood, Mario Herrero, Andrew J Hoskins, Erica Johnson et al., "Sustainable development must account for pandemic risk," Proceedings of the National Academy of Sciences, 2020, 117 (8), 3888–3892.
- McNeil, Alexander J, Rüdiger Frey, and Paul Embrechts, Quantitative risk management: concepts, techniques and tools-revised edition, Princeton university press, 2015.
- Morris, Stephen and Hyun Song Shin, "Illiquidity Component of Credit Risk," International Economic Review, November 2016, 57 (4), 1135–1148.
- NGFS, "Origin and Purpose," September 2019.
- _, "NGFS climate scenarios for central Banks and supervisors," June 2020.
- _, "NGFS Climate Scenarios for central Banks and supervisors," June 2021.
- **NGFS**, "Running the NGFS Scenarios in G-Cubed: A Tale of Two Modelling Frameworks," *Running the NGFS Scenarios in G-Cubed: A Talke of Two Modelling Frameworks*, 2022.
- Nguyen, Duc Duy, Steven Ongena, Shusen Qi, and Vathunyoo Sila, "Climate change risk and the cost of mortgage credit," *Review of Finance*, 2022, 26 (6), 1509–1549.
- Nordhaus, William D and Joseph Boyer, "Warming the world," 2000.
- Oehmke, Martin and Marcus M. Opp, "Green Capital Requirements," February 2022.
- Office of Science and Technology Policy, "Climate and Energy Implications of Crypto-Assets," 2022.
- Painter, Marcus, "An inconvenient cost: The effects of climate change on municipal

bonds," Journal of Financial Economics, February 2020, 135 (2), 468–482.

- Pankratz, Nora and Christoph Schiller, "Climate change and adaptation in global supply-chain networks," Board of Governors of the Federal Reserve System: Finance and Economics Discussion Series 2022-056, 2021.
- Pástor, L'uboš, Robert F Stambaugh, and Lucian A Taylor, "Sustainable investing in equilibrium," *Journal of Financial Economics*, 2021, 142 (2), 550–571.
- _ , _ , and _ , "Dissecting green returns," Journal of Financial Economics, 2022, 146 (2), 403–424.
- Roncoroni, Alan, Stefano Battiston, Luis O. L. Escobar-Farfán, and Serafin Martinez-Jaramillo, "Climate risk and financial stability in the network of Banks and investment funds," *Journal of Financial Stability*, June 2021, 54, 100870.
- Seltzer, Lee H., Laura Starks, and Qifei Zhu, "Climate Regulatory Risk and Corporate Bonds," April 2022.
- Sibuya, Masaaki, "Bivariate extreme statistics, I," Annals of the Institute of Statistical Mathematics, June 1960, 11 (3), 195–210.
- Steindl, Frank G and Maurice D Weinrobe, "Natural hazards and deposit behavior at financial institutions: A note," Journal of Banking & Finance, 1983, 7 (1), 111–118.
- Stroebel, Johannes and Jeffrey Wurgler, "What do you think about climate finance?," Journal of Financial Economics, 2021, 142 (2), 487–498.
- van Benthem, Arthur A, Edmund Crooks, Stefano Giglio, Eugenie Schwob, and Johannes Stroebel, "The effect of climate risks on the interactions between financial markets and energy companies," *Nature Energy*, 2022, 7 (8), 690–697.
- van Dijk M. A., "Assessing climate risk for investment portfolios," 2020.
- Vermeulen, Robert, Edo Schets, Melanie Lohuis, Barbara Kölbl, David-Jan Jansen, and Willem Heeringa, "An energy transition risk stress test for the financial system of the Netherlands," October 2018.
- Weitzman, Martin L, "Rare disasters, tail-hedged investments, and risk-adjusted discount rates," Technical Report, National Bureau of Economic Research 2012.
- _ , "Fat tails and the social cost of carbon," American Economic Review, 2014, 104 (5), 544–546.

Juri.	Org.	Acro.	Scenarios	Description	Corresponding	Example macro
					Scenarios	outcome
Australia	Australian		Scenario 1	A delayed but then rapid	Disorderly	-
Australia	Prudential	АРКА		reduction in emissions by	Transition:	
	Regulation			2050	Delayed	
	Authority				Transition	
					Scenario (NGFS	
					2020)	
			Scenario 2	A continuation of current	Hot House	-
				global policies and forecasts	World: Current	
					Policies Scenario	
					$(NGFS \ 2020)$	
			Baseline scenario:	No further action to limit	Hot House	-
Canada	Bank of	BoC	Business as usual	global warming is taken;	World: Current	
Canada	Canada	DUC		Emissions rise unabated and	Policies Scenario	
				lead to a substantial rise in	$(NGFS \ 2020)$	
				average global temperatures		
			Nationally	Beginning in 2020, countries	Hot House	A 4% reduction in
			determined	act according to their pledges	World: NDCs	annual GDP compared
			contributions	under the Paris Agreement,	Scenario (NGFS	to baseline scenario by
			(NDCs) scenario	but actions are not enough to	2020)	2050
				limit warming to 2° C by 2100		
			$2^{\circ}C$ (consistent)	Countries act to limit global	Orderly	A 13% reduction in
			scenario	warming to 2° C by 2100	Transition: Net	annual GDP compared
					Zero 2050	to baseline scenario by
					Scenario (NGFS	2050
					2020)	
			$2^{\circ}C$ (delayed	New policies will not be	Disorderly	A 21% reduction in
			action) scenario	implemented until 2030; By	Transition:	annual GDP compared
				2100, Global warming is	Below 2°C	to baseline scenario by
				limited to 2°C	Scenario (NGFS	2050
					2020)	

 Table 1: Comparison of Central Bank Climate Stress Testing Pratices

			Transition:	Climate policies are	Orderly	EU cumulative GDP
	Б		long-term orderly	introduced early and	Transition: Net	growth in 2050 versus
European	European		scenario	gradually become more	Zero 2050	2021 is $65%$
Union	Central	ECB		stringent	Scenario (NGFS	
	Bank			C C	2020)	
			Transition:	New climate policies are not	Disorderly	EU cumulative GDP
			long-term	introduced until 2030; Limit	Transition:	growth in 2050 versus
			disorderly	warming to below 2°C	Delayed	2021 is $58%$
			scenario		Transition	
					Scenario (NGFS	
					2020)	
			Transition:	No new climate policies are	Hot House	EU cumulative GDP
			long-term Hot	implemented; Emissions grow	World: Current	growth in 2050 versus
			house world	until 2080, leading to about	Policies Scenario	2021 is $57%$
			scenario	3° C of warming	$(NGFS \ 2020)$	
			Transition:	Carbon price increase is	Disorderly	EU GDP grows
			short-term	frontloaded to 2022 , 2023 and	Transition:	cumulatively by around
			disorderly	2024	Delayed	7.4% in the period
			transition risk		Transition	2021-2024, compared
			scenario		Scenario (NGFS	with 10.5% in a
					2020)	baseline scenario
			Physical: drought	A severe drought and	-	-
			and heat scenario	heatwave is assumed to hit		
				Europe on 1 January 2022		
			Physical: flood	Severe floods take place	-	-
			risk scenario	across Europe on 1 January		
			D. 4	2022		
	Autorite de	1 0 5 5	Reference	The transition starts as early	Orderly scenario	Average annual growth
France	Controle	ACPR-	scenario	as 2020; Limit rise of	(NGFS 2019)	rate of the real GDP
	Prudentiel	BqL,		temperatures below 2°C		stabilises in 2050 at 1.1%
	et de					around 1%
	Resolution					
	- Banque					
	de France					

			Variant 1: late reaction scenario	More stringent measures will be implemented in 2030	Disorderly scenario (NGFS 2019)	Volume of GDP in 2050 is down 2.1% compared to the reference scenario
		_	Variant 2: scenario of a swift and abrupt transition	Renewable energy technologies are not so mature as expected in the reference scenario, resulting in higher energy prices	Alternative Disorderly scenario (NGFS 2019)	Volume of GDP in 2050 is down 5.5% compared to the reference scenario
			Physical risk scenario	A society with medium population growth and income, high emissions, technological progress, production, and consumption patterns are a continuation of past trends	SSP2-RCP8.5 scenario (IPCC 2019)	-
Hong Kong	Hong Kong Monetary	НКМА	Physical scenario	High emission pathway	RCP8.5 scenario (IPCC 2019)	-
(China)	Authority	-	Orderly transition scenario	Early and progressive actions to achieve the climate goals of the Paris Agreement	Orderly scenario (NGFS 2019)	CO2 emission will be around 5 billion tonnes per year in 2050, CO2 price will reach around \$300 per tonne
		-	Disorderly transition scenario	Climate policies will not be implemented until 2030	Disorderly scenario (NGFS 2019)	CO2 emission will be zero in 2050, CO2 price will reach around \$750 per tonne
Netherlands	De Neder- landsche Bank	DNB	Technology shock scenario	The share of renewable energy in the energy mix doubles due to a technological breakthrough	-	A 2.0% increase in GDP level compared to baseline model in the fifth year after the shock

		Double shock scenario	The carbon price rises globally by \$100 per ton due to additional policy measures. The share of renewable energy in the energy mix doubles due to a technological breakthrough	-	A 0.9% increase in GDP level compared to baseline model in the fifth year after the shock
		Confidence shock	Corporations and households	-	A 0.6% reduction in
		scenario	consumption due to		baseline model in the
			uncertainty about policy		fifth year after the
			measures and technology		shock
		Policy shock	The carbon price rises	-	A 0.5% reduction in
		scenario	globally by 100 per ton due		GDP level compared to
			to additional policy measures		baseline model in the
					fifth year after the
				0.1.1	shock
dBank of	$\mathbf{D}_{\mathbf{r}}\mathbf{F}$	Early Action	I ne transition to a net-zero	Orderly Transition: Not	By 2050, UK GDP is around 1.407 holow of
England	DOE		2050 carbon omissions are	Zoro 2050	around 1.4% below a
			reduced to net-zero. Global	Scenario (NGES	which there are no
			warming is limited to 1.8°C	2020)	additional headwinds
			0)	from climate risks
		Late Action	New policies will not be	Disorderly	By 2050, UK GDP is
			implemented until 2031 and	Transition:	around 4.6% below a
			is then more sudden and	Delayed	counterfactual path
			disorderly; By 2050, Global	Transition	
			warming is limited to 1.8° C	Scenario (NGFS	
				2020)	
		No Additional	No new climate policies	Hot House	By 2050, UK GDP is
		Action	introduced beyond those	World: Current	around 7.8% below a
			arready implemented; By	(NCES 2020)	counterfactual path
			levels reach 3.3°C	(INGF 5 2020)	

United

Kingdom

			Current Policies	No new climate policies	Hot House	By 2030, US GDP is
United	Federal	Fed		introduced beyond those	World: Current	around $$24,030$ billion
States	Reserve	геа		already implemented; By	Policies Scenario	(in 2012 prices); carbon
				2100, global temperature	$(NGFS \ 2020)$	price reaches \$17 per
				levels reach 3°C		tonne (in 2010 prices)
			Net Zero 2050	The transition to a net-zero	Orderly	By 2030, US GDP is
				economy starts in 2023; By	Transition: Net	around $$23,574$ billion
				2050 carbon emissions are	Zero 2050	(in 2012 prices); carbon
				reduced to net-zero. Global	Scenario (NGFS	price reaches \$162 per
				warming is limited to 1.5° C	2020)	tonne (in 2010 prices)
			Physical risk	A severe hurricane resulting	SSP2-	-
			scenario	in both storm surge and	4.5& RCP 4.5	
			(common shock)	precipitation-induced	scenario and	
				flooding in the Northeast	SSP5-	
				region of the United States	8.5& RCP 8.5	
					scenario (IPCC	
					2019)	
			Physical risk	Participants should select a	SSP2-	-
			scenario	hazard event and geographic	4.5& RCP 4.5	
			(idiosyncratic	regions based on materiality	scenario and	
			$\operatorname{shock})$	to their business models and	SSP5-	
				exposures	8.5& RCP 8.5	
					scenario (IPCC	
					2019)	

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