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How Does Climate Change Interact with the Financial System? A Survey

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Abstract

We survey the growing literature on the interaction between climate change, which is likely associated with a growing intensity and frequency of natural disasters, and the financial system. Assets, in particular real estate properties, do not adequately price in climate risks although disclosure and communication help alleviate the mispricing of assets. Further, natural disasters restrict the credit supply from affected banks even in areas not directly hit by the disaster; however, this negative impact is less severe for banks with more capital. Meanwhile, insurance provides some protection for the economy, firms, and households against the impact of natural disasters, but there are several challenges such as low coverage and moral hazard. Finally, our survey considers policy implications for financial authorities.

Key words: Asset Pricing, Banking, Insurance, Climate Change, Natural Disaster, Financial Stability

JEL classification: G12, G21, G22, G41, Q54, R31

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1. Introduction

Recent years have seen a growing interest in global warming and the associated changes in the climate. Climate science suggests that rising temperatures are likely associated with changes in climate patterns, including a growing intensity and frequency of extreme weather events such as floods and wildfires. With mounting scientific evidence that climate change is driven by human activities, the concerns over climate change culminated in the adoption of the Paris Agreement in December 2015.[1] Global leaders now view environmental risks, such as extreme weather and climate action failure, as the most significant global threats (World Economic Forum, 2020).[2]

Against this backdrop, financial authorities around the world, including central banks, and international bodies have taken an interest in climate change and launched a range of initiatives. For example, in 2015, the Financial Stability Board (FSB) formed the Task Force on Climate-related Financial Disclosures (TCFD), which aims to develop voluntary and consistent climate-related financial risk disclosures. In 2017, eight central banks and supervisors launched the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) to share best practices, contribute to the development of environment and climate risk management in the financial sector, and mobilize mainstream finance to support the transition towards a sustainable economy. As of September 2020, it had 72 members and 13 observers. Recently, the Basel Committee

[1] The Paris Agreement set the goal of "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change." The agreement requires all parties to report regularly on their emissions and on their implementation efforts. There will also be an assessment of the collective progress towards the goal of the agreement every 5 years. As of September 2020, 189 countries had ratified the agreement.

[2] The World Economic Forum released the report ahead of its annual meeting in Davos in January 2020. The report shows the results of a survey that asks business, government, civil society, and other leaders about the top threats facing the world in terms of their likelihood and the impact they would have over the next 10 years. All of the top 5 risks in terms of their likelihood concern the environment: extreme weather; biodiversity loss; climate action failure; natural disasters; and human made environmental disasters. A majority of the top 5 risks in terms of their potential impact also concern the environment, with the only non-environmental risks in the top 5 being weapons of mass destruction and water crises, which are categorized as geopolitical and societal risks, respectively. The results are in stark contrast with those just 5 years ago: in 2015, only extreme weather events (in second place in terms of likelihood) and failure to mitigate and adopt to climate change (in fifth place in terms of impact) ranked among the top 5 risks.

on Banking Supervision (BCBS) established a high-level Task Force on Climate-related Financial Risks, which is charged with contributing to the BCBS's mandate of enhancing global financial stability by undertaking lead-off initiatives to work on the development of effective supervisory practices on climate-related financial risks. Both the BCBS and the FSB in 2020 published their first stocktake reports on financial authorities' initiatives and experience with regard to climate-related financial risks.

Financial authorities and international bodies have also conducted a range of research to study the implications of climate change on the financial system and the role that central banks and supervisors can play. For instance, among others, Batten, Sowerbutts, and Tanaka (2016) from the Bank of England, Krogstrup and Oman (2019) from the International Monetary Fund (IMF), and Bolton et al. (2020) from the Bank for International Settlements (BIS) and the Banque de France, survey the vast science and economics literature on climate change and its impacts on the economy. These papers also discuss how climate change affects the financial system through the economy and how policy makers, including financial authorities, can address the problem of climate change within their mandates.

While these papers can be seen as excellent surveys of the literature on climate change and its impacts on the economy, there is a large volume of academic literature that is not covered in their discussions. Part of the reason may be that this strand of literature is growing rapidly. For instance, while research on the link between climate change and the real economy goes back a while, research, largely empirical, on the relationship between climate change and the financial system has surged only in recent years.[3] Such research potentially yields important implications for policy measures to address climate change. Another aspect that is not necessarily highlighted in existing survey papers is the causality from the financial system to climate change through people's mitigation and adaptation efforts. Mitigation efforts focus on containing climate change itself, for

[3] This development is illustrated by the publication of the special issue on "Climate Finance" of *the Review of Financial Studies* in 2020. Hong, Karolyi, and Scheinkman (2020), who provide an overview of the special issue, observe: "Even though we financial economists are late to the game, we hope that this climate finance issue illustrates that there are many important questions where financial economists are naturally suited given their toolkit and interests." How rapidly the literature has changed can also be seen from the study by Diaz-Rainey, Robertson, and Wilson (2017), who find that 3 highly regarded finance journals, including *the Review of Financial Studies*, had not published a single article related to climate finance between January 1998 and June 2015.

instance through the reduction of greenhouse gas emissions, while adaptation reduces the impact of climate change, for instance through the construction of better flood defenses. The financial system may impede such efforts for a variety of reasons. For example, if stock markets in their valuation of firms do not adequately distinguish between firms with high and low carbon emissions, this can deter efforts to reduce emissions. Evidence on the causal links from the financial system to climate change is important since without a shared understanding of such links discussing financial policies to address the challenges will be difficult. On the other hand, there is also ample room for further understanding the causal links from climate change to the financial system. In particular, while recent discussions often focus on the relatively long-term impacts of climate change, it is also important to deepen our understanding of the shorter-term impacts of climate-related natural disasters that can happen in the near future.

Against this background, the purpose of this paper is to provide an extensive survey of the literature on the interaction between climate change and the financial system. In particular, the aim is to consider the causal links from the financial system to climate change through mitigation and adaptation, as well as specific channels of the causal links from climate change to the financial system in relatively short time horizons. With this aim in mind, this survey paper focuses particularly on asset prices, bank behavior, and insurance. Further, our survey covers not only the literature on climate-related natural disasters (such as floods) and environmental performance (such as reductions in greenhouse gas emissions) but also extends the horizon to natural disasters and environmental performance not related to climate change, such as earthquakes and toxic emissions, since they share many similarities and the literature often arrives at similar conclusions. Our survey suggests that climate change and the financial system interact in a fundamental way: climate change threatens financial stability and at the same time the financial system has the potential to reduce the cost of climate change and even to slow its progression.

The structure of this paper is as follows:

Section 2 provides an overview of recent discussions on climate-related financial risks. There have been many discussions on how the real economy and the financial system are affected when climate risks materialize. At the same time, the causal links from the financial system to climate change through the real economy are also important. For instance, corporate incentives could be distorted through the mispricing of their equity and result in increased greenhouse gas emissions. Looking at the policy debate,

many argue that increased disclosure is an important measure. The use of stress tests has also been recommended, although there are difficulties, for instance, in designing appropriate scenarios. On the other hand, many are cautious about policies that directly intervene in resource allocation, such as preferential treatment of green assets in financial regulation.

Section 3 reviews whether asset prices factor in climate-related risks. While many studies show that prices of assets, such as stocks, corporate and municipal bonds, syndicated loans, and weather derivatives, factor in climate-related risks to some extent, many other studies show that real estate and stock prices do not adequately reflect climate risks. For instance, several studies show that property prices tend to be higher in areas with a lower percentage of residents who believe in global warming, all else being equal. A number of studies provide evidence that investor behavior and asset prices change and can overreact when risks become more clearly recognized due to, for instance, natural disasters occurring in nearby regions. These results suggest that asset prices could fall substantially as climate-related risks materialize. Moreover, the misevaluation of climate risks can lead to the misallocation of resources. Several studies show that disclosure and risk communication are effective in achieving an accurate pricing of assets, showing, for instance, that real estate properties tend to be overvalued in areas where there is insufficient disclosure. On the other hand, the literature suggests that stock prices are undervalued due to a lack of disclosure, particularly for firms with low emissions. Meanwhile, the results for the premium on the yields of green bonds – i.e., bonds issued to support specific climate-related or environmental projects – are mixed.

Section 4 discusses bank behavior when natural disasters occur. It has been observed that the health of banks deteriorates when the areas in which they operate are affected by a natural disaster. Several studies show that while the demand for credit increases in the affected areas, the supply of loans is suppressed due in part to a lack of bank capital. Some studies suggest that young and small firms are particularly susceptible to borrowing constraints. A number of studies, however, find that local banks in affected areas are more likely than non-local banks to continue lending to households and firms, including young and small firms. Many studies find that credit supply also tends to be restricted in unaffected areas. This effect is stronger when banks have a low capital ratio, the unaffected areas are not important to banks (for instance, because the areas account for a small share of the banks' business), and the unaffected areas are exposed to a high risk of disasters. Meanwhile, public support for banks through government-sponsored

enterprises (GSEs) and other instruments has the side effect of distorting resource allocation. For instance, banks are more willing to make mortgage loans in high-risk areas on the assumption that they can sell higher-risk loans to GSEs.

Section 5 investigates the role of insurance and related challenges. Insurance plays an important role in alleviating disaster risk and often complements bank finance. There are, however, at least 3 challenges related to insurance: increasing the coverage of insurance in order to provide more protection and to improve risk sharing, maintaining the solvency of insurance firms when climate-related risks materialize, and avoiding the problem of moral hazard. Research shows that less than 30 percent of the world's losses from natural disasters are covered by insurance. The problem of inadequate insurance coverage is particularly prevalent among low-income households and young and small businesses. Some studies suggest that this is partly due to a lack of awareness on the demand side and that it could be improved with better risk communication. Other studies suggest that, among other things, the fact that natural disaster risk is difficult to diversify is holding back the supply of insurance and reinsurance. Some studies suggest that natural disasters have resulted in a deterioration of the health of insurance firms, leading to the fire-sale of assets, higher insurance fees, and reduced underwriting of insurance. Meanwhile, there are concerns that insurance creates moral hazard and slows down efforts to reduce the impact of climate change.

Finally, Section 6 concludes this paper. While the studies surveyed in this paper are diverse and wide-ranging, we here focus on 3 major policy implications. We also call for further research and evidence-based policy debates.

2. Recent discussions on climate-related financial risks

This section provides a brief overview of what we know about climate change and how economists have attempted to study its interaction with the real economy (Section 2.1), transmission channels between climate change and the financial system (Section 2.2), and potential policy measures that governments and financial authorities may take (Section 2.3). This overview provides readers with the background to why and how climate change matters for the financial system and why policy makers need to intervene in order to reduce the risks associated with climate change. Finally, we summarize this section and describe the contribution of this paper (Section 2.4).

2.1. The literature on climate change and its interaction with the real economy

Climate science predicts climate change that is associated with a growing intensity and frequency of extreme weather events such as floods and wildfires. IPCC (2014) reports that the global mean temperature rose by 0.85°C between 1880 and 2012 and that it is likely to continue to rise by 0.3–4.8°C by the end of the century.[4] There is a growing concern that this rise in temperatures will have a substantial impact on the planet. For instance, IPCC (2014) warns that melting glaciers and ice sheets are likely to lead to a rise in sea levels of 0.26–0.82m by the end of the century. Further, IPCC (2018) reports that global warming could lead to an increased frequency and severity of extreme weather events such as floods, droughts, and tropical cyclones. An added concern is that there may be certain tipping points: if global warming goes beyond these points, changes to the ecosystem may be catastrophic and irreversible. Scientific evidence strongly suggests that climate change is anthropogenic. Consequently, whether global temperatures will actually rise by less than 1.5°C above pre-industrial levels, as set out in the Paris Agreement, crucially depends on the course of action that humans will take. However, the scale of the required reductions in the emission of greenhouse gases, including carbon dioxide (CO_2), is enormous: to limit the rise in temperatures to 1.5°C, we need to achieve a carbon-neutral economy by around 2050 (IPCC, 2018).[5]

Given the scale of the potential implications of climate change, economists have long been trying to understand the interplay between climate change and economic activities. One of the most prominent approaches relies on the use of integrated assessment models (IAMs) – a type of models that integrate climate and economic models. The first attempt to model the interaction between the climate system and economic activities was made by Nordhaus (1975, 1977). The approach has been elaborated extensively since then, resulting in a large body of literature. IAMs have arguably laid the

[4] The Intergovernmental Panel on Climate Change (IPCC) is an intergovernmental body created to provide policymakers with regular scientific assessments on climate change, its implications, and potential future risks, as well as to put forward adaptation and mitigation options.

[5] The reason why the focus is on CO_2 emissions is that CO_2 plays a much larger role in global warming than other greenhouse gases, partly because it takes longer to leave the atmosphere.

groundwork for understanding the interaction between the climate and economic systems. They are also widely used: for instance, the IPCC uses the models in its evaluation reports. However, IAMs are not without their critics and it has, for example, been argued that the results are very sensitive to the selection of parameter values (Pindyck, 2013).

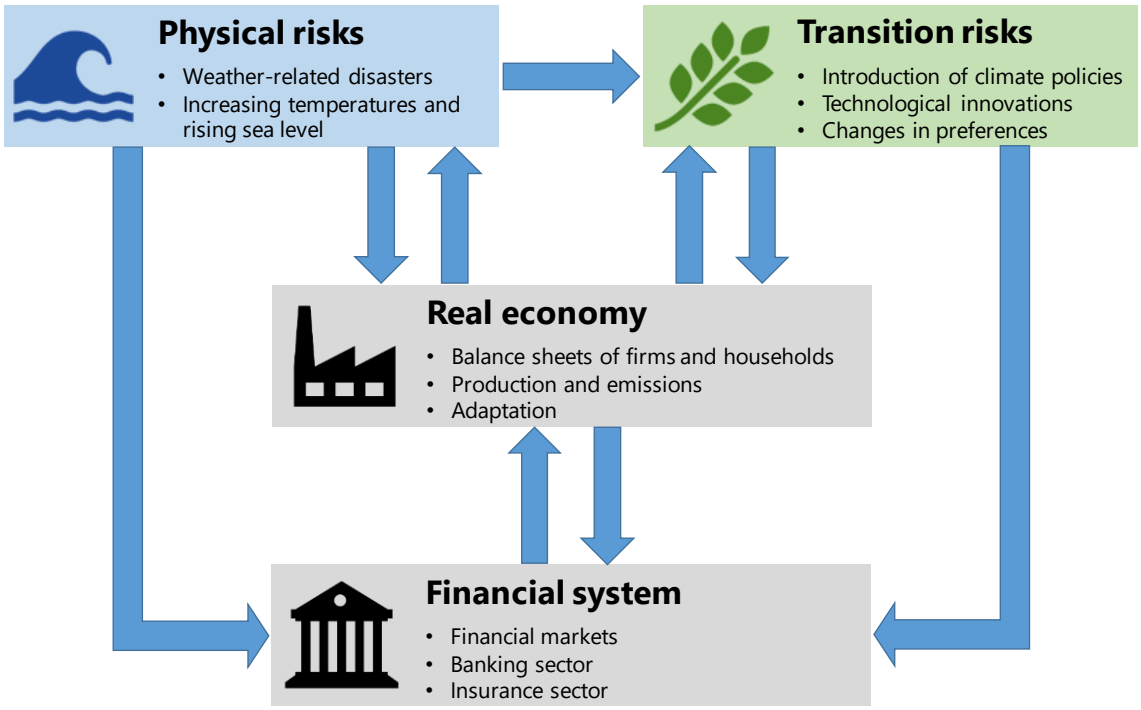
Recent work increasingly focuses on statistical approaches that use historical data, in particular of weather variations or natural disasters. Although the economic response to short-run weather fluctuations may be fundamentally different from that to a long-run change in the distribution of those fluctuations (i.e., the climate) since people can adapt to climate change, for example by constructing flood defenses, the impact of weather variations provides useful insights into the potential impact of climate change, in particular when adaptation is difficult, costly, or takes time.[6] In addition, it is very difficult to accurately estimate the economic impact of climate change using data on climate change directly, since such change only occurs slowly. For these reasons, many recent papers exploit the rich information on high-frequency weather fluctuations. These studies are useful also to consider the impact of natural disasters that can occur in the near future or before people adapt to evolving climate change, given that the intensity and frequency of extreme climate-related weather events already seem to have grown.

2.2. Channels through which climate change and the financial system affect each other

There is increasing attention on the effects of climate change on financial stability, in particular as central banks and supervisors have expressed their growing interest in this issue (see, e.g., Carney, 2015; Lagarde, 2020). At the same time, it is also important to deepen our understanding of the way that the financial system can affect climate change. Against this background, this section provides an overview of discussions on how climate change and the financial system affect each other. The channels are summarized in Figure 1.

[6] Further, some studies argue that with recent advances in methodologies, the effects of climate change can be estimated from weather variations, taking adaptation into account. See Dell, Jones, and Olken (2014), Hsiang (2016), and Kolstad and Moore (2020) for such methods as well as surveys of empirical studies.

Figure 1. Interaction between climate change and the financial system



Recent discussions appear to be reaching the consensus that climate-related risks can largely be classified into physical risks and transition risks. When these risks materialize, the financial system is affected through, broadly speaking, 2 types of channels: direct channels, and indirect channels via the real economy. Furthermore, once the financial system is affected, feedback loops between the real economy and the financial system may start to operate, as suggested in the finance, banking, and macroeconomic literature. For more detailed figures of the channels through which physical risks and transition risks affect the financial system, see Batten, Sowerbutts, and Tanaka (2016) and Batten, Sowerbutts, and Tanaka (2020), respectively.

Physical risks are those risks that arise from the physical impacts of climate change and can be further divided into *acute physical risks*, i.e., risks driven by extreme weather events such as floods and droughts, and *chronic physical risks*, i.e., risks driven by longer-term shifts in climate patterns such as rising sea levels. When physical risks materialize, physical capital, such as factories and houses, is damaged. This leads to a deterioration in firms' and households' creditworthiness, which in turn affects banks' balance sheets. Physical destruction can also lead to a reduction in the value of collateral, which in turn limits the ability of firms and households to borrow. For these reasons,

credit supply from banks is restricted exactly when firms' and households' demand for recovery and liquidity purposes increases. It is also possible that if the losses caused by the materialization of physical risks are covered by insurance, insurers may conduct a fire-sale of assets to finance payouts. If payouts are sufficiently large, this can lead to a deterioration in the solvency of insurers. Moreover, large expected losses may make physical risks uninsurable, reducing the availability of insurance for firms and households. Financial institutions may also be directly affected by physical destruction in the form of damage to their offices, systems infrastructure, and human resources, which can reduce their operational capacity. When physical risks materialize, their impact on the economy is likely to be uncertain for a while, leading to a drop in asset prices as well as more cautious behavior on the part of firms, households, and financial institutions.[7]

Meanwhile, *transition risks* are those risks that arise from transition to a lower-carbon economy. Specific factors that drive such risks include policy changes, technological breakthroughs, and shifts in preferences and social norms. For instance, if a carbon tax is introduced in an attempt to reduce greenhouse gas emissions, the market value of fossil fuels such as oil and coal may drop substantially, leaving firms with "stranded assets" that are no longer able to earn an economic return, such as fossil fuels in the ground, production and processing facilities, and distribution infrastructure. As a result, the balance sheets of firms that own those assets may be greatly damaged. On the other hand, energy prices overall may rise as cheap fossil fuels are no longer available, which may reduce firms' profitability. It is also possible that technological changes that spur the transition to a low-carbon economy affect the profitability of certain firms and industries. For instance, technological advances in electric vehicles may make conventional automobile manufacturers obsolete. Further, financial institutions with large exposure to such industries may incur losses as a result of technological changes, even though technological progress benefits the economy in the long run. Lastly, there have already been large shifts in preferences and social norms associated with climate change that are affecting financial markets. One of the first shifts took shape when the Principles for Responsible Investment (PRI), a United Nations-supported international network of

[7] Kruttli, Tran, and Watugala (2019), for example, find that the implied volatility of stock options on firms with establishments located in hurricane landfall counties in the United States remains high for a long time after a hurricane has struck, suggesting that uncertainty regarding the impact that hurricanes have on the economy in the counties is persistently high.

investors, was launched in April 2006.[8] The number of signatories has been increasing over time and has reached more than 3,000, including some of the largest institutional investors, such as Japan's Government Pension Investment Fund, the largest pension fund in the world. The growing awareness of environmental responsibilities can potentially influence asset prices and firm behavior. Note that transition risks may materialize even before actual transition occurs through the expectations of financial markets, firms, and households.[9]

Although physical risks and transition risks are conceptually distinct and independent, in reality they will likely interact with each other if and when they materialize. For instance, if physical risks become clear to anyone to see via natural disasters or a warmer climate, voters may become more aware of climate change and urge politicians to make abrupt and radical policy changes, which will influence transition risks.[10] On the other hand, transition risks may also alter physical risks through the real economy and the financial system. For instance, if the introduction of a carbon tax is much slower than is warranted, for example due to lobbying, mitigation efforts of firms and households would be insufficient to contain climate change, leading to high physical risks.[11]

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[8] The PRI comprise 6 principles and aim "to understand the investment implications of environmental, social and governance (ESG) factors," and "to support its international network of investor signatories in incorporating these factors into their investment and ownership decisions."

[9] For instance, Ramadorai and Zeni (2020), constructing measures of firms' beliefs about climate regulation, plans for future abatement, and current actions on emissions mitigation using Carbon Disclosure Project data, find that firms steadily downgraded their expectations regarding the impact of future regulation and progressively increased their actual carbon footprint between 2011 and 2015, prior to the Paris Agreement announcement. On the other hand, firms reported upwardly revised beliefs regarding the impact of climate regulation and sharply increased carbon abatement over the years following 2015.

[10] This is illustrated by Gagliarducci, Paserman, and Patacchini (2019). Using data on the universe of federal disaster declarations between 1989 and 2014 in the United States, they document that congress members from districts hit by a hurricane are more likely to support bills promoting more environmental regulation and control in the year after the disaster.

[11] There is some evidence that lobbying has delayed the transition to a low-carbon economy. Meng and Rode (2019) examine the case of the Waxman-Markey bill, which failed to be enacted, using comprehensive U.S. lobbying records. They find that lobbying by firms expecting losses from the bill was more effective than lobbying by firms expecting gains and that lobbying lowered the probability of the bill being enacted by 13 percentage points.

There are also transmission channels in the opposite direction through which the financial system affects climate change and its impacts on the real economy. The financial system may impede the mitigation and adaptation actions of economic agents such as firms and households. One possible source of this impediment is the mispricing of assets. For instance, if stock markets in their valuation of firms do not adequately distinguish between firms with high and low carbon emissions, this can deter efforts to reduce emissions. As discussed by Anderson et al. (2019), if property markets fail to incorporate climate change risks, they may induce excessive investment in areas that are exposed to high risks of weather-related disasters such as floods and tropical cyclones, and, at the same time, discourage development of areas that are relatively shielded from these risks. Furthermore, public policy, such as the provision of public disaster insurance at subsidized rates, can induce moral hazard and distort resource allocation.

Another potential source of impediment is financial constraints. Although conceptually one might think that tight financial conditions would be good for the environment by reducing production and associated emissions, the literature suggests that they are actually bad for the environment because they prevent firms from taking action. Using county-, plant-, and bank-level data, Levine et al. (2019), for example, find that bank liquidity shocks that tighten firms' credit conditions are linked with an increase in their toxic emissions. Similarly, examining data on environmental spills such as leaks of oil, of which approximately 30,000 are reported in the United States and its coastal waters each year, Cohn and Deryugina (2018) find that such spills increase following a negative shock to firms' financial resources. They also find some evidence that this relationship is stronger for firms for which cash constraints are likely tighter, such as firms with high levels of debt and, especially, smaller firms. Meanwhile, Brown, Martinsson, and Thomann (2018) find that firms respond to higher taxes on air pollution by increasing research and development (R&D), but this response is substantially weaker among firms facing financing constraints: small firms increase R&D only when they have access to external financing. Further, using data on applicants to the U.S. Department of Energy's Small Business Innovation Research grant program, Howell (2017) finds that such grants increase the probability that a firm receives subsequent venture capital and have a large, positive impact on patenting and revenue. These effects are stronger for more financially constrained firms. She also provides evidence that such grants are useful in sectors likely to have large positive spillovers, such as hydropower, carbon capture and storage, building and lighting efficiency, and automotive technologies, while there is no measurable effect for conventional energy technologies, like natural gas and coal,

suggesting that firms in these sectors are not financially constrained. Further, looking back at previous episodes of financial and economic stress, a study by IMF (2020a) finds that tighter financial constraints and adverse economic conditions are generally detrimental to firms' environmental performance, reduce green investments, and set back their progress by several years.

The characteristics and behavior of investors can also drive the environmental performance of firms. This is illustrated, for example, by Dyck et al. (2019), who construct firm-level environmental and social (E&S) performance measures across 41 countries using line items (covering areas such as CO_2 emissions, renewable energy use, and human rights violations) from several data providers. They also construct a social norms index using data from the World Values Survey, which interviews several thousand individuals in more than 100 countries to assess people's values and beliefs on many items such as environmental activism. Employing these data, the authors find that institutional ownership improves E&S performance, when institutional investors come from countries where there is a strong community belief in the importance of E&S issues. Meanwhile, Choi, Gao, and Jiang (2020a) examine the actions of financial institutions and firms regarding greenhouse gas emissions. They find that financial institutions around the world have reduced their exposure to stocks of high-emission industries since 2015, especially of firms located in countries with high climate awareness. In the presence of divestment, firms in these countries have tended to experience lower price-to-earnings and price-to-book ratios, which make equity financing costlier, but they have increased capital expenditure and R&D expenses, suggesting that high-emission firms are investing in methods to reduce emissions. These results support the notion that divestment by financial institutions exerts pressure on firms to adopt climate-friendly policies and decrease their carbon footprint. Further, conducting an event study using the introduction of mandatory greenhouse gas emissions reporting for firms listed on the Main Market of the London Stock Exchange in 2013, Jouvenot and Krueger (2020) provide evidence that U.K. firms, in particular those with higher emissions prior to the introduction of mandatory reporting, responded to the disclosure requirement by reducing their emissions. The authors argue that one reason for the reduction in emissions is fear of a decline in investment from institutional investors, based on their finding that following the introduction of mandatory reporting, institutional investors decreased their holdings in firms with high greenhouse gas emissions relative to those with low emissions. In addition, they provide evidence that 2 other reasons have played a role: fear of bad media coverage and heightened peer pressure within the industry. Finally, using data for 2007–2016,

Shive and Forster (2020) find that, within public firms, emissions are negatively associated with mutual fund ownership and board size, suggesting that increased oversight may result in firms improving their environmental performance.

Recent studies also examine the roles of equity and debt finance in environmental performance and provide mixed evidence. For instance, using a large panel of 48 countries and 16 industries over the period 1990–2013, De Haas and Popov (2019) find that for given levels of economic and financial development and environmental regulation, CO_2 emissions per capita are lower in economies that are more equity-funded than in economies that are more credit dependent. Their analysis reveals 2 distinct channels. First, stock markets reallocate investment towards less polluting sectors. Second, stock markets facilitate the adaptation of greener technologies and the production of green patents. The authors also document that when carbon-intensive sectors reduce domestic carbon emissions, they increase imports that are associated with emissions, although the increase in carbon emissions associated with the production of imported goods is equivalent to only around one-tenth of the reduction in domestic emissions. Further, Levine et al. (2019) provide some evidence that access to finance other than bank credit helps to mitigate emissions. Specifically, they find that shocks that tighten bank liquidity increase the toxic emissions of private firms, which tend to have poorer access to finance beyond the credit provided by banks operating in the firms' headquarters-county, much more than those of public firms. In contrast, Shive and Forster (2020) find that private firms that are not sponsored by private equity funds are less likely to emit greenhouse gases and incur administrative penalties than comparable public firms, while there are no differences between private sponsor-backed firms and public firms.

2.3. Potential policy measures

Why would people continue to emit too much CO_2? The important drivers are negative externalities and insufficient information. Negative externalities arise when production or consumption of a good imposes a cost on those who do not benefit from the production or consumption of that good. In the case of CO_2 emissions, the costs are shared by essentially everyone on the planet through the impacts of emissions on the climate. Since producers or consumers usually do not pay the full costs of CO_2 emissions resulting from their economic activities, they have the incentive to produce or consume to the point that the associated CO_2 emissions exceed the socially optimal level. Negative externalities may also be generated by financial institutions; for instance, banks may enable

inefficiently large investment in carbon-intensive capital if they do not consider the cost of associated climate change. The literature also suggests that there is generally not sufficient public information to accurately assess the value of assets or to optimize decisions with regard to, for instance, stock investment. This shortage of information can distort resource allocation; for instance, if, due to a shortage of information, the stock prices of low-carbon firms are not higher than those of otherwise similar but carbon-intensive firms, firms have little incentive to reduce emissions.

As discussed above, negative externalities and insufficient information result in a failure of markets to achieve an optimal allocation of resources. Such market failure means that policy interventions may be justified. While mandatory disclosure, for instance, could be used to address insufficient information, carbon pricing is widely regarded as the first best option to deal with negative externalities. Carbon pricing involves imposing a fee on the emission of CO_2 and is generally implemented via a carbon tax or carbon emission trading. Greenhouse gas emission trading has already been introduced in some areas, such as the European Union and California.[12] The carbon pricing schemes introduced so far are, however, limited and insufficient in the eyes of leading economists.[13] Under these circumstances, Krogstrup and Oman (2019), for example, argue that fiscal tools, including a carbon tax, are first in line and central, but can and may need to be complemented by other policy instruments, including financial policy tools.

Recent discussions provide some support for the use of financial policy measures, such as climate-related stress tests of financial institutions and the enhancement of disclosure requirements for financial institutions, although policy makers and scholars are more cautious about policies to actively promote greening, such as lower risk weights

[12] Evidence suggests that such emission trading schemes have had some effect. Investigating the effects of Southern California's NOx Trading Program using data on individual facilities, Fowlie, Holland, and Mansur (2012) find evidence that average emissions fell. In addition, although there have been concerns that emission trading may lead to pollution flowing into areas where poorer or minority population lives, they did not find evidence for this. Similar results have been found for CO_2 trading in California (Walch, 2018; Hernandez-Cortes and Meng, 2020; Mansur and Sheriff, 2019).

[13] In January 2019, more than 40 economists, including 27 Nobel laureates, signed the Economists' Statement on Carbon Dividends, which states that "[a] carbon tax offers the most cost-effective lever to reduce carbon emissions at the scale and speed that is necessary." It argues that "a carbon tax should increase every year until emissions reductions are met" and that such a tax "will encourage technological innovation" (Source: https://www.econstatement.org).

for "green" loans and investment in calculating financial institutions' regulatory capital ratios (Batten, Sowerbutts, and Tanaka, 2016; Campiglio et al., 2018; Krogstrup and Oman, 2019; Dikau and Volz, 2019; Bolton et al., 2020). For instance, Dikau and Volz (2019) discuss policy measures from the viewpoint of central banks' mandate. They examine the mandates and objectives of 133 central banks using the IMF's Central Bank Legislation Database and argue that central banks should incorporate climate-related risks into their core policy implementation frameworks, given that such risks can directly affect central banks' traditional core responsibilities. They also point out, however, that for a majority of central banks, active contribution to greening of the financial system and the economy as a whole is not covered by their mandate and that requiring central banks to promote sustainability is contentious, partly because of potential conflicts with central banks' primary mandate. In what follows, we briefly survey the discussion on stress tests and risk weight adjustments, which have featured prominently in the literature.

An important area of financial policy measures to help counter climate change is stress tests that assess financial institutions' exposure to climate-related risks. Some central banks have already started to conduct stress tests that incorporate climate aspects and others are considering following suit (see, e.g., Vermeulen et al., 2018; Allen et al., 2020; Roncoroni et al., 2020). Although stress tests are a useful tool to quantify future risks to financial institutions, there are concerns that they often rely on arbitrary scenarios and unrealistic assumptions such as constant balance sheets over a long period of time (NGFS, 2020a). Moreover, most methodologies assume that climate change is exogenous or fail to consider how financial institutions' behavior affects climate change.

Regarding the adjustment of risk weights to promote green lending and investment, many are skeptical. In a Staff Working Paper by the Bank of England, Batten, Sowerbutts, and Tanaka (2016) argue that prudential regulations are fairly blunt instruments for dealing with climate-related externalities and that relaxing capital requirements just to encourage particular types of lending could jeopardize the safety and soundness of financial institutions, while tightening regulations on financial exposures to carbon-intensive firms could reduce their ability to invest in emission-reducing technologies. Meanwhile, Brunnermeier and Landau (2020) argue that although capital ratios could be used in a more proactive way by applying favorable regimes to loans and investments deemed "green" by supervisors, 3 challenges would need to be addressed *ex ante*: green investments may be intrinsically riskier; regulators may not be equipped to

define loans and investments as "green;" and there might be severe lobbying pressure from various interest groups. Even the NGFS, which aims at greening the financial system, expresses caution about the adjustment of risk weights (NGFS, 2020b). Box 26 of this report argues that risk weight adjustments seem to be problematic and to play a very limited role from a prudential perspective for the following reasons. A "brown" company that has sufficient capital, a strong management, and a credible long-term strategy might manage the transition well, while green companies can face transition risks, too, for instance because their business model might be based on new technologies that have yet to be proven at scale. In addition, given that different risk profiles of individual assets should ultimately be fully reflected in the calculation of regulatory risk assets, for example through internal models and external ratings, adjustment factors could lead to double-counting of climate-related risks, resulting in distortions.

2.4. Contributions of this paper

We have so far provided a brief overview of the literature on climate science and economics, the transmission channels between climate change and the financial system, and recent discussions on policy measures that financial authorities could potentially implement. One aspect that is not necessarily highlighted in the literature on climate-related financial risks is the causal link from the financial system to climate change and people's efforts to mitigate and adapt to climate change. This is important since, without evidence on the causal connections in this direction, it is difficult to build a common understanding based on which to discuss a large part of potential financial policies, including risk weight adjustments. On the other hand, there is also ample room for further understanding the causal links from climate change to the financial sector. In particular, while recent discussions often focus on the relatively long-term impacts of climate change, it is also important to deepen our understanding of the shorter-term impacts of climate-related natural disasters that can happen in the near future.

The contribution of this survey paper is to help us understand the interaction between climate change and the financial system through the following 2 tasks: first, we explore the causal link from the financial system to climate change risks through mitigation and adaptation. Second, we also explore specific channels of causation from climate change under relatively short time horizons. These 2 tasks are among those with

a high priority in analyzing climate-related financial risks (NGFS 2020c).[14] With these tasks in mind, Sections 3 to 5 survey the literature on asset prices, bank behavior, and insurance, respectively.

3. Do asset prices reflect climate-related risks?

Whether prices of assets, such as real estate, stocks, bonds, and loans, reflect climate change risks has significant implications for the stability of the financial system. If they do not, or do so only partially, there is a risk that asset markets will experience significant disturbance when climate change risks materialize or people become more aware of the risks. This disturbance, in turn, will have implications for the real economy as households', firms', and financial institutions' balance sheets may be damaged as a result of abrupt repricing of their assets. Moreover, if these assets are used as collateral, a decline in asset prices may severely impair agents' ability to borrow. Misevaluation of climate change risks can also lead to misallocation of resources. For instance, if stock markets do not adequately price firms with low carbon emissions relative to those with high emissions, this can deter efforts to reduce emissions. Similarly, if real estate property prices do not reflect the risk of floods or a rise in sea levels, this may encourage excessive development in risky areas, which poses an immense threat to housing, infrastructure, and people's lives. Conversely, properly priced assets can encourage preemptive actions to reduce the costs of climate change (Anderson et al., 2019). Furthermore, asset prices are frequently used to extract information on climate risks; therefore, knowing to what extent, and

[14] NGFS (2020c) lays out research priorities along 2 themes: climate-related financial system risks and transmission channels; and macroeconomic assessment and monetary policy. One of the 5 questions NGFS (2020c) sets out for the first theme is what the direct and indirect transmission channels are through which physical and transition risk could affect financial stability. On this question, NGFS (2020c) states that "[t]he literature currently shows some of the theoretical channels through which physical and transition risk could affect financial stability, but there is room for additional research in more precisely identifying the possible risks, particularly in the relatively short-term." Chapter 4 of this survey paper addresses this question. The discussion on the causal link from the financial system to climate change risks explored in Chapter 3 relates to 2 other questions raised by NGFS (2020c): "To what extent do markets and investors price carbon-related risks and how much transition risk is factored into the value of securities?" And: "What are the potential feedback and contagion effects (e.g. fire-sales, network effects) of a re-pricing of climate-related financial risks on the financial sector and the real economy?"

ensuring that, asset prices accurately reflect climate risks is of critical importance from a range of perspectives, not least in terms of maintaining the stability of the financial system.

Against this background, in the present section we review the literature investigating whether – and to what extent – prices of a wide range of assets incorporate climate change risks. We start with the market for real estate, on which there is a rich literature on the association with climate change risks and which provides a good illustration of what factors encourage (or hinder) the incorporation of climate change risks into prices (Section 3.1). We then review the literature on stocks (Section 3.2) and other types of financial assets such as corporate and municipal bonds, green bonds, syndicated loans, and weather derivatives (Section 3.3). Finally, we briefly summarize this section (Section 3.4).

3.1. Real estate property

Many recent studies – most using data for the United States – find that property prices do not adequately reflect the physical risks of climate change, such as a rise in sea levels and floods. For instance, Bernstein, Gustafson, and Lewis (2019) find that, on average, homes exposed to sea level rise sell at a discount relative to unexposed properties, but this discount is concentrated in the non-owner occupied segment of the market, in which buyers tend to be more "sophisticated."[15] They also find that although the prices of owner occupied properties are not significantly related to sea level rise exposure on average, such exposure does affect prices when local residents are sufficiently worried about sea level rise, which suggests that "unsophisticated" buyers are susceptible to local beliefs.[16] As another piece of evidence that buyers of owner occupied properties do not adequately price in climate risks, the authors show that the discount increased only for non-owner occupied properties after upward revisions of sea level rise projections by scientists.

[15] The authors find that descriptive statistics are consistent with the idea that non-owner occupiers are more sophisticated as they tend to come from zip codes with higher education levels and income. Further, owner-occupier to non-owner occupier sales earn higher returns than non-owner occupier to owner-occupier transactions.

[16] The study by Bernstein, Gustafson, and Lewis (2019), as well as many others, such as Baldauf, Garlappi, and Yannelis (2020) and Murfin and Spiegel (2020), use data from the Yale Climate Opinion Survey (Howe et al., 2015). This survey provides answers of respondents in the United States at the county level to questions such as (i) whether they think that global warming is happening, (ii) whether they will be personally harmed by global warming, and (iii) how worried they are about global warming.

Based on these findings, the authors warn about the possibility of a large negative shock to owner-occupied house prices. Furthermore, they suggest that an important question for future research is whether the observed sea level rise exposure discount among sophisticated buyers correctly incorporates all information; if it does not, even larger shocks can be expected.

Another study examining whether house prices reflect different beliefs about climate change is that by Baldauf, Garlappi, and Yannelis (2020), who use comprehensive transaction data to relate prices to flood projections of individual homes and measures of beliefs about global warming in each county in the United States. They find that houses projected to be underwater due to sea level rise in believer neighborhoods (i.e., counties with a relatively large share of people believing in global warming) sell at a discount compared to houses in denier neighborhoods. As a placebo test, they also examine commercial properties, for which differences in local beliefs are likely less important because the participants in those transactions tend to be more sophisticated than those in residential real estate transactions. Additionally, firm headquarters may be located somewhere else and decisions by corporations may therefore be made in a different geography from where the real estate is located, which is not the case in residential housing transactions. Consistent with this intuition, the authors find that differences in beliefs about climate change do not appear to affect the price of commercial real estate.

Meanwhile, using 2 decades of sales data covering the universe of homes in the United States, Hino and Burke (2020) compare the discounts on properties located in floodplains to the expected damage estimated from premiums of the National Flood Insurance Program (NFIP), the dominant public insurer for flooding, and find that such discounts do not adequately reflect the expected damage. Their findings indicate that floodplain homes are currently overvalued by US$34 billion in total.[17] They also find that the home price discount is larger for commercial buyers, which are defined based on

[17] Hino and Burke's (2020) estimate of overvaluation of these homes may underestimate the scale of the issue, since they do not take into account that the NFIP insurance premia may be lower than would be warranted by the flood risk, although the authors recognize that the NFIP offers subsidized insurance rates. Relatedly, Bakkensen and Barrage (2017), based on a report by the U.S. Government Accountability Office, point out that the NFIP is considered to be fiscally unsustainable and has been labeled as a "high risk" program due to its failure to charge actuarially fair rates for many of its policies. Further, Kahn and Smith (2017) document that the NFIP offers reduced insurance rates for homes built before hazard rate maps were drawn and grandfathers rates for homes when new maps increase their risk ratings.

the name (for instance, all buyers ending in "LLC" are interpreted as being limited liability companies and tagged as commercial) and are regarded as a group likely to have more experience purchasing real estate and greater resources to seek out flood-related information than individuals and households. Furthermore, a large discount tends to be observed in states where sellers must disclose information about flood risk to potential buyers. This result suggests that policies to enhance risk communication could improve the functioning of the market, although the discount in these states is still insufficient compared to the expected damage.

That a lack of information disclosure leads to the overpricing of houses is also shown by Giglio et al. (2018). They construct a "Climate Attention Index" for the housing market by performing a systematic textual analysis of for-sale listings to measure the frequency with which climate-related text (e.g., mentions of hurricanes or flood zones) appears in the written description of the listed properties. They show that when the fraction of property listings with climate-related text doubles, there is a 2–3 percent relative decrease in the prices of properties that are in a flood zone compared to other comparable properties.

While the studies mentioned so far suggest that house prices partially reflect sea level rise risk, Murfin and Spiegel (2020) consistently find no evidence for effects of sea level rise exposure on real estate prices in a variety of specifications and test settings. They highlight the identification problem that arises from the presence of correlation between amenity and risk exposure. In particular, while the literature often uses data on housing elevation (i.e., the elevation above sea level) and assumes that this is negatively associated with sea level rise exposure, housing elevation is also correlated with housing amenity, such as scenic views. Thus, even if house prices are found to be higher for higher elevations, we cannot identify whether this is due to less sea level rise exposure or greater amenity. To address this identification challenge, Murfin and Spiegel (2020) exploit cross-sectional differences in trends in vertical land motion due to land subsidence and land rebound, which provide variation in the expected time to flood due to sea level rise for properties of similar elevation.[18]

[18] Relatedly, while being close to the waterfront increases the exposure to sea level rise and flood risks, it also improves amenity by providing scenic views and access to water activities. To identify the effects of flood hazard and ocean view on coastal house prices and confirm that flood risk reduces property values, Bin et al. (2008) construct a three-dimensional measure of ocean view.

The importance of heterogeneity in risk perceptions as a source of overpricing in housing markets is highlighted by Bakkensen and Barrage (2017). Constructing a theoretical model with heterogeneity, they argue that the impact of risks on property prices may be suppressed since optimistic people move to high-risk regions in place of non-optimistic people when the risks increase.[19] Conducting their own survey, they indeed find significant heterogeneity in flood risk perceptions and amenity values. Using this survey result, they calibrate their theoretical model while controlling for the amenity value of properties and find that house prices as of the time of their study exceeded fundamentals by 10 percent. Their model also shows that ignoring heterogeneity leads to a four-fold underestimation of coastal home price declines due to sea level rise over the next 25 years.

In sum, recent papers find that property prices do not adequately reflect climate change risks. In particular, properties tend to be overpriced when buyers are unsophisticated or do not believe in global warming or when information disclosure is insufficient. These results suggest that property prices may drop significantly once people become aware of the risks. In fact, several studies find that when natural disasters happen, property prices decline even in areas that are not directly affected or damaged. For instance, Hallstrom and Smith (2005) find that although Hurricane Andrew did not hit Lee County, Florida, in 1992 and the storm was a "near-miss," home values in high-risk flood areas of the county declined by at least 19 percent relative to those in low-risk areas of the county. This suggests that the large hurricane conveyed risk information to homeowners in the county.

Another study examining the role of perceptions is that by Muller and Hopkins (2019). Highlighting that Hallstrom and Smith's (2005) results regarding the information effect may be contaminated by confounding factors – the study coincided with legal changes that made flood insurance in high-risk areas mandatory, making it more expensive to own a high-risk home – they examine the response of home prices in the coastal real estate market in New Jersey to several well-publicized hurricanes and tropical storms that did not strike the area. In addition, they investigate the effects of the NFIP's flood awareness activities, in which each town can choose to participate. They find that homes in high flood risk zones incur a 7 to 16 percent decrease in price after a non-local

[19] Bunten and Kahn (2014) also construct a theoretical model with heterogeneity to explain a weak impact of risks on property prices.

shock when the town participates in the awareness activities. This result suggests that people's perceptions of, and communication with regard to, climate risks have an important impact on asset prices.

Further evidence in this regard is provided by Ortega and Taşpınar (2018), who use Hurricane Sandy in 2012 as a natural experiment. They estimate the effect on the New York City housing market employing a dataset that contains all housing sales up to 2017. Their measure of damage covers over 300,000 buildings, including all structures in the flood area, and is constructed using aerial imagery. This extensive coverage means that sample selection bias is unlikely to be a concern. They show that Hurricane Sandy persistently reduced house prices in the city's flood zone relative to similar properties in the rest of the city, even if the properties were not damaged by the hurricane: a price penalty among non-damaged properties in the flood zone has gradually emerged, reaching 8 percent in 2017 and showing no signs of disappearing. Examining several hypotheses to explain their finding, such as out-migration or damaged neighbors (residential properties, businesses, and infrastructure), they conclude that the persistent price decline was likely driven by updated perceptions of flood risk.

While this subsection focused on the market prices of real estate properties, financial institutions' valuations of property as collateral also matter. Overvaluation of collateral can lead to distortions in the allocation of resources, and a downward adjustment in prices of collateral can pose a threat to financial stability. For instance, Garbarino and Guin (2020) find that after a severe flood event in England in 2013–14, market prices of properties declined but lenders did not adjust interest rates or loan amounts because their valuations of properties (used for mortgage refinancing) did not "mark-to-market" against the market price declines in neighborhoods. Their result implies that the lenders may have effectively provided subsidies for borrowers to invest in high-risk areas.

3.2. Stocks

The findings for stocks somewhat mirror those for real estate. A major difference is that while the literature on real estate focuses on physical risks such as floods and sea level rise, many studies on stocks focus on transition risks faced by firms. Typical examples of firms with high transition risks are those that emit large amounts of CO_2: if policy measures are taken to penalize CO_2 emissions, such firms could face difficulties in their business. If a firm is more exposed to climate change risks than others, then investors

should demand higher returns from its stock in compensation, all else being equal. Many studies show that firms more exposed to climate change risk indeed provide higher returns, which suggests that stock prices to some extent incorporate some types of climate change risk. However, the literature also finds evidence of the mispricing of stocks. In what follows, we first survey recent studies on the relationship between risk exposures and stock prices and then discuss the potential problems arising from mispricing and the usefulness of disclosures.

Studies examining the link between risk exposures and stock prices have employed a variety of approaches, using firm- or portfolio-level data, event study approaches, and so forth. Starting with studies using firm-level data, many find evidence that stock markets do price in climate-related risks to some extent. Hsu, Li, and Tsou (2020), for example, find that, once other factors are controlled for, firms with higher toxic emission intensity generate higher stock returns. They examine several possible explanations for this pollution premium and attribute it to policy uncertainty with respect to environmental regulations. They explain the mechanism underlying this premium using a general equilibrium model: if the shift to a strong regulation regime results in an economy-wide downturn, the market penalizes firms that are susceptive to this regime shift (i.e., firms with a highly negative beta on regime change risk). Meanwhile, Bolton and Kacperczyk (2020a), using data for the United States, find evidence of a positive carbon premium; that is, stock returns are higher for companies with higher carbon emissions. Further, in a separate study, Bolton and Kacperczyk (2020b) estimate the carbon premium for over 14,400 firms in 77 countries and find that there is a widespread carbon premium in all sectors over 3 continents, Asia, Europe, and North America; stock returns are affected by both direct and indirect emissions through the supply chain; the carbon premium has been rising in recent years; and divestment based on carbon emissions by institutional investors is widespread around the world but investors tend to focus their divestment on foreign companies. Next, Ilhan, Sautner, and Vilkov (2020) show that uncertainty around climate policy is priced in in the option market, and that the cost of option protection against downside tail risks is larger for firms with more carbon-intense business models. They also show that the results are robust to dropping oil and gas firms. Meanwhile, Hoepner et al. (2018) find that firms' engagement in environmental, social, and governance (ESG) issues, in particular environmental topics (primarily climate change), benefits shareholders by reducing firms' downside risk, such as value at risk estimated from stock prices.

While the preceding studies use firm-level data, Bansal, Kiku, and Ochoa (2019) use portfolio-level data to empirically show that equity valuations are negatively associated with the long-run trend in global temperatures, while this relationship is weaker for the shorter-run trend. They also find that fluctuations in the long-run temperatures carry a positive risk premium. These results suggest that investors are concerned about the long-run implications of rising temperatures for the economy. The authors then use a theoretical framework with consumer preferences for early resolution of uncertainty which can explain the empirical finding and find that the welfare cost of rising temperatures is economically large.

A widely used approach in the literature to examine the causal impact of climate risks on asset pricing is the event study approach. Some studies, for instance, use announcements of the issuance of green bonds as the event. An example is the study by Flammer (2020), who documents that stock market investors respond positively to the announcement of the issuance of green bonds, a response that is stronger for first-time issuers and bonds certified by third parties. She also finds that, after the announcement, issuers' environmental rating improves, their CO_2 emissions fall, and they experience an increase in ownership by long-term and green investors. The findings are consistent with the signaling argument that by issuing green bonds, companies credibly signal their commitment towards the environment. The stronger response for first-time issuers than seasoned issuers is also consistent with this argument; that is, the first time a firm issues green bonds this provides the market with substantial new information about the firm's commitment to green projects, while the new information content of subsequent issues is likely to be smaller. Along similar lines, Tang and Zhang (2020) examine the announcement returns and real effects of green bond issuance by firms in 28 countries during 2007–2017. Compiling a comprehensive international green bond dataset, they document that stock prices positively respond to green bond issuance. They also show that institutional ownership, especially from domestic institutions, increases after a firm issues green bonds. Moreover, stock liquidity significantly improves upon the issuance of green bonds.

Yet another strand of the literature focuses on political events to examine the impact of transition risks: since the likelihood of the introduction of climate change policies depends heavily on the political environment, transition risks may evolve in a discontinuous fashion in the wake of political events. Cases in point are the adoption of the Paris Agreement in 2015 and the election of U.S. President Trump in 2016. If the

Paris Agreement helped strengthen markets' expectations of transition to a lower-carbon economy, asset prices may have started to reflect transition risks to a greater extent. On the other hand, the election of President Trump, a climate skeptic, potentially lowered expectations of climate change policies. This may have resulted in asset prices reflecting transition risks to a lesser extent.

In fact, there are quite a number of studies focusing on the election of President Trump. Ramelli et al. (2019), for example, find that, as expected, firms with high current carbon emissions enjoyed relatively high abnormal returns after the election of President Trump and his nomination of Scott Pruitt, a climate skeptic, to lead the Environmental Protection Agency. Somewhat surprisingly, relatively high returns are also observed for companies with responsible strategies on climate change, which the authors measure in terms of their ESG scores with regard to, for instance, future emission targets.[20] The authors also examine investors' portfolios and find that long-horizon investors shifted to climate-responsible stocks. They then argue that the surprising result is at least in part due to long-horizon investors expecting a post-Trump rebound to green policies. Another study using these election-related events is that by Hsu, Li, and Tsou (2020), who suggest that, as expected, 3-day window returns around these events for firms with a higher toxic emission intensity are higher than for firms with a lower emission intensity. Meanwhile, Ilhan, Sautner, and Vilkov (2020) show that the cost of option protection against downside tail risks of carbon-intensive firms decreased after the election of President Trump. They also find that the cost rises when public attention to climate change spikes, which they measure using Google search volume data for the topic "climate change" and Engle et al.'s (2020) negative climate change news index, which captures the share of news articles that are about "climate change" and have been assigned to a "negative sentiment" category.

Although many of the papers reviewed so far suggest that stocks to some extent price in some types of climate change risks, in particular transition risks, the literature also finds evidence for mispricing of physical risk. For instance, examining the stock prices of food companies, which rely on water and hence are sensitive to drought risk,

[20] Although a growing number of academic studies rely on ESG ratings for empirical analysis, ratings from different providers are found to disagree substantially. The divergence in ratings poses a challenge for empirical research, as using one versus another may alter a study's results and conclusions. See Chatterji et al. (2016), Liang and Renneboog (2017), and Berg, Koelbel, and Rigobon (2020) for further discussions.

Hong, Li, and Xu (2019) find that a stronger long-term trend toward droughts in a particular country predicts lower profit growth and stock returns of food companies in that country. This predictability of returns indicates that stocks of food companies are mispriced. Other studies also find the anomaly that higher climate risks are associated with lower returns. For instance, using the sensitivity of stock returns to abnormal temperature changes in the United States to measure firm-level climate sensitivity, Kumar, Xin, and Zhang (2019) first show that some of estimated sensitivities can be interpreted. For instance, because the demand for energy rises on cold days, firms in the coal and oil industries tend to earn higher returns during periods with abnormally low temperatures, which means that their stock returns are more negatively sensitive to temperature anomalies. The authors then find that profits and stock returns tend to be lower for firms with a higher absolute value of climate sensitivity. Extending the analysis of Kumar, Xin, and Zhang (2019) to a sample of 27 economies, IMF (2020b) finds a similar temperature-related pricing anomaly in more than half of the economies considered.

One concern that arises from the mispricing of climate-related risks is potential sudden changes in risk perceptions, which could lead to a shift away from risky assets, a plunge in stock prices, and serious financial instability. In fact, the literature indicates that events that raise the awareness of risks, such as abnormal weather events, lead to a larger decline in stock prices of firms with greater climate-related risks. For instance, using temperature data from 74 cities around the world where stock exchanges are located, Choi, Gao, and Jiang (2020b) find that the number of Google searches on global warming-related topics in those cities increases significantly when they experience abnormally warm temperatures, implying that beliefs about climate change of individual investors are revised upward. They also find that stocks of carbon-intensive firms underperform those of firms with low carbon emissions in abnormally warm weather. In addition, retail investors (not institutional investors) sell off carbon-intensive firms in such weather, which is consistent with the conjecture that retail investors are more prone to limited attention and influenced by notable events. Moreover, stock returns are affected by extreme temperatures regardless of whether the firms are domestic or international, or whether firms belong to certain industries, such as utilities and leisure, whose earnings are likely to be directly affected by rising temperatures. These results suggest that changes in returns are due to changes in investor perceptions rather than changes in firms' fundamentals or future cash flows. The authors therefore argue that, as investors become more aware of climate risk, they seem to avoid holding stocks of high-emission firms in

a way similar to "sin" stocks (stocks of alcohol, tobacco, and gaming companies).[21] This argument is further supported by a study by Hartzmark and Sussman (2019). In March 2016, Morningstar, a financial research website, published its first sustainability ratings of more than 200,000 mutual funds. The worst 10 percent of funds were rated one globe, while the best 10 percent were rated five globes. Regarding the introduction of these sustainability ratings as a large shock that influences investors' perceptions but does not directly impact fundamentals, Hartzmark and Sussman (2019) find that funds that were awarded one globe saw net outflows of funds, while those that were awarded five globes registered inflows. On the other hand, they find no significant differences in terms of inflows and outflows after the introduction of the sustainability ratings across funds in the 3 middle categories. Furthermore, although Morningstar also released the sustainability score and percentile rank underlying the globe for each fund, the authors find that these had a minimal impact on fund flows. These results by Hartzmark and Sussman (2019) suggest that investors focus only on simple and extreme information rather than more detailed information.

Another important issue is that investors may not only suddenly price in climate change risks when facing climate risk-related events but also overreact to them due to a salience bias – that is, the tendency to overestimate the risk of events based on their vividness, proximity, or emotional impact. For instance, Alok, Kumar, and Wermers (2020) find that professional money managers within a major disaster region underweight disaster zone stocks to a much greater degree than distant managers. They argue that this aversion to disaster zone stocks is related to a salience bias rather than to superior information held by managers in close proximity, citing the following evidence. First, the post-disaster change in the return on assets or sales growth of firms in the disaster zone relative to firms close to the disaster zone is statistically indistinguishable from zero. Second, disaster zone stocks that are most underweighted by disaster zone funds subsequently outperform stocks that are overweighted by those funds, indicating a potential price pressure effect due to the misjudgment and overreaction of the funds.

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[21] Hong and Kacperczyk (2009) hypothesize that there is a societal norm against funding operations that promote vice and that some investors pay a financial cost in abstaining from these stocks. Consistent with this hypothesis, they find that sin stocks are less held by norm-constrained institutions such as pension plans as compared to mutual or hedge funds that are natural arbitrageurs, and sin stocks receive less coverage from analysts than stocks with otherwise comparable characteristics. The authors also show that sin stocks have higher expected returns than otherwise comparable stocks.

Finally, many studies examine the impact of disclosure on how stocks price in climate change risks. Ilhan et al. (2020) examine whether investors value carbon risk disclosure, using a survey on institutional investors and empirical tests on the survey data. They conclude that many institutional investors consider climate risk reporting to be as important as financial reporting. With regard to the relative importance of physical, technological, and regulatory risks related to climate change for disclosure, their survey reveals that concerns about physical risks matter the most, while regulatory risks matter the least. This result may be due to the fact that physical risks are potentially more difficult to observe because they are generally firm and location specific, while regulatory risks tend to be firm independent and regulator dependent, making information on regulatory risks easier to obtain from sources outside of the firm. The vast majority of respondents to their survey believe that current disclosures on climate risks are uninformative and imprecise. Respondents who believe that necessary information in current reporting is lacking tend to judge there to be more overvaluation of stocks. The authors' empirical tests show that greater institutional ownership, particularly by investors from high social norm countries,[22] is associated with a higher propensity of firms to voluntarily disclose their carbon emissions and to provide higher quality information by asking third parties to audit and verify the emissions data they disclose.

In contrast to the views of the vast majority of respondents in the survey conducted by Ilhan et al. (2020), studies based on stock price data suggest that current information disclosure is useful to some extent. Furthermore, such studies suggest that, in the absence of disclosure, stocks tend to be undervalued particularly for firms with low emissions. This suggests that stock markets do not adequately distinguish between firms with high and low emissions, deterring efforts to reduce emissions. A study examining the link between disclosure and stock prices is that by Matsumura, Prakash, and Vera-Muñoz (2014), who use carbon emissions data voluntarily disclosed to the Carbon Disclosure Project by S&P 500 firms. Correcting for self-selection bias in managers' decision to disclose carbon emissions, they find that firm value decreases as carbon emissions increase. They also find that the median value of firms that disclose their carbon emissions is about US$2.3 billion higher than that of comparable non-disclosing firms. This result indicates that a penalty is imposed on firms that do not disclose. Meanwhile,

[22] Ilhan et al. (2020) use the Environmental Performance Index developed by the Yale Center for Environmental Law and Policy as a summary of social norms in a country.

Jouvenot and Krueger (2020) examine the introduction of mandatory greenhouse gas emissions reporting for firms listed on the Main Market of the London Stock Exchange and find that firms disclosing low (high) emissions relative to industry peers exhibit positive (negative) abnormal returns. Further, Flammer, Toffel, and Viswanathan (2019) find that, in the absence of mandated disclosure requirements, environmental shareholder activism increases the voluntary disclosure of climate change risks. This is especially true if initiated by long-term institutional investors. The authors suggest that this is because institutional investors are more powerful and requests from long-term investors are more legitimate due to their holding stocks for a long period of time. They also find that firms that voluntarily disclose climate change risks following environmental shareholder activism achieve a higher valuation, suggesting that investors value transparency with respect to climate change risks.

3.3. Other assets

We now turn to the literature on other asset classes such as corporate and municipal bonds, green bonds, syndicated loans, and weather derivatives. The findings essentially mirror those presented so far: the prices of such assets appear to incorporate some types of climate change risks to some extent.

For instance, a number of studies show that corporate bond yields and lending rates incorporate firms' environmental profile. Using U.S. data, Seltzer, Starks, and Zhu (2020) find that firms with a poor environmental profile tend to have a lower credit rating and a higher bond yield spread, particularly when the firm is located in a state with more stringent environmental regulations. Moreover, treating the Paris Agreement as a shock to expected climate regulation, the authors provide evidence of a causal link from environmental profiles to credit ratings and yield spreads. Meanwhile, Delis, de Greiff, and Ongena (2020) collect global data on fossil fuel reserves already discovered by firms, which are used as an indicator of exposure to the transition risk that such reserves will become unburnable or stranded and thereby lose their economic value due to policy developments. The authors match this data with data on syndicated loans and subsequently compare the loan rate charged to fossil fuel firms with that to other firms. They find that although before 2015 banks did not price climate policy exposure (represented by fossil fuel reserves), they did so after 2015, when – relatively unexpectedly – the Paris Agreement was reached.

Further, studies suggest that municipal bond markets also reflect climate change risks. For instance, Painter (2020) finds that U.S. counties with greater exposure to sea level rise pay more in underwriting fees and initial yields to issue long-term municipal bonds, although no such relationship is observed for short-term bonds. He also finds that the effect of sea level rise risk on issuance costs is driven by bonds with low credit ratings, which suggests that lower rated counties are more likely to be susceptible to climate change risks, as they generally have weaker infrastructure and smaller fiscal capacity. Moreover, he shows that the market started to price in climate change risks after the release of the 2006 Stern Review on climate change.[23] Meanwhile, Goldsmith-Pinkham et al. (2020) obtain somewhat different results from Painter (2020). Discussing potential reasons behind the difference in results, they highlight that they measure sea level rise exposure at the school district level, while Painter (2020) uses a measure of climate risks for 17 major metropolitan areas that does not differentiate among coastal and inland municipalities in the same region. Goldsmith-Pinkham et al. (2020) find that both short- and long-term municipal bond markets began pricing sea level rise exposure at the end of 2011, coinciding with upward revisions of sea level rise projections by scientists. The effect is concentrated on the East and Gulf coasts, where storm risk is greatest, but statistically insignificant on the West coast, which has experienced few storm-related flooding events. These results suggest that municipal bond prices reflect the near-term risk of flooding from storm surges rather than the long-term risk of slowly rising oceans that will eventually inundate all coastal municipalities similarly.

Turning to studies on weather derivatives, Schlenker and Taylor (2019) argue that the market for weather futures is accurately anticipating rising temperatures in line with scientific predictions. Weather futures are products whose prices are determined by how much average daily temperatures fall below or above a certain benchmark in a month. Weather futures have been traded on the Chicago Mercantile Exchange since 2001 and there are products for 8 different cities across the United States. Schlenker and Taylor (2019) show that weather futures prices indicate that the market is anticipating an increasing number of hot days in the summer and a decreasing number of cold days in the winter. Moreover, the authors find that this price trend approximates the projections of scientific models and is not influenced by year-to-year temperature fluctuations. This

[23] The Stern Review highlights that climate change may potentially cause irreversible damage if it is not addressed. The report was released in 2006 and published as Stern (2008).

result suggests that market participants fully internalize the scientific forecasts and do not myopically update their predictions based on short-term weather outcomes. A surprising finding of their study is that the futures market expects an increasing number of cold days in February, which, they argue, suggests that market participants agree with the theory that a shift in the jet stream will reduce February temperatures as it allows for cold air from the arctic to influence weather on the East Coast.

Finally, another type of asset on which much research has focused is green bonds and many studies estimate the premium – or "greenium" – on such bonds. Many of these studies focus on municipal green bonds in the United States. As highlighted by Larcker and Watts (2020), U.S. green municipal bonds are identical to ordinary municipal bonds in all ways except that the use of proceeds is allocated to environmentally friendly projects. They argue that any differences in security pricing are attributable to investor preferences for non-monetary security features, rather than differences in expectations about future cash flows or risk. If their argument is correct, even when green bonds are overvalued relative to ordinary bonds, this may simply reflect investor preferences and we therefore cannot conclude that green bonds do not reflect climate change risks. It is, however, still important for us to understand this growing market related to climate change risks.

The empirical results on the greenium are mixed. Using data on secondary market yields, Karpf and Mandel (2018), for example, find that green bonds display a positive premium. However, their result is questioned by Baker et al. (2018), who observe that Karpf and Mandel (2018) compare taxable and non-taxable securities, although pricing in the U.S. municipals market is highly sensitive to tax features. To address this problem, Baker et al. (2018) focus on after-tax yields. Using a pooled regression model for yields at issue, they find a minus 6 basis points premium on average. Further, they find that the absolute value of this premium doubles or triples for bonds that are not only self-labeled as green but also formally certified by a third party, although this result may to some extent be due to reverse causality; that is, because issuers know that their bonds are sufficiently green, they apply for external certificates. Meanwhile, focusing on the period from 2013 to 2017, Zerbib (2019) uses observations for green bonds traded in the secondary market and for which the counterfactual yields of ordinary bonds with the same characteristics, such as the issuer and the currency, can be estimated. He finds a statistically significant green bond premium of minus 2 basis points after controlling for the difference in liquidity between green and ordinary bonds using bid-ask spreads.

Moreover, negative premiums are larger in absolute terms for financial and lower-rated bonds.

In contrast, other studies find little evidence of a greenium. For instance, comparing green securities to nearly identical securities issued for non-green purposes by the same issuers on the same day, Larcker and Watts (2020) find essentially no premium on municipal green bonds. In addition, they point out shortcomings in the estimation methods used in previous studies and rule out several plausible alternative explanations for the lack of an observed premium. For instance, using several liquidity proxies including issuance size, they dismiss the possibility that a negative greenium is offset by a positive liquidity premium due to lower liquidity of green bonds. Moreover, using the certification by the Climate Bonds Initiative, which ensures that issuers of green bonds are actually using the financing proceeds for environmentally friendly purposes, they also show that the lack of an observed premium is unlikely to be driven by the presence of greenwashing (the practice of trying to make people believe that an entity is doing more for sustainability than it really is). Since investment banks appear generally to charge fees to issue green bonds in part due to the cost associated with certification processes, the authors argue that their results suggest that the borrowing costs of municipalities increase if they issue green bonds. Another study that finds little – or at best mixed – evidence on a greenium is that by Tang and Zhang (2020). Examining green bonds issued by firms in 28 countries, they do not find a consistently significant premium for green bonds.

3.4. Key takeaways of Section 3

While many studies show that prices of assets, such as stocks and bonds, factor in climate-related risks to some extent, many other studies show that real estate and stock prices do not adequately reflect physical risks. A number of studies provide evidence that investment behavior and asset prices have changed due to revised perceptions of risks as a result of disasters or local signs of the impact of climate change. Consequently, there are concerns that asset prices could fall substantially as climate-related risks materialize. When asset prices do not adequately factor in risks, they can hinder adaptation and mitigation actions, for instance, through excessive lending to high-risk areas and deterring financing by companies with low carbon emissions. Many studies demonstrate the effects of information disclosure and communication, for example, by providing evidence that in the absence of adequate information disclosure property prices do not sufficiently factor in physical risks. Meanwhile, the results on premiums on green bonds are mixed.

4. Natural disasters and bank behavior

We now turn to the literature on how banks are affected by and consequently respond to natural disasters. While recent discussions on climate-related risks often focus on the relatively long-term impacts of climate change, it is also important to deepen our understanding on the shorter-term impacts of climate-related natural disasters. This section therefore explores the literature on the impact of natural disasters on bank behavior. In particular, we focus on whether the banking sector is sufficiently resilient to supply credit to satisfy liquidity needs and aid in the recovery after a severe disaster. In the conventional banking literature, natural disasters are often utilized as a natural experiment, where the disaster is regarded as an exogenous shock to the financial system, which makes it possible to identify credit demand and supply factors. As climate change advances and concerns over the growing frequency and intensity of natural disasters rise, these studies are becoming increasingly relevant in understanding the threats that natural disasters pose to the financial system. Furthermore, an increasing number of studies investigate the relationship between banks and natural disasters with specific reference to climate change. Our survey of these studies finds that banks' solvency and their role as credit suppliers are adversely affected by natural disasters (Section 4.1). We also review the rich literature on how the geographical expansion of banks, which is another prominent topic in the banking literature, leads to the transmission of negative shocks to distant unaffected regions (Section 4.2). We next investigate the heterogeneous responses of banks, areas, and loan types to natural disasters (Section 4.3). We then consider the benefits and side effects of public support related to the banking sector (Section 4.4). Finally, we conclude this section (Section 4.5).

4.1. Damage to banks and credit constraints

Natural disasters affect banks' solvency through various channels: disasters can lead to a deterioration in the balance sheets of affected lenders, reduce the value of collateral, and directly damage banks' assets such as their offices and system infrastructure. For instance, using data for more than 160 countries for the period 1997–2010, Klomp (2014) finds that large-scale natural disasters adversely affect commercial banks' z-score (a measure of bank soundness or, more accurately, the inverse distance to default). Similarly, using the Spatial Hazard Events and Losses Database for the United States (SHELDUS), which provides county-level information on presidentially declared natural disasters such as

thunderstorms, hurricanes, floods, wildfires, and tornados, Noth and Schüwer (2018) show that property damages from weather-related natural disasters significantly weaken the stability of banks as reflected in lower z-scores, higher non-performing assets ratios, higher foreclosure rates, lower returns on assets, and lower bank capital ratios. Meanwhile, Schüwer, Lambert, and Noth (2019) find that the z-scores of banks affected by Hurricane Katrina and 2 other hurricanes that hit the U.S. Gulf Coast in 2005 decreased and that these banks became significantly more risky than banks that were not affected. Further, Koetter, Noth, and Rehbein (2020) examine the effects of a major flood in Germany in 2013. Their main analysis disregards banks in flooded counties to avoid confounding loan supply and credit demand responses in those counties. They compare exposed banks, which are defined as banks with a critical share of corporate borrowers located in flooded counties, with unexposed banks. Although they do not detect any significant difference in changes in z-scores between exposed and unexposed banks after the flood, they do find a relative increase in the share of non-performing loans for exposed banks that are not part of geographically diversified banking groups.

The literature also examines the impact of natural disasters on financial outcomes for borrowers. For example, using comprehensive merged data on fires, mortgage and property characteristics, and weather in California from 2000 to 2018, Issler et al. (2020) find a significant increase in mortgage delinquency and foreclosure after a wildfire. They also find that these effects decrease as the size of the fire increases. They argue that this result is driven by the California Insurance Code, under which homeowners who rebuild their property receive insurance payments corresponding to the expenses. Meanwhile, a substantial number of studies examine the impact of the flooding in New Orleans in the wake of Hurricane Katrina. For instance, Gallagher and Hartley (2017) investigate the impact on household finance, using individual-level credit and debt information from the Federal Reserve Bank of New York Consumer Credit Panel/Equifax (CCP), a panel of 5 percent of adult Americans' credit reports that is available from 1999. They find that overall delinquency rates on credit cards increased and credit scores decreased for the most flooded residents, although these changes were modest in size and short-lived. Next, focusing on household finance following a natural disaster, Gallagher, Hartley, and Rohlin (2020) find little evidence that federal cash grants diminish negative financial outcomes such as bill delinquency and mortgage foreclosure rates. Specifically, using the CCP data, which enables them to identify whether an individual is likely to be credit constrained, they estimate the causal effect of the grants on household finance following 34 very large tornadoes that hit the United States between 2002–2013 while

addressing the endogeneity problem that arises from the fact that decisions on grants are linked to incurred damage and expenses. They find that the grants reduce credit card debt only for less credit-constrained individuals, while credit-constrained individuals who have access to grants are more likely to increase consumption.

When natural disasters strike, affected firms' and households' credit demand often increases because they need to rebuild destroyed or damaged physical capital, bridge financing gaps until they receive monetary support from the government and/or payments from insurance firms, or secure their liquidity positions. The increase in credit demand is illustrated in a number of studies. For instance, Brown, Gustafson, and Ivanov (2020) show that firms, in particular solvent small firms, draw on their credit lines and increase the size of credit lines in response to a significant cash flow decline after unexpectedly severe winter weather. For their analysis, the authors use a dataset of bank loan portfolios compiled by the Federal Reserve since 2012. The dataset contains detailed information on each bank loan contract, including loan and borrower characteristics, and covers the full set of firms in a bank's loan portfolio with outstanding loan commitments of at least US$1 million. They combine this dataset with county-level data on daily snow cover. Meanwhile, Collier et al. (2019) use data from the Small Business Credit Survey conducted by the Federal Reserve Bank of New York, polling businesses with fewer than 500 employees about their financing. The survey conducted in November 2013, roughly 1 year after Hurricane Sandy, included a series of questions regarding the event. The authors find that negatively affected firms were about 60 percent more likely to report that they had applied for credit than other firms after the hurricane. In particular younger firms and larger firms were more likely to have applied for credit. Similarly, in their study on a major flood in Germany mentioned earlier, Koetter, Noth, and Rehbein (2020) find that exposed banks increased lending relative to unexposed banks by 3 percent after the flood. This relative increase in lending can be interpreted to be due to demand from firms, since in their analysis both exposed and unexposed banks are located outside of flooded counties and these banks essentially differ only in their exposure to corporate borrowers in flooded counties. Next, Dessaint and Matray (2017) show that after hurricane events, firms located in the neighborhood of the disaster area substantially increased cash holdings and managers expressed greater concern about hurricane risk, even though the actual risk remained unchanged. The authors also find that over time, the perceived liquidity risk decreases and the bias in risk perceptions disappears. Based on these findings, they argue that the managerial reaction can be explained by a salience bias. Berg and Schrader (2012) use client-level information from an Ecuadorian financial institution

focusing on lending to micro, small, and medium-sized enterprises, combined with monthly data on the eruptions and seismic activity of Ecuador's most active volcano Tungurahua. They find that the number of loan applications, which is their indicator of credit demand, significantly increases after volcanic eruptions.

Whether banks can meet the heightened credit demand in the wake of a natural disaster is critical for the affected economies. The literature indicates that natural disasters limit both banks' ability to lend and firms' ability to borrow. For example, using data from a survey conducted for several years after the Great East Japan (Tohoku) Earthquake in Japan in 2011, Uesugi et al. (2018) find that both damage to firms' tangible assets and to the net worth of its primary banks significantly increased the probability that firms faced borrowing constraints for 2–3 years after the disaster, providing evidence of the existence of both a so-called collateral and a bank lending channel. They also show that firms that faced a tighter credit constraint after the earthquake saw a fall in the level of production and sales activities. Meanwhile, in their study on Ecuador mentioned earlier, Berg and Schrader (2012), using data on a binary variable of whether a credit applicant has received a loan, show that volcanic activity restricts access to credit. Further, Collier et al. (2019) find that Hurricane Sandy increased credit constraints among negatively affected firms through higher interest rates and the need to secure loans with collateral. Negatively affected firms were more than twice as likely to report that their access to financing had decreased relative to the previous year: these firms were 35 percent more likely to be required to secure loans with collateral and 2.7 times as likely to experience interest rate increases as unaffected firms. Further, larger firms were more likely than smaller ones to receive all the credit that they had requested, which seems to be explained by their ability to secure loans with collateral. Meanwhile, Brown, Gustafson, and Ivanov (2020) find that in response to demand for new credit lines from firms after unexpectedly severe winter weather, banks charge borrowers via increased interest rates and less borrower-friendly revisions of non-price loan terms. For example, loans become shorter in maturity, more likely to be secured, and less likely to have fixed interest rates. These credit line adjustments occur within a few months after the shock and persist for at least 9 months.

Several studies find that, in response to natural disasters, bank deposits increase, which can alleviate negative shocks to credit supply. For instance, Koetter, Noth, and Rehbein (2020) find that both customer and interbank deposits of exposed banks increased significantly relative to unexposed banks although wholesale funding did not. While there is some consensus that total deposit volumes increase after natural disasters,

the literature provides mixed evidence about whether banks raise the deposit rate to attract deposits. We review studies on deposit rates in the next subsection.

4.2. Reduction in credit supply in unaffected areas

We just saw that natural disasters lead not only to higher lending demand from firms and households but also to restrictions in lending supply by banks. Clearly, this is bad news because firms may not be able to access credit when they need it the most. We next take a more granular look at banks' credit supply and review how banks propagate the impact of natural disasters to distant regions, relying on a strand of the banking literature that studies the impact of the geographical expansion of banks. This literature suggests that the geographical expansion of banks has both harmful aspects such as the propagation of negative shocks and beneficial aspects such as risk sharing and new business creation (Demyanyk, Ostergaard, and Sørensen, 2007; Morgan, Rime, and Strahan, 2004; Black and Strahan, 2002). Our survey shows that these findings in the literature are also relevant in the context of natural disasters.

Several studies find that after a natural disaster, banks reduce credit supply in unaffected regions. For instance, like Koetter, Noth, and Rehbein (2020), Rehbein and Ongena (2020) examine the effects of the 2013 flooding in Germany. While Koetter, Noth, and Rehbein (2020) focus on lending into the affected region after the flood, Rehbein and Ongena (2020) examine the impact on unaffected regions. To this end, they identify firms in non-flooded areas that are connected to disaster-exposed banks, which are defined as banks that provided credit to corporate borrowers in flooded counties to a larger extent, and compare them to firms that are located in the same region but do not have a connection to a disaster-exposed bank. The authors show that the impact of the flood was transmitted to firms in non-disaster areas via their banks: firms connected to disaster-exposed banks reduced total borrowing, employment, and tangible assets. They also show that the more firms in a non-flooded area were connected to disaster-exposed banks, the greater the reduction of GDP in the area was.

A similar result is provided by research on earthquakes in Japan. For instance, Hosono et al. (2016), utilizing the natural experiment provided by the Great Hanshin-Awaji (Kobe) Earthquake in Japan in January 1995, find that the investment ratio (investment per capital stock) of firms located outside of the earthquake-affected area but whose main banks were inside the area was lower than that of firms that both were located

and had their main banks outside of the area. This result implies that the weakened lending capacity of damaged banks exacerbated the borrowing constraints on the investment of their undamaged client firms.

Studies using U.S. data provide similar results. For instance, combining data for 1992–2014 from the Shared National Credit Program on syndicated loans with information on presidentially declared natural disasters for each county from SHELDUS,[24] Ivanov, Macchiavelli, and Santos (2020) find that banks meet the increase in credit demand in affected regions in part by reducing credit to distant regions. While non-bank financial institutions offset the reduction in bank credit supply on term loan syndicates, they do not offset the loss in credit line financing. As a result, corporate credit still falls in unaffected regions by approximately 3 percent on average. Further, also using data from SHELDUS, Cortés and Strahan (2017) find that mortgages in unaffected but connected markets decline by a little less than 50 cents per dollar of additional mortgage lending in affected areas after properties in these areas are damaged due to natural disasters.

As for the reason why banks propagate the shocks of natural disasters to unaffected areas (we will refer to this propagation as "network effects" hereafter), Garbarino and Guin (2020) argue that the reallocation of lending from unaffected areas to affected areas may be due to biased valuations of property collateral that prevent a tightening of credit supply in affected areas. Specifically, they find that after a severe flood in England, market prices of properties declined but lender valuations did not "mark-to-market" against local price declines, as reviewed in Section 3.

While so far we have focused on natural disasters – i.e., physical risks – as sources of network effects, transition risks, for instance, through regulatory and technological changes, can also have network effects. For instance, if a carbon tax is introduced, the market value of fossil fuels may drop significantly as they become

[24] The Shared National Credit Program is a program governed by an interagency agreement among the 3 U.S. Federal banking regulators (the Board of Governors of the Federal Reserve System, the Federal Deposit Insurance Corporation, and the Office of the Comptroller of the Currency) to monitor the credit risk of syndicated bank loans in a uniform manner. The Shared National Credit Program covers all syndicated deals that exceed US$20 million and are held by 3 or more supervised institutions both at the time of the loan origination and during the life of the loan.

unusable, rendering them stranded assets. Consequently, the balance sheets of firms that own those assets may be greatly damaged, which may adversely influence the lending capacity of branch networks of banks exposed to those firms. In fact, given Gilje, Loutskina, and Strahan's (2016) finding for the United States that oil and natural gas shale discoveries have been associated with an increase in the supply of mortgage loans, it is plausible that a drop in the market value of fossil fuels could have the opposite effect – i.e., result in a significant decline in the supply of loans. Specifically, focusing on the wealth windfalls made possible by an unexpected technological breakthrough that made vast amounts of shale oil and natural gas economically profitable to develop, Gilje, Loutskina, and Strahan (2016) examine the impact of the resulting deposit supply shock for banks with branches in shale boom counties on their lending. The authors find that the average exposed bank grows its mortgages in counties in which it has branches 13 percentage points faster than a similar non-exposed bank.

Another topic examined in the literature is whether there are network effects on deposits. Some studies find evidence of such effects while others do not. Cortés and Strahan (2017), for instance, find that after a natural disaster, banks bid up the rate on deposits in connected markets – markets where banks lend before the disaster strikes but that are not directly affected by the disaster itself – in order to finance lending in the affected areas. Meanwhile, Dlugosz et al. (2020) examine the impact of decision-making delegation allowing bank branches to decide their own deposit rates in their local market. They find that if local branches can set deposit rates, they raise rates more to attract higher deposit volumes when a natural disaster hits. They also show that in affected areas where bank branches can set their own deposit rates, they extend around 10 percent more mortgages. The authors find that this effect is driven by mortgages retained on the balance sheet rather than sold loans, which seems consistent with the fact that bank branches do not need to raise deposits to fund loans once they have sold them. Moreover, in such areas, property prices recover more quickly and there are fewer bankruptcy filings of consumers. These results suggest that the delegation of decision-making in banks can play an important role in post-disaster recovery and points to the presence of bank internal capital market frictions. Further, Ivanov, Macchiavelli, and Santos (2020) find that banks raise

additional deposits only in the region affected by a natural disaster, and only 40 cents for each dollar of damages. On the other hand, they do not find evidence that deposit rates are affected by local disasters and network shocks, which appears to conflict with the results obtained by Dlugosz et al. (2020). Ivanov, Macchiavelli, and Santos (2020) argue that this may be because they focus on multi-county banks: when, like Dlugosz et al. (2020), they include single-county banks in the sample they find that banks do raise deposit rates in response to local shocks. This result suggests that single-county banks, which can be considered as a type of local banks, have to raise deposit rates to continue lending after a natural disaster since they cannot rely on internal capital markets.

4.3. Heterogeneity

There is likely to be considerable heterogeneity in the impact of a natural disaster, depending on a range of circumstances. The literature identifies several factors that affect the size of the adverse impacts after natural disasters, such as capital regulation and supervision, bank-borrower relationships, age and size of firms, and alternative sources of funding. For instance, Klomp (2014) finds that the impact of a natural disaster is negatively associated with the rigorousness of capital regulation and supervision, as well as the level of financial and economic development of a particular country.[25] Another potential source of heterogeneity in the impact of disasters is the presence of relationships. In their study of an Ecuadorian microfinance institution, Berg and Schrader (2012) suggest that repeat clients already known to the financial institution are about equally likely to receive loans after volcanic eruptions as before, while new clients face difficulty in receiving financing. In other words, relationships between a financial institution and its clients can lower lending restrictions. The importance of relationship banking is also highlighted by Koetter, Noth, and Rehbein (2020), who find that after the 2013 flood in Germany, firms located in flooded counties on average increased their borrowing by 16 percent if they were connected to banks in unaffected counties. Yet another source of heterogeneity is firm characteristics. For example, Uesugi et al. (2018) find that firms with a smaller number of employees and/or with higher leverage were more likely to be

[25] To examine how capital regulation and supervision influence the impact of natural disasters, Klomp (2014) uses the first principal component of indicators corresponding to various questions on capital regulation and supervisory control taken from Barth, Caprio, and Levine (2004, 2008).

credit constrained after the Tohoku Earthquake. Meanwhile, Collier et al. (2019) show that young firms and small firms were more likely to report that they did not receive all of the credit financing that they requested after Hurricane Sandy. A further source of heterogeneity is access to non-bank credit. For instance, Morse (2011) finds that access to high-interest credit (payday loans) mitigates individual financial distress. Using natural disasters as an exogenous shock and zip-code level data for California, she shows that foreclosures increase by 4.5 units per 1,000 homes after a natural disaster but access to payday finance mitigates 1.0–1.3 foreclosures per 1,000 homes. When disasters are covered by homeowner insurance, however, access to payday lending has no mitigation effect.

A number of studies examine the impact of natural disasters focusing on differences between local and non-local banks. Theoretically, local banks in affected areas should be more vulnerable to the shock and potentially tighten credit supply to a larger extent. On the other hand, local banks may also be more willing to continue lending after a natural disaster because borrowers in the disaster area are more important to their business than they are for non-local banks, or because local lenders face lower costs of monitoring borrowers in the reconstruction phase. In fact, the literature suggests that local banks have a comparative advantage in accessing soft information about borrowers (Berger et al., 2005; Agarwal and Hauswald, 2010).

Empirical studies, many of which examine the effects of Hurricane Katrina, generally find that local banks in affected areas are more likely to continue lending than non-local banks. For instance, Schüwer, Lambert, and Noth (2019) compare the response to the exogenous shock posed by Katrina of banks that are part of bank holding companies and other banks, which the authors refer to as "independent banks" in their study and which can be regarded as local banks. They find that independent banks based in the affected areas and with a high capital ratio before the hurricane increased their risk-based capital ratios after the hurricane, while other banks did not. Independent and highly capitalized banks increased their holdings of government securities and new lending to firms in the local market while reducing their total loan exposures to non-financial firms, including exposures in distant areas. Affected counties with a relatively large share of independent banks and relatively high average bank capital ratios show higher economic growth in total personal income and employment than other affected counties following the catastrophic event. Further, Gallagher and Hartley (2017) find that after Hurricane Katrina hit New Orleans, areas more affected by flooding saw larger reductions in total

household debt since homeowners used flood insurance to repay their mortgages rather than to rebuild. The authors discuss potential drivers behind the reductions in debt, including high rebuilding costs in New Orleans. They also find that mortgage reductions are larger in areas where homeowners were likely to have a home loan originated by non-local lenders. Furthermore, 2 years after Katrina, local banks' lending returned to the level before Katrina, while a large share of non-local banks exited from the market. Meanwhile, Chavaz (2016) examines the effects of hurricanes in the United States in 2005 including Katrina. He finds that compared to geographically diversified banks, local banks originated a higher share of new mortgage and small business loans in areas affected by the hurricanes. He then investigates how local banks adjusted lending after the shock and identifies 2 main margins of adjustment. First, he finds that local banks cut lending to unaffected counties, which allowed them to accommodate more new mortgage lending in affected counties. Specifically, using bank-level data, he shows that the higher acceptation volume in affected counties was compensated for by an equal share of denied applications in unaffected counties. Second, he also finds that local banks sold a higher share of the new mortgages into the secondary market. These results indicate that local banks have special abilities or incentives to seize opportunities in a distressed market, while loans in affected areas are increasingly transferred to agents that can better support the associated risk. On the other hand, he finds that local banks did not accept more loans in an affected area in which they owned a higher share of outstanding mortgages, suggesting that local banks did not aim at influencing local house prices and economic activity.

A number of studies use other natural disasters in the United States to examine differences between local and non-local banks. For example, using data from SHELDUS, Cortés (2014) finds that the presence of local lenders helps in the recovery of the real economy after natural disasters. Specifically, she defines a bank as "truly local" if it has roughly a two thirds majority of its deposits in an area. She then shows that the presence of local lenders improves job retention and creation, particularly among young and small firms: in the event of a disaster, areas with 1 standard deviation more local deposits experience 1–2 percent less employment loss for young and small firms. Importantly, she also finds that areas with a greater share of local lenders recover faster after a disaster. Somewhat in contrast, Garmaise and Moskowitz (2009) find that, in the wake of the January 1994 Northridge earthquake in California, local banks were less likely to make loans to high earthquake risk properties; however, this disruptive effect lasted only for a few months.

Other factors likely to give rise to heterogeneity in the impact of a natural disaster include bank, area, and loan characteristics. In particular, many studies show that bank characteristics are an important determinant of the network effects. As mentioned above, Schüwer, Lambert, and Noth (2019) find that independent banks increase new lending to firms in the local market only when they are highly capitalized. Bank capitalization is an important determinant of network effects, too. For example, Rehbein and Ongena (2020) find that low bank capital carries a negative externality because it amplifies local shock spillovers. They show that firms connected to banks with strong exposure to the 2013 flood in Germany and falling into the bottom quartile in term of their capitalization experienced a significant decline in borrowing of 4.8 percent, employment of 2.7 percent, and tangible assets of 7.5 percent relative to similar firms connected to a well-capitalized bank. Similarly, Ivanov, Macchiavelli, and Santos (2020) find that capital constraints play a key role as banks with lower capital ratios propagate disasters to unaffected regions to a greater extent. Meanwhile, Cortés and Strahan (2017) suggest that bank size is another important factor determining the network effects. Specifically, they find that exogenous shocks to credit demand are transmitted to connected markets through the reallocation of funds only in the case of small banks but not large banks. Hosono et al. (2016) find that the network effects differ depending on whether main banks' headquarters or branches are damaged. Moreover, the timing of the impact also differs: while the impact of damage to main banks' headquarters emerged immediately after the Great Hanshin-Awaji earthquake, the impact of damage to main banks' branches emerged only with a one-year lag.

Turning to studies on area characteristics as a determinant of the strength of bank network effects, Ivanov, Macchiavelli, and Santos (2020) focus on the strategic importance of counties for banks' corporate lending business. Specifically, they define a county to be strategically important for a bank if the committed amount to borrowers in that county is in the top 10 percent of the county commitments distribution as of the previous year. They then show that banks reduce credit in unaffected regions only when these regions are less strategically important. Similarly, Cortés and Strahan (2017) also find that a reduction of lending is mainly observed outside banks' core markets in which they own branches. Somewhat in contrast, the study by Gilje, Loutskina, and Strahan (2016) on shale boom windfalls, as mentioned earlier, found that banks exposed to the shale boom grew mortgages faster than similar non-exposed banks only in counties where the banks had branches. This suggests that if those windfalls were to disappear, banks might then shrink their lending again in counties where they had increased their mortgage

lending due to the shale boom. Meanwhile, Rehbein and Ongena (2020) find that, following a disaster, banks reduce their exposure to areas that, although currently unaffected, are generally disaster-prone.

Finally, studies examining the role of loan characteristics suggest that another factor determining the network effects of natural disasters is whether loans are easy or difficult to securitize. For instance, Gilje, Loutskina, and Strahan (2016) show that banks exposed to the shale boom expanded lending more in segments that were less likely to be securitized. This suggests that if banks were to experience a tightening in liquidity constraints due to, for example, a natural disaster, they might find it more difficult to extend loans that are hard to securitize. Relatedly, Chavaz (2016) finds that securitization enables local banks to continue lending in areas affected by hurricanes. Specifically, he finds that compared to geographically diversified banks, local banks originate a higher share of new mortgage loans in areas affected while selling them into the secondary market.

4.4. Benefits and side effects of public support

Many governments provide direct or indirect public support for banks, firms, and individuals in the event of a disaster. While such support can have positive effects on lending and economic conditions of firms and individuals, it can potentially also have negative side effects by distorting the behavior of banks and borrowers. In this context, a number of studies examine both the positive and negative effects of public support provided by government-sponsored enterprises (GSEs) in the United States. For instance, Cortés and Strahan (2017) find that after natural disasters, banks originate more small loans, which are more liquid, since loans above a certain cutoff may not be sold to the GSEs. This result suggests that GSEs meet the legislative goal of promoting access to mortgage credit for low- and moderate-income households. Similarly, Ouazad and Kahn (2020) find that, after large-scale hurricanes, there is a substantial increase in mortgage securitization for loan amounts right below a cutoff called the "conforming loan limit." Loans sold to GSEs are more likely to default, suggesting that banks may have an incentive to sell their worst disaster risk to the GSEs. The increase in loans sold is larger when the disaster is "new news," which suggests that lenders may learn about local risk. The authors use a structurally estimated model that can explain their empirical findings to conduct a simulation of increasing disaster risk with and without the GSEs. The

simulation suggests that the GSEs incentivize households to live in risky areas and banks to lend to these households.

Meanwhile, in a study on the Tohoku earthquake in Japan, Uchida et al. (2015) examine the impact of damage to lender banks on firms' probability of bankruptcy and find that capital injections into banks after the earthquake appear to have produced negative side effects. Specifically, to extract the impact of purely exogenous financial shocks on bankruptcy, they focus on firms located outside the earthquake-affected area but transacting with banks located inside the area. They first find that, somewhat counterintuitively, damage to a bank reduces the probability of bankruptcy of its borrowers and weakens the natural selection mechanism, whereby less efficient firms are more likely to go bankrupt. Concretely, they find that the sensitivity of the probability of bankruptcy with respect to their measure of firm efficiency is smaller in absolute value for firms transacting with damaged main banks than for those transacting with undamaged ones. They then obtain some evidence that the probability of bankruptcy is reduced and natural selection is weakened by the injection of public capital into damaged banks.

A number of studies examine the impact of public support to individuals after natural disasters. These similarly suggest that while such support has positive effects it can also distort resource allocation. In their study examining the impact of federal cash grants to individuals following a natural disaster, Gallagher, Hartley, and Rohlin (2020) find that such grants ameliorate the negative impact of very large tornadoes in affected neighborhoods, resulting in 18 percent more establishments and 29 percent more employees relative to disaster-affected neighborhoods in which individuals did not receive grants. These positive effects on businesses are concentrated among small non-manufacturing establishments that rely on local demand. On the other hand, Bleemer and van der Klaauw (2019) show that public support distorts resource allocation. Using CCP data to examine the long-run impacts of the flooding in New Orleans after Hurricane Katrina, they find that, ten years after the hurricane, credit scores and homeownership among flooded residents of New Orleans are lower than among their non-flooded neighbors. They also find, however, that residents of the large Gulf Opportunity Zone surrounding New Orleans, who were eligible for various federal programs like residents of New Orleans, obtained net financial benefits. A decade later, those residents, in particular young and low-income ones, had higher rates of consumption, credit scores,

and homeownership and lower rates of bankruptcy and foreclosure than residents outside the Gulf Opportunity Zone.[26]

4.5. Key takeaways of Section 4

The review of the literature presented here suggests that when the area in which banks operate is affected by a natural disaster, banks' health deteriorates and the demand for borrowing increases while the supply of loans, especially to young and small businesses, falls. Supply of bank credit also declines in unaffected areas, which has a negative impact on the real economy in those areas. Further, there is considerable heterogeneity in the impact that natural disasters have, with factors determining this impact including bank, area, and loan characteristics. For instance, local banks in affected areas are more likely to continue lending, and the effects are less severe when banks have high capital ratios. Finally, while public support through GSEs and other instruments mitigates the impact of a disaster, it has the negative side effect of distorting resource allocation.

5. The role of insurance and related challenges

Another important part of the financial system that is significantly relevant to climate change is the insurance sector. On the one hand, insurance (and economically equivalent public support) serves as a means for insureds to mitigate the impact of negative shocks caused by climate change: if losses caused by weather-related natural disasters are covered by insurance, the payouts provide an important source of funding for recovery. On the other hand, the insurance sector may become a source of financial instability if large payouts impair insurers' solvency or lead to a fire-sale of assets. Furthermore, insurance may cause moral hazard, resulting in a delay of adaptations to reduce the costs of climate change. In this section, we cover a wide range of topics regarding the link between insurance and climate change. We start with a review of the empirical literature on the role of insurance in mitigating disaster risk and complementing bank finance

[26] Relatedly, Deryugina (2017) shows that U.S. hurricanes lead to substantial increases in non-disaster government transfers such as unemployment insurance and public medical payments in affected counties in the decade after a hurricane. The present value of this increase significantly exceeds that of the direct disaster aid. This implies that without counting this increase, the fiscal costs of natural disasters have been significantly underestimated.

(Section 5.1). We then consider 3 challenges that need to be addressed with regard to insurance: how to increase insurance coverage for climate-related risks to provide more protection and improve risk sharing, how to maintain the solvency of insurers when climate risks materialize, and how to avoid moral hazard. Concretely, we provide evidence that insurance take-up is currently low and explore possible reasons (Section 5.2). Next, we investigate how insurance firms themselves have been exposed to losses caused by natural disasters and how they have responded (Section 5.3). Further, we review the literature on whether insurance causes moral hazard and impedes adaptation to climate change (Section 5.4). Finally, we sum up the key takeaways (Section 5.5).

5.1. The role of insurance

Insurance mitigates the adverse effects of natural disasters on economies. According to Kousky's (2019) survey focusing on catastrophe insurance for housing in advanced economies, the literature indicates that insurance speeds up post-disaster recovery, at both the household- or small business-level and the level of the economy as a whole, although rigorous empirical work on these topics is limited. Some studies conduct cross-country analyses and find a positive correlation between insurance coverage and recovery following a natural disaster. von Peter, von Dahlen, and Saxena (2012) find that major natural catastrophes have large and significant negative effects on economic activity. However, only the uninsured part of the losses has negative macroeconomic effects in a statistically significant manner, whereas the impacts of the insured losses are statistically insignificant or even significantly positive in some specifications. On the financial market side, IMF (2020b) examines the effects of insurance penetration, measured by the ratio of non-life insurance premiums to GDP, on equity returns in the wake of large disasters. It shows that the penetration rate considerably differs across countries, ranging from 0 to 5 percent of GDP. It then finds that greater insurance penetration cushions the negative impact of large disasters on cumulative abnormal returns for about 2 months around large-scale disasters, especially when the impact is large.

Insurance also influences the availability of, repayments on, and demand for bank credit. As we saw in Section 4, the literature finds that following natural disasters, borrowing constraints tighten, delinquency rates rise, and credit demand increases. Insurance can alleviate these impacts to some extent. Uesugi et al. (2018), using the Tohoku Earthquake in 2011 as a natural experiment, find that earthquake insurance payouts alleviated firms' borrowing constraints or reduced the probability that firms were

not able to obtain the desired amount of loans following the disaster. They also find some evidence that government subsidies for reconstruction investment mitigated borrowing constraints to a larger extent for firms that suffered a larger amount of damage. This result makes sense since investment subsidies were proportional to the amount firms were planning to invest after the earthquake, which in turn likely reflects the amount of damage. Meanwhile, Gallagher and Hartley (2017) find that after Hurricane Katrina hit New Orleans in 2005, the greater the flood damage households experienced the larger was the reduction in their total debt because they used flood insurance to repay their mortgages rather than to rebuild. Issler et al. (2020) study wildfires in California from 2000 to 2018 and find results consistent with those obtained by Gallagher and Hartley (2017). Specifically, they show that mortgage defaults and foreclosures increased to a lesser extent after a bigger fire. They then argue that insurance payouts played a role in this result. Further, Collier et al. (2019) examine the impacts of Hurricane Sandy on the New York area and find that businesses that suffered large losses and were not covered by insurance were significantly more likely to apply for credit than businesses that experienced large losses that were fully paid by insurance. In addition, Morse (2011), in her study on natural disasters in California, finds that access to payday loans reduces foreclosures after natural disasters only when disasters are not covered by homeowner insurance.

While the studies mentioned so far examine the impact of catastrophe insurance on credit *after* a disaster has struck, insurance can also influence credit provision *before* a disaster has even occurred. Using a theoretical model and empirical analysis, Garmaise and Moskowitz (2009) find that insurance market imperfections can restrict credit supply. In their theoretical model, they assume that insurance firms are able to monitor whether property owners are taking safety-enhancing actions while banks cannot. This assumption is consistent with earlier studies showing that lenders require borrowers to purchase earthquake insurance for risk properties (Glickman and Stein, 2005; Porter et al., 2004). The model shows that with a well-functioning insurance market, there should be no link between earthquake risk and loan provision since insurance can cover all of the risk. Empirical analysis, however, indicates that there is a link between earthquake risk and loan provision: the authors document that in California only 35 percent of commercial properties in earthquake zones carried earthquake insurance in the 1990s and find that properties with higher earthquake risk were less likely to be financed with bank debt. This observation suggests that the insurance market is imperfect. Their results indicate that commercial real estate bank loan provision is reduced by 22 percent due to distortion

arising from insurance market imperfections. They also show that the 1994 Northridge earthquake increased this distortion, although only for about 3 months: bank-financed transactions were concentrated in lower-risk properties following the earthquake, while cash-financed transactions displayed no such shift. The authors also find evidence that properties with higher hurricane risk than other properties tended to receive less bank financing and that this effect is magnified when the price of catastrophe insurance is high.

5.2. Insurance coverage

The preceding section discussed the important role insurers play in cushioning the financial impact of natural disasters on households, firms, and the economy overall. Given this important role insurance can play, an important question is how high insurance coverage currently is. Extensive coverage would imply that more people and firms enjoy protection against natural disasters and hence the economy would be more resilient to the adverse effects of such disasters. However, existing evidence suggests that coverage is low. According to Swiss Re, worldwide, more than 70 percent of natural disaster losses are not covered by insurance, and this ratio is particularly high for floods and earthquakes (Holzheu and Turner, 2018).

Even if households or businesses are covered by insurance of some kind, they may not be covered for the specific types of losses that they incur. For instance, Collier et al. (2019) find that Hurricane Sandy in 2012 had a negative financial impact on one-third of firms in New York. The event damaged firms' assets and disrupted their operations (e.g., through utilities outages and customer relocation). Many negatively affected firms were uninsured: 29 percent had no insurance of any kind. Moreover, insured businesses often did not have coverage for the kinds of losses that Sandy created: 74 percent of businesses with property insurance, 72 percent with business interruption insurance, and 52 percent of businesses with flood insurance reported that *none* of their losses from the event had been covered by their policies. The low level of insurance payments seems to be explained by the types of losses created by a severe storm or hurricane, which may differ from the types of losses that are protected by the most common forms of insurance. For instance, flood insurance from the National Flood Insurance Program (NFIP) protects against flood-related property losses but does not cover flood-related business interruptions. All the businesses with flood insurance that did not receive any insurance payments reported that they did not have property damage from Sandy. This suggests that the requirements of insurance policies seem to poorly

match the losses stemming from customer and utility disruptions commonly reported by negatively affected firms. Consequently, insurance played a less important role than credit in financing recovery for firms negatively affected by Sandy; more negatively affected firms took on debt because of Sandy (39 percent) than received insurance payments (15 percent).

Existing studies also show that there is heterogeneity of coverage and indicate that insurance fails to cover those who need it the most. Botzen, Kunreuther, and Michel-Kerjan (2019) survey more than 1,000 homeowners in New York City after they experienced Hurricane Sandy and find that income had a significant impact on whether homeowners purchased flood insurance: homeowners with lower incomes were less likely to buy flood insurance than those with higher incomes due to affordability concerns. Moreover, Collier et al. (2019) find that younger and smaller firms were significantly less likely to be insured. These results suggest that the most vulnerable groups – low-income homeowners as well as younger and smaller firms – are the ones who were the least likely to be covered by insurance.

The literature also finds that international risk-sharing through reinsurance is low. Ito and McCauley (2019) find that losses from natural disasters are shared internationally to a generally very limited extent. This finding of home bias in disaster risk-bearing poses a puzzle of international risk-sharing. They decompose international risk-sharing into the portion of losses insured and the portion of insurance that is internationally re-insured. They find that the failure of international risk-sharing begins at home with low participation in insurance. They propose a new method to measure international reinsurance payments with balance of payments data. This method identifies the cross-border flows of reinsurance payments to 88 economies in the 1985–2017 period. Using regression analysis, they find that more internationally wealthy economies reinsure less, suggesting that net foreign assets substitute for international sharing of disaster risk. For advanced economies, a lack of international risk-sharing is correlated with a lack of fiscal space. This means that governments subject to pressure to provide *ex post* government insurance through the budget have less room to maneuver to do so. The authors argue that, at high levels of public debt, a lack of *ex ante* insurance can turn disaster risk into financial risk.

Examining the reasons for low insurance coverage, the literature suggests that both demand and supply factors are responsible for the low take-up. For instance, Gallagher (2014) suggests that demand for flood insurance is positively related to

experience of flooding. Employing a nation-wide panel dataset for the United States on all flood insurance policies for each calendar year and whether a community is hit by a large flood in that year, he finds that the take-up of insurance spikes in the year following a flood and then steadily declines back to the pre-disaster level over the next decade. Showing that there are more flood news stories in media markets when there is a large flood, he also finds that residents in non-flooded communities in the same television media market increased take-up at one-third the rate of flooded communities. He then argues that these observations can be explained with a learning model that discounts past floods. Possible explanations are that people forget about past floods or migrant homeowners were not sufficiently aware of the local flood risks. These results indicate that the infrequent nature of natural disasters may be one reason for the low demand for insurance. At the same time, the author also indicates that raising awareness of risks may help increase insurance demand.

The literature also finds that there is heterogeneity in the demand for insurance. For instance, Collier et al. (2020) examine the flood insurance decisions of over 100,000 households in the United States and find that consumers are typically willing to pay premiums well above the expected value of their contracts, although consumers' decisions vary substantially. Meanwhile, Botzen and van den Bergh (2012) use data from a survey among approximately 1,000 homeowners in the Dutch river delta to examine risk attitudes to climate change risks. Among many other questions, the survey asks whether respondents would be willing to purchase flood insurance and how much they would be willing to pay (WTP) under the current flood probability of 1 in 1,250 years and under higher probabilities of 1 in 600 and 1 in 400 years as a result of climate change. The survey is hypothetical in the sense that flood insurance was not available in the Netherlands at that time. They find that a significant proportion of homeowners neglect the low-probability flood risk; even when the flood probability increased to 1/400, at most around 50 percent of respondents would purchase flood insurance. On the other hand, the WTP of those who would purchase flood insurance is on average considerably higher than the expected value of the objective risk derived from geographical characteristics. Moreover, the WTP is less than proportionally related to increased flood probabilities that were presented to respondents in the questionnaire: in a scenario in which the flood probability doubles the WTP would increase by only 16 percent, which means that the increase in demand would be insufficient to keep up with the increase in risk. The authors also examine the effects of communication, using a risk ladder that illustrates the probability of more common risks for which Dutch households are used to purchasing

insurance (for instance, the probability of car theft is 1/450). They present the risk ladder to one group of respondents while not to the other group. They then find that communication increases the risk awareness of respondents and has a considerable impact on the WTP and its sensitivity to probability changes.

Another reason why insurance coverage is low is supply constraints. Supply of catastrophe insurance may be constrained for a number of reasons, such as information asymmetries (and adverse selection resulting from such asymmetries) and limited availability of reinsurance. A defining characteristic of disasters is that large numbers of people, properties, and businesses are impacted simultaneously. Thus, in contrast with other types of insurance, such as automobile insurance and health insurance, the law of large numbers does not work well. Under this circumstance, insurance firms build up reserves, purchase reinsurance, or issue catastrophe bonds. However, the literature shows that such steps by insurers make disaster insurance more expensive. For instance, Froot (2001) documents that although risk management theory suggests that risk sharing against the largest catastrophic events is most valuable, most insurers purchase relatively little catastrophe reinsurance against large events, and reinsurance premiums are high relative to expected losses. To understand why the theory fails, he develops 8 theoretical explanations and finds the most compelling to be supply restrictions associated with capital constraints on the part of reinsurers and market power enjoyed by the relatively small number of reinsurers. Relatedly, research shows that financial markets require an extremely high risk premium on catastrophe bonds, which make it possible to transfer risks to a broad range of investors. This is shown, for example by Lane and Mahul (2008), who use data from about 250 catastrophe bonds to investigate how catastrophe risks are priced. Their analysis reveals that the market-based catastrophe risk price is estimated to be 2.69 times the expected loss over the long term. Climate change may exacerbate this problem since it is changing the probability distribution of weather-related disasters, making quantification of expected costs and thus supply of catastrophe insurance difficult. This concern is illustrated by the view of Thomas Buberl, CEO of insurer AXA, who observed: "[W]e can clearly say that at a scenario between 3 and 4 degrees, it's not insurable anymore" (see, e.g., Hirtenstein, 2018).

Due to the difficulties for private insurers to supply disaster insurance, governments often have intervened in the insurance market to guarantee the availability and/or affordability of disaster coverage. The literature, however, often finds that in

contrast to private insurance, public insurance is too cheap and too insensitive to risk, causing issues such as moral hazard, as will be discussed below.

5.3. Insurance firm losses and their implications

It is important to note that insurance firms themselves may be made vulnerable by climate change risks: if they underestimate natural disaster risks *ex ante*, collected premiums may not be sufficient to pay out for covered damages *ex post*.

A possible consequence of unexpectedly large disasters is that the solvency of insurance firms is affected. For instance, following Hurricane Andrew, which made landfall on the eastern coast of the United States in 1992, several insurance firms became insolvent. Even if insurance firms remain solvent, they may conduct a fire-sale of assets in order to meet insurance claims, which could undermine financial stability. The effects of insurers' fire-sales on financial markets are illustrated in a study by Massa and Zhang (2020), who examine the impact of the liquidation of corporate bond holdings by (re)insurance firms in the wake of Hurricane Katrina. They find that property insurance firms with large exposure to Katrina reduced their corporate bond holdings by 14 percent, while other property insurers reduced theirs by only 1 percent and life insurance firms slightly increased their holdings of the same bonds.[27] The authors further show that, as a result, firms whose bonds were held by Katrina-exposed property insurers faced a larger decline in their risk-adjusted bond returns. Further, these affected firms shifted from bond financing to bank loans at least in the next 3 years after Katrina.

Another concern is that insurers may raise premiums to cover expected losses, which will likely result in lower participation. It is also possible that insurers consider the costs of natural disasters too large to insure and consequently stop providing insurance. Existing evidence finds that this has indeed happened in the past. For example, following the 1994 Northridge earthquake in California, insurers paid out more in claims than they had collected in earthquake premiums over the preceding 30 years. Although no insurer became insolvent, some came very close. Consequently, many insurers began to pull back from offering insurance coverage for homeowners, since California state law requires

[27] Massa and Zhang (2020) use data on institutional bond holdings from Lipper's eMAXX fixed-income database, which provides information on quarterly ownership of more than 40,000 fixed-income issuers, both public issues and private placements.

insurers providing homeowners coverage to also offer earthquake coverage. This retreat of insurers triggered a housing market crisis in California (Insurance Information Institute, 2018). Similarly, Froot (2001) shows that reinsurance of catastrophic event risks became considerably more expensive following Hurricane Andrew, which led to a decline in purchases of reinsurance, limiting insurers' ability to share risks. He further showed that the amount of reinsurance purchased fell by more, and the premium paid rose by more, for those insurers that had greater exposure to hurricanes.

5.4. Moral hazard

Another key issue in the context of insurance is moral hazard. Moral hazard occurs when insurance causes the insured to engage in risk-taking activities because they know that they will be compensated for a loss by the insurance. In the context of climate change, moral hazard arises when insureds fail to take measures that reduce the costs of climate change and natural disasters. As a result, the costs of providing insurance eventually outstrip insurers' premium receipts, which negatively affects their profitability. Moreover, it is possible, at least in theory, that the social costs of induced risk-taking activities exceed the benefits brought about by insurance.

Existing empirical studies find some evidence of moral hazard induced by public insurance, although, as will be discussed later, there is little evidence of moral hazard induced by private insurance. An example is the study by Annan and Schlenker (2015), who examine the impact of the Federal Crop Insurance Program in the United States on the incentive to adapt to extreme heat. To do so, they combine county-level corn and soybeans yields in 1989–2013 with the fraction of the planting area that is insured under the program. They find that insured corn and soybeans yields decline more significantly than uninsured crops when they are subject to extreme heat. They conclude that federal crop insurance acts as a disincentive for farmers to engage in possible adaptation strategies to cope with extreme heat. The authors point out that climate change is likely to amplify the problem as it will increase the frequency of extremely hot temperatures. Another study suggesting that public insurance provides the wrong incentives and creates moral hazard is that by Kahn and Smith (2017), who document that the National Flood Insurance Program (NFIP) offers reduced insurance rates for homes built before hazard maps were drawn and grandfathers rates for homes when new maps increase their risk ratings. They also provide evidence that high income households are more likely to select coastal locations in the Gulf Coast states of the Unites States while the NFIP offers

reduced rates for those high-risk areas based on the incorrect assumption that low income households live in those areas. In other words, the NFIP appears to provide incentives for households to move into high-risk areas and to support high income households. Relatedly, as mentioned in Section 3, Bakkensen and Barrage (2017) point out that the NFIP is regarded to be fiscally unsustainable, which suggests that the program does not provide sufficient incentive for households to fully take into account flood risk. Meanwhile, Anderson et al. (2019) in their literature review find that urban, coastal, and agricultural land markets provide effective signals of the emerging costs of climate change and that these signals encourage adjustments by both private owners and policy officials in taking preemptive action or adaptation to reduce costs. On the other hand, after surveying the evidence of the NFIP and government wildfire policies, the authors argue that political intervention makes it difficult to adjust these programs to further encourage adaptation.

While moral hazard may pose a problem, theory suggests that properly designed insurance programs can reduce it. For instance, many types of insurance involve deductibles, based on the expectation that if insureds have to pay for part of the losses, this will encourage them to engage in risk-reducing activities. Moreover, insurance can play a critical role in improving resilience to natural disasters not only by promoting recovery but also by providing incentives for climate adaptation or investment in hazard alleviation. While studies often find a positive correlation between having disaster insurance and investing in hazard alleviation among individuals, recent research by Botzen, Kunreuther, and Michel-Kerjan (2019) finds conflicting results for before and after the disaster. The authors survey more than 1,000 homeowners in New York City after they experienced Hurricane Sandy. On the one hand, those who had purchased insurance were more likely to undertake loss reduction measures well before the threat of suffering a loss such as dry proofing walls of a building to make them impermeable to water. If this correlation is a causal relationship, namely, if insurance encourages adaptive actions, then there are few concerns about moral hazard in the insurance market. On the other hand, however, those people were less likely to undertake emergency loss reduction measures such as moving contents to higher floors to avoid them suffering flood damage. Further, Kousky (2019) points out that the correlation observed in the literature may reflect that both insurance purchases and alleviation investments may be driven by a

common factor such as high risk aversion or high risk perceptions. She then concludes that rigorous empirical work on these topics is limited. Moreover, the correlation can also be explained by adverse selection: riskier agents tend to purchase more insurance coverage.[28]

5.5. Key takeaways of Section 5

Insurance mitigates the negative impact of natural disasters and also influences the availability and repayment of, and demand for, bank lending. There are, however, also some challenges. Insurance coverage is particularly low among low-income households and young and small businesses, with some studies pointing to both supply and demand factors as underlying reasons and implying that insurance coverage could be improved with better communication. Natural disasters can lead to a deterioration in the financial health of insurers, resulting in a fire-sale of assets, higher insurance fees, and a reduced supply of insurance. While there is some evidence that public insurance programs have resulted in moral hazard, there is a lack of rigorous empirical studies that show whether private insurance can reduce or leads to moral hazard.

6. Conclusion

This paper attempted to provide a comprehensive literature survey on the interaction between climate change and the financial system. While our survey covered a broad range of issues, we conclude by focusing on 3 policy implications of the findings in the literature.

First, our survey finds that real estate properties and stocks do not adequately price in physical risks. It also finds that investors update their risk perceptions when they personally experience the impacts of climate change. These findings indicate that asset prices may decline significantly as climate change risks materialize. Moreover, mispricing of assets can distort incentives for financial institutions as well as households and businesses to take mitigating and adapting actions against climate change. Meanwhile,

[28] See Cohen and Siegelman (2010) for a survey on the empirical literature on adverse selection in insurance markets, including methods for distinguishing between moral hazard or adverse selection.

several studies provide evidence that disclosure and appropriate communication on climate change risks help alleviate these problems. While these findings do not immediately warrant stricter regulations on disclosure since there are associated costs and limits on market participants' ability to process information, they nonetheless provide valuable insights into how policy makers may encourage asset markets to price in more climate change risks.

Second, natural disasters restrict the credit supply of banks affected by the disaster, which has adverse effects on the real economy, even in unaffected areas. Public support to address the adverse effects potentially has negative side effects by distorting resource allocation. On the other hand, some studies argue that the impact of a natural disaster on banks – and hence credit supply and the economy overall – is less severe for banks with a higher capital ratio and located in countries with stricter financial regulations and supervision. These results imply that regulatory frameworks, including capital requirements, originally intended to maintain the resiliency of banks and the financial system against non-climate shocks are also effective with regard to climate change risks. Jurisdictions and international institutions agreed upon revised regulatory frameworks, including Basel III, in response to the global financial crisis of 2007–2008 and have been working to fully implement them. Our survey indicates that these efforts are also relevant in the context of climate change, and jurisdictions and international institutions should therefore continue their endeavors to implement them.

Third, while insurance plays a critical role in mitigating the adverse effects of climate change, the literature also points to challenges, such as the need to increase coverage in order to provide more protection and to improve risk sharing, maintain insurers' solvency when climate change risks materialize, and avoid the problem of moral hazard. It is important for policy makers to be aware of the benefits and challenges when they design monitoring and supervisory frameworks for the insurance sector under climate change.

Our survey illustrates that the literature on the interaction between climate change and the financial system has grown rapidly in recent years. While our understanding on this subject has advanced considerably as a result, a great deal of work remains to fill the remaining gaps in our knowledge. Consequently, it is important to ensure that future policy discussions are evidence-based and incorporate the growing body of research findings in this area.

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