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# FIRM ADAPTATION TO CLIMATE CHANGE

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**ABSTRACT**

We survey the microeconomics literature that studies how firms in the developing world are adapting to extreme weather, local pollution, and natural disasters. Climate change increases the uncertainty that every firm must address as it decides where and how to produce and who to trade with. We study how expectations, market structure and firm heterogeneity determine investment in self-protection. A firm’s resilience also depends on government policies, market insurance access and infrastructure investments. We explore the strategic interactions between firms and governments that together determine firm risk exposure. We discuss benchmarks for measuring adaptation progress at the firm, industry and macroeconomic level.

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# 1 Introduction

We survey the microeconomics literature that studies how firms in the developing world are adapting to extreme weather, local pollution and natural disasters. Every firm makes investment decisions while uncertainty about future market conditions. Climate change accentuates these risks and could significantly lower a firm's expected present discounted value of profits. For example, climate change has the potential to trigger a cascade of global consequences, including tipping points, international migration patterns, disruptions in supply chains, and change in patterns and volume of trade flows. While firms have incomplete information on emerging risks, the anticipation that the climate change "treatment effect" could cause significant losses provides them with an incentive to take proactive steps to offset this damage. If firms can successfully adapt to rising weather risks, say through technology adoption, then this will reduce the overall macroeconomic impact of weather on national economic growth rates (Hallegatte, 2016; Hallegatte and Rozenberg, 2017; Nath et al., 2024).

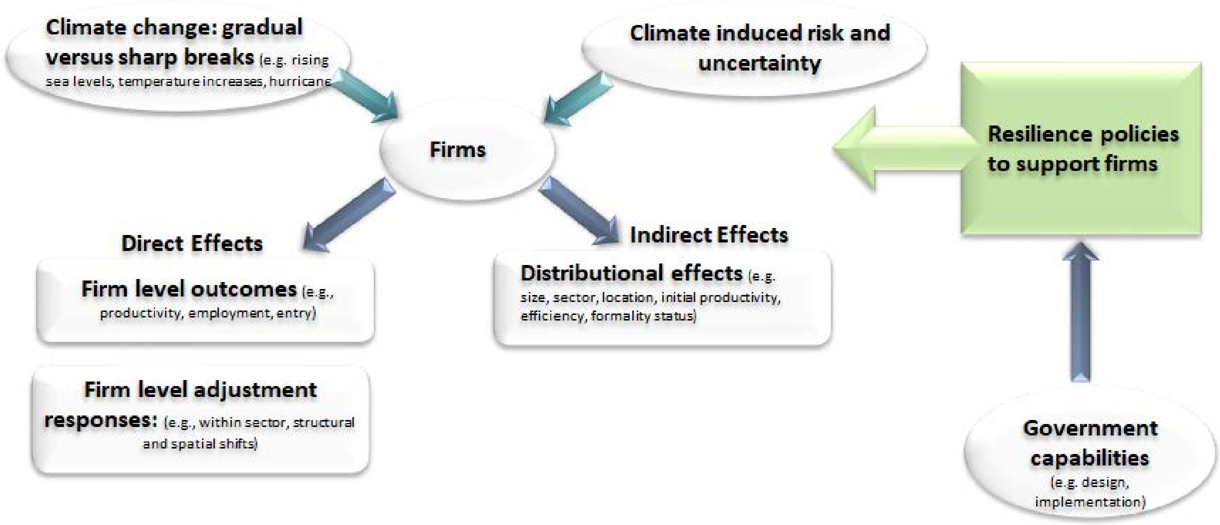
Our survey melds several strands of research including; the economic geography literature that has emphasized the costs of "bad geography" for productivity and economic development Gallup et al. (1999). Many developing nations are located in regions that face greater *natural disaster* risks such as typhoons and are exposed to *extreme* heat and precipitation (Bakkensen and Barrage, 2018; Hsiang and Jina, 2014). The *risks and uncertainty* posed by extreme weather to firms in the developing world are amplified by *weak governance* capacity (Acemoglu and Robinson, 2013; Porta et al., 2008). One important implication of weak governance is unreliable local infrastructure. If roads flood and if the electricity grid breaks down, then exposed firms will be even less productive as supply chains are immediately disrupted by shocks (Allcott et al., 2016; Chong et al., 2014). Developing countries have limited resources - both human and financial - to undertake investments in responding to such disruptions. We explore cases where private and public resilience *policies and investments* are substitutes and cases where they are complements.

Figure 1 illustrates the key themes explored in our survey on firms in the context of climate change adaptation.

The key insights from our survey include:

*First*, climate change has deep and persistent impacts on firm outcomes, such as operational status, employment, productivity, investments and growth. Under certain conditions, firms may also bounce back in the aftermath of climate shocks, in line with the Schumpeterian theory of creative destruction.

Figure 1: Key themes for firms in the context of climate change adaptation




*Second*, the intensity of the impact varies across time and space, and depends on attributes of the firm. A firm's ownership structure, sector, and spatial location determine the severity of the impact. Within countries, larger and more productive firms which have better financial and managerial capabilities are more resilient to climate shocks. Across countries, recovery among firms in developing countries is slower due to poor quality infrastructure that gets destroyed with disasters; disparity in access to natural-disaster insurance facilities; shallow credit markets; and differences in capabilities of firms to mitigate disaster risk exposure.

*Third*, the damages from climate-related changes are not only felt directly but can be propagated indirectly to other firms through production networks and reallocation effects. As workers and firms move spatially to adapt to weather changes, they induce changes in the composition of economic activity, and trade patterns.

*Fourth*, climate change induced uncertainty affects private sector investment. Firms with greater exposure to climate risks have reduced valuation of assets such as plants and property and increased operating costs pertaining to insurance costs. They also face difficulty in accessing finance even at higher interest rates relative to firms with lower vulnerability. These effects are significantly greater for smaller firms, especially in high-risk sectors and countries and those with weaker capacity to adapt to and mitigate the consequences of climate change. Several market frictions, especially those pertaining to information, insurance markets, and distortions limiting reallocation of resources can affect adaptation and resilience to climate change.

*Finally*, policymakers have access to a growing menu of strategies to encourage a firm's adaptive investment. These include; (i) encouraging risk taking through development of insurance markets; (ii) improving information flows on risks and insurance; (iii) supporting upgrading of managerial capabilities; and (iv) financial support for rebuilding firms. Policymakers will be more likely to achieve their adaptation goals if they anticipate how optimizing firms will respond to the evolving "rules of the game".

The paper is organized as follows. In Section 2, we sketch out the microeconomics of how a profit maximizing firm responds to expected changes in weather. If firms have perfect foresight concerning weather patterns, how would they configure their activities to maximize profits? We explore key aspects of firm heterogeneity in determining adaptive capacity. In Section 3 we then pivot and explore how weather risk and uncertainty affects the firm's choices and outcomes. Section 4 explores the interplay between government policies and how firms respond to the implicit incentives they face and thereafter introduce a framework for evaluating the effectiveness of government interventions. Section 5 discusses empirical benchmarking of adaptation progress, while Section 6 ends with concluding remarks and directions for future research.

## 2 Adaptive Capacity in the Perfect Foresight Case

Consider a firm that has already chosen a production location. Suppose that the firm has perfect foresight concerning weather shocks. This firm anticipates when it will be very hot and when it will be very rainy or polluted. The firm is endowed with a production function and the owner of the firm understands how the firm's production is affected by each possible weather realization. Consider a case where the omniscient manager knows that over the next two weeks the weather will be awful. This firm can adapt by cancelling production during that time or by investing in protective gear to protect the production facility. The firm could undertake the less drastic approach to adaption through *within sector shifts* and accelerate its production before the onset of terrible weather and store the production in a dry shed. In these cases, the marginal cost of adaptation to the firm is the cost of renting the shed and paying the workers overtime for their long days during the dry time. If the firm cancels work and does not pay the workers for those lost days, then these workers bear the cost of the weather induced downtime. For those families who do not have buffer savings, they can suffer large consumption drops if the earner's income plummets due to horrible weather.

Firms that anticipate that over the medium term that they will face more extreme weather events have several margins of adjustment. *Sectoral* adaptation includes diversifying into additional product lines within the same sector (Pelli et al., 2020), by investing in innovation (Gasbarro et al., 2016), labor saving technologies or by adopting of establishment-level climate controls (Somanathan et al., 2021). *Structural* shifts imply a drastic switch in the sector, for instance, by transitioning out of agribusiness sector to those that are less exposed to climate risks (Colmer, 2021) through (gradual or sudden) reallocation of factors of production (Zhang et al., 2018). *Spatial* transformation takes place by physically relocating (Linnenluecke et al., 2011; Khanna et al., 2021) or diversifying production across locations (Pankratz and Schiller, 2021). Firms can also adapt by establishing financial links to other regions which can act as an effective spatial risk sharing tool (Albert et al., 2021).

**Firm Attributes that Enhance Adaptive Capacity**

The firm dynamics literature emphasizes the birth, the growth and the exit rate for different firms in different industries (Davis et al., 1998). Improved access to administrative data and the creation of firm level unbalanced panel data sets have allowed researchers to study firm growth dynamics in many nations around the world. Empirical benchmarks of a failure to adapt to weather risks include firm closings, new formal business formation, firm growth and a lower average product of labor in areas facing more weather shocks. These dynamics are likely to vary as a function of firm attributes.

*Firm Size*

Consistent with the Schumpeterian 'cleansing hypothesis' (Schumpeter et al., 1939), evidence from the Hurricane Katrina, which hit the United States in 2005, reveals that firms with larger *initial size and productivity* had a lower impact on their survival and revenue and also recovered more quickly (Basker and Miranda, 2018). Nevertheless, evidence also showed that the advantages offered by external firm attributes such as firm size dissipate over time.[1]

Firm size proxies for access to capital markets, better management and technical capabilities and hence heightened productivity and profitability. For instance, a firm's scale of operations will affect the profitability of adopting various adaptation strategies. Many adaptation strategies are lumpy such that they require bearing a fixed cost. Such lumpy investments feature scale economies so that larger firms will be more likely to adopt these measures Graff Zivin et al. (2018). Firms that do not have access to capital will be less likely to have access to lumpy adaptation strategies. Workers at these firms will face more risk and will demand to be paid higher wages.

[1] The authors studied 12,300 geocoded establishments in Mississippi from the Census Bureau's Longitudinal Business Database (LBD), including over 1,500 businesses in four counties that experienced significant storm damage as determined by the Federal Emergency Management Administration (FEMA).

*Manager Quality*

Larger and more productive firms have better financial and managerial capabilities Bloom et al. (2010). For instance, European firms with more *intangibles assets* (e.g., patents and trademarks) experienced higher post-flooding employment growth and lower productivity decline (Leiter et al., 2009). The most vulnerable firms are less likely to engage in adaptation measures perhaps due to lack of *managerial capability* to explore alternative business opportunities (*structural adjustments*) or rational inattention of managers to productivity-enhancing climate change (*sectoral*) adaptations. In Uganda, firms with higher ability managers are more likely to adapt to pollution by protecting their workers through the provision of equipment and flexibility in work schedule, that is, via *within sector adaptation* mechanisms rather than avoiding locating in well-connected polluted areas (*spatial adjustments*) (Bassi et al., 2021).

The latest wave of the World Management Survey (WMS) includes new questions regarding firms' perceptions of climate change and their adaptation behavior. Using these data from 33 countries over 30 years, Van Reenen and Keiller (2024) demonstrate that natural disasters adversely affect firm performance. They show that exposure to natural disasters increases firm exit and reduces growth in capital, employment, and value added for surviving firms. However, firms with structured management practices exhibit greater resilience, experiencing smaller declines in capital and employment growth after natural disasters. This resilience may stem from their more accurate perceptions of climate-related risks and their proactive implementation of climate adaptation measures. Decentralized firms also perform better in dealing with disasters and implementing climate adaptation measures. However, their perception of climate change as a risk is stronger in areas with infrequent natural disasters, suggesting potential inefficiencies in their adaptation strategies. As natural disasters are expected to rise due to climate change, the relationship between management practices and disaster resilience becomes increasingly crucial, with poorly-managed firms at greater risk

*Firm ownership structure*

'Footloose' multinationals or foreign-owned plants are more likely to exit the market (*spatial adjustments*) after floods because these events destroy local suppliers and raise the cost of sourcing local inputs (Kato and Okubo, 2018). Nevertheless, these firms are also larger and better managed and hence, conceptually, they could be more resilient. There are not many studies that have considered this distinction in a systematic manner.

By comparison, single-person firms appear to be more resilient to crises. They are more likely to reopen in the first 3 months after the shock partly because (i) employment is flexible with family participating in business operations (ii) absence of other means of income opportunities for the owner and family members; and (iii) ability to react faster when making such decisions than larger firms. This was substantiated in a study of 673 Mississippi establishments that were tracked weekly in the year following Hurricane Katrina, (LeSage et al., 2011). Nevertheless, given that these firms are, by definition, small they are the hardest hit by the shock. This could be because the firms that disappear are not the same as those that emerge after the crisis.

**Sectors**

Some sectors are more vulnerable to climate change than others. For instance, evidence on the impact of the 1959 Ise Bay Typhoon in Nagoya City, Japan suggests that firms in retail and wholesale have a lower probability of surviving typhoon-induced disruptions, compared to those involved in manufacturing and construction (Okubo and Strobl, 2021). This vulnerability arises due to broken production links and damaged storage facilities, which significantly impact retailers' ability to continue operations. In comparison, the construction sector often benefits from the increased demand and new opportunities associated with rebuilding after a disaster.

Uneven access to financial aid and assistance, including insurance payments, plays a role in explaining the differential response of firms to climate shocks. Aguilar-Gomez et al. (2024) find that a single day of extreme temperature per quarter in a Mexican municipality raises the delinquency rate by 0.17 percentage points, and thereby causing financial distress. Such climate shocks have varying impacts across sectors, with agriculture experiencing particularly negative effects. The impacts extend beyond directly affected sectors, affecting non-agricultural industries, especially those reliant on local demand like services and retail. Their work suggests that more integrated markets tend to buffer firm profits from dramatic fluctuations resulting from weather-induced quantity changes.

*Reallocation across Sectors*

The varying impact of natural disasters across industries and sectors yield an empirical prediction that labor and capital will flow to those sectors with a higher rate of return. In India, evidence from storms during the period 1995-2006 suggests that the impact on the formal and listed firms can be transmitted through reallocation within- and between-industries (Pelli et al., 2020) because capital destruction leads to a reallocation of sales towards better performing firms and industries. That is, shocks trigger reallocation *within sector, structural shifts or spatial* adjustments. An optimistic twist on the creative destruction hypothesis is that firms that survive extreme events will "build back better" (Leiter et al., 2009; Coelli and Manasse, 2014; Noth and Rehbein, 2019; Pelli et al., 2020).

*Informality*

Poor people who run informal firms are the most likely to set up production in risky places because of the low demand for locating on such land parcels. Tradeoffs emerge between encouraging entrepreneurship while protecting people from engaging in excessive risk taking. Lowering the costs of entry for firms fosters competition and can contribute to achieving upward income mobility for those entrepreneurs who succeed. At the same time, informal production areas are most likely to emerge in areas exposed to flood risk and mudslide risk.

Evidence from India using data on both formal and informal firms suggests that floods led to significant decline in employment in the formal sector, especially in the least productive establishments, and towards informal household-run enterprises (Hossain, 2020). This is consistent with the view that such reallocation results from survival strategy of workers who ended up unemployed and suffer from labor market contraction in the formal sector (Tybout, 2000; La Porta and Shleifer, 2014). Given the large productivity gap across formal and informal sectors, such climate-induced reallocation generates a significant reduction in aggregate productivity.

## 2.1 Firm Migration as an Adaptation Strategy

The economic geography literature emphasizes a type of "chicken versus the egg" dynamic concerning whether people move to places where the jobs are available or do firms locate in places where people cluster. In the aftermath of major natural disasters, people move to places offering greater economic opportunities. Some examples include Hurricane Katrina's impact on New Orleans and the 1930s Dust Bowl's impact on Kansas where longitudinal research has documented that many people who were forced to move away from these shocked places prospered later on as they moved to more vibrant local labor markets (Deryugina et al., 2018; Hornbeck, 2012).

In choosing their location, firms tradeoff balancing the agglomeration benefits derived from sharing, matching and learning on the one hand, versus the costs they must pay for land and labor and the risks they will face at a given location. Taking the hedonic land and labor market pricing gradients as given, firms will chose a profit maximizing location. New firms will take into account the competitive effects of whether they want to locate close to or far from incumbent firms.

If certain areas experience repeated horrible weather, then rents of such land should decline and the most productive firms should be less likely to locate there (Rentschler et al., 2023). Such areas would likely be populated by less productive firms. In this sense, the equilibrium hedonic land price gradient sends signals about locational productivity and quality of life.

Given that it is costly for a firm to migrate, firms have strong incentives to research the risks and challenges that each location faces. In the United States, there has been a growth in climate science information firms that provide location specific "climate report cards" for different geographic areas regarding their flood and fire risk. Such sufficient statistics are based on academic models and recent geocoded natural disaster realization data. In the short run, we expect that if such tailored risk report cards are introduced in the developing world this will accelerate the learning process and that geographic site selection will be better informed about the recent shocks and the expected future shocks (Burlig et al., 2024).

Migration in response to climate change induces reallocation of activity. For example, weather change induced migration of labor leads to reallocation of factors across space (Cai et al., 2016; Cattaneo and Peri, 2016; Mueller et al., 2014), as evidenced among localities in rural India that experienced higher-than-normal local rainfall. Such migration shifted labor towards non-agricultural non-tradable sectors (e.g., construction, retail, and education sectors) and consequentially increased productivity in the agricultural sector and led to an increased demand for non-tradables (Emerick, 2018). Higher temperature in India also led to reallocation of agricultural employment towards local manufacturing and services (Colmer, 2021). Such cross-sectoral labor movements are bounded within districts due to severe liquidity constraints (Cattaneo and Peri, 2016).

*The Geography of Supply Chains*

Firms differ with respect to where they locate their supply chains. When disasters strike in the risky areas, other firms who have "played it safe" by sourcing their supply chains in safer areas have an edge. One recent study used a structural discrete choice model to study how car manufacturers respond to the risks posed by local natural disaster on supply chains (Castro-Vincenzi, 2022). Severe floods close to a car assembly site is associated with an economically significant reduction in subsequent production at that plant. Multi-establishment firms respond to the shock by increasing their production at other establishments. Related recent research based on micro data from India shows that flood events disrupt local supply chains and firms respond by diversifying across locations which has significant distributional consequences (Castro-Vincenzi et al., 2024). Firms that produce durable goods and anticipate supply chain risk can hold inventories in order to decouple sales revenue from short run production disruption.

Production networks are formed through a complex web of contracts between firms and these firms use public infrastructure to trade goods. During times of extreme weather, public goods such as logistics infrastructure that facilitate production networks and trade in goods faces disruptions due to the "Tragedy of the Commons" problem. In addition to direct effects, firms in unaffected locations are indirectly impacted through production networks. For example, suppliers and buyers suffer from reduced revenues as a result of suppliers' exposure to extreme heat and flooding incidents. In Tanzania, floods destroyed the fragile supply chain infrastructure and led to a disruption in the access of necessary inputs for firms even in unflooded areas. This caused 30-50% of all supply and delivery delays in the region and a drop in sales. Such disruptions in production networks transcends national borders as evidenced in a storm that affected not only Chinese plants' performance but also reduced their foreign transactions (Elliott et al., 2019). Japanese affiliates in Thailand experienced a drop in sales following 2011 floods, while imports from China and Japan increased (Hayakawa et al., 2015). Hurricanes-induced job losses occurring within multi-plant firms were propagated across undisturbed distant regions in the US (Seetharam, 2018). For every job loss of the firm in an affected county, 0.19-0.25 jobs are also lost across other sites in unaffected regions.

Firms that buy key inputs can adapt to climate change risk by diversifying away from weather-stricken suppliers (Pankratz and Schiller, 2021). Firms may also adapt by establishing financial links to other regions; viewed as an effective risk sharing and consumption smoothing tool (Albert et al., 2021). Such adjustments also occur in an international context, as illustrated in a study where the exports of poor countries to the United States decreased by 2.0-5.7 percentage points for each °C rise in temperature (Jones and Olken, 2010).[2] In sum, the volatility in domestic production translates to greater variation in trade, with the effects being larger for poorer countries (Dell et al., 2009).

As more firms seek out "climate resilient" supply chains, areas seeking to attract footloose firms will have a greater incentive to invest in local resilience infrastructure because this becomes an economic development strategy. Urban and regional economic studies of local agglomeration have documented how by attracting a major factory, a location can then attract other firms to co-locate nearby to reduce transportation costs in shipping (Greenstone et al., 2010). Developing world agglomerations are now taking root. They will be more likely *materialize* if the location is *safer*. The empirical question is whether safety is produced by

[2]In China, Li et al. (2015) suggest a negative effect of rising temperatures on exports ranging from 8.8% to 12.6%.

exogenous features or can it be produced through strategic investments in urban planning and infrastructure. Infrastructure in developing countries are often more vulnerable to climate hazards, which, if destroyed, can delay recovery and increase coping costs (Rentschler et al., 2019). This may perhaps explain why firms in advanced economies of Europe experienced the *build back effects* (Leiter et al., 2009; Coelli and Manasse, 2014; Noth and Rehbein, 2019) compared to those in developing countries such as India (Hossain, 2020) and Tanzania (Rentschler et al., 2021) where the impacts of similar natural hazards are devastating and persistent (Rentschler et al., 2021).

## 2.2 Adaptation to Sharp Climate Shocks versus Gradual Changes

Not all climate-related hazards have immediate impacts. Gradual changes such as increased temperature and precipitation, and accelerated sea level rise, are not extreme weather changes by themselves, however, their cumulative impact overtime can be significant (Seneviratne et al., 2012).

Extreme events such as storms and floods can have large negative effects on firms' output, employment, operational cost, demand and productivity. These consequences are more likely to take place if such shocks are unexpected or if the risks are known but firms do not have the managerial or financial capacity to self-protect against the anticipated shocks. Evidence from tropical storms in India during the period 1995-2006 show an immediate decline in sales and physical assets by 99% and 75%, respectively, among manufacturing firms, compared to their pre-shock levels (Pelli et al., 2020). In China, typhoons cost an annual damage of about US$3.2 billion (2017 prices) or about 1 percent of average turnover of Chinese plants (Elliott et al., 2019). In Viet Nam, the reduction in firm income per worker due to typhoons is around 33% (Vu and Noy, 2018). For gradual changes, evidence suggests that heat stress reduces firm output, efficiency and profits. The productivity of large garment manufacturers operating in Bangalore, India, starts to decline by as much as 2 efficiency points (i.e., realized output versus target output) for every °C increase in temperature after reaching an equivalent outdoor temperature level of $27 - 28$°C (Adhvaryu et al., 2020). In China, manufacturing plants experienced a reduction in output by 45% in days when temperature is above 32° compared to days when temperature is between 10°C and 15° (Zhang et al., 2018). More frequent days with heat stress also resulted in significant production losses in automobile industry in the US by as much as 8% (Cachon et al., 2012).

A "silver lining" caused by extreme events is to create the possibility of a type of Schumpeterian creative destruction (Schumpeter et al., 1939). If firms choose to rebuild after a disaster in the same location and if they now update their subjective assessment that the same type of disaster could occur again in the future, then they have stronger incentives to "build back better" so that the future shock causes less damage to the firm.

Gradual changes in local weather induced by climate change also pose a threat to firms in the developing world. In India, the increased ambient temperature is not only associated with productivity declines but also with increases in *worker absenteeism* (reduced labor supply) (Somanathan et al., 2021). Thermal stress can lead to workers' degradation of both *cognitive and psychomotor task* performance (Hancock et al., 2007), leading to reduced productivity (Niemelä et al., 2002; Tham, 2004). Temperature changes affect firms in both developed and developing country-settings, reducing time allocated for work (Graff Zivin and Neidell, 2014; Garg et al., 2020; Neidell et al., 2021). These effects are generally nonlinear; that is, marginal changes in firm performance at lower levels of temperature but significant declines at high temperatures (Hancock et al., 2007; Zhang et al., 2018; Adhvaryu et al., 2020).

Changes in weather induces reallocation of activity due to greater demand for certain products (e.g., air conditioners, refrigerators) or in response to supply shortages. In India for example, a rise in temperature has been found to have reduced agricultural productivity, which also dampens demand for non-farm goods and services (Colmer, 2021). On the financial side, exposure to sea-level rise (SLR) is associated with increased credit spread or an exposure premium due to rising uncertainty (Goldsmith-Pinkham et al., 2021), while extreme heat significantly increased the rates of credit delinquency of small businesses in Mexico (Aguilar-Gomez et al., 2024).

# 3 Climate Change Induced Weather Uncertainty

Climate change science remains an active field of inquiry with many unsettled issues pertaining to the timing and the possible extent of shifts in weather distributions. Put simply, what will be the empirical distribution of July temperature highs for each city around the world in the year 2060? Within India what will be the probability distribution of rainfall in the years 2030, 2035, 2040? Will there be another flood in Brazil or Dubai? This section describes firms' responses and adaptation strategies in the face of such climate risks and the uncertainty in the changes in weather conditions.

The future annual flow of emissions is a random variable. The Intergovernmental Panel on Climate Change (IPCC) and other entities seeking to predict the future climate change challenge have created different scenarios with names such as representative concentration pathway (RCP) 4.5 and the more pessimistic RCP 8.5 scenario for helping policymakers anticipate the extent of the future emissions paths. Climate scientists continue to try to measure the climate sensitivity equation that maps global GHG concentration levels into the warming of the world.

Scientific progress plays a crucial role in shaping expert expectations about emerging risks. The social media platforms, non-profits and the news media educates the public about these emerging risks. The challenge here is the signal extraction problem. Given the considerable uncertainty associated with both climate science predictions concerning the timing and the severity of likely disaster risks, firm managers may have trouble forming updated beliefs about the short run risks they face. Information about emerging risks plays a central role in helping firms to adapt to expected shifts in the weather Burlig et al. (2024).

Expectations concerning place-based climate risks influences economic geographic outcomes. For example, in the United States the risk of floods negatively affects firm entry, employment and output, and is associated with a reduction in aggregate output, of which only 20% is attributed to direct damages while the remaining 80% stems from expectation effects (Jia et al., 2022). In a recent study, Cevik and Miryugin (2022) document the impact of climate change vulnerability on corporate performance using a large panel dataset of more than 3.3 million non-financial firms from 24 developing countries over the period 1997–2019. Their results suggest that firms operating in countries with greater exposure to climate risks have difficulty in accessing debt financing even at higher interest rates, while being less productive and profitable relative to firms in countries with lower vulnerability. These effects are significantly greater for smaller firms, especially in high-risk sectors and countries, and those with weaker capacity to adapt to and mitigate the consequences of climate change. Their results are in line with previous findings suggesting the positive relationship between climate risks and cost of debt, which can result in a decline in firms' leverage (Ginglinger and Moreau, 2019).

Such exposure to climate risks are detrimental to the firm's financial position. For instance, while actual climate changes negatively affects firms' stock returns, earnings and equity valuations (Venturini, 2022; Bansal et al., 2016; Addoum et al., 2021; Hugon and Law, 2019; Pankratz et al., 2019), the risks of such events may lead to a reassessment of the value of a large range of firms' assets (plants, property, and equipment) and to increased operating costs, such as relocation costs and insurance costs, resulting in lower profits and reduced repayment capacity. Greater physical climate risk led to lower leverage in the post Paris Agreement period, owing to both demand and supply side effects. On the demand side, firm's optimal leverage reduced due to the larger expected distress costs, while on the supply side higher operating costs induced bankers and bondholders to increase the spreads when lending to riskier firms (Ginglinger and Moreau, 2019). It is therefore not surprising that firms exposed to climate change risk bear higher costs in financial markets when trying to access credit. In the United States one-standard-deviation increase in the risk of sea-level rise is associated with a loan spread that is 4.2 basis point higher (Jiang et al., 2019). The effects are larger on corporate bonds, reaching up to 7 basis points, especially for firms and industries vulnerable to extreme weather conditions (Allman, 2021).[3]

## 3.1 Adapting to Extreme Rare Events

The theoretical literature on rare disasters has emphasized that both the probability of such events and the loss incurred in those states of the world play a key role in determining their costs (Barro, 2015). Empirical research has documented the large macroeconomic effects such shocks can cause Hsiang and Jina (2014); Cavallo et al. (2013). Both these lines of research, however, underscore the importance of uncertainty in realized outcomes. How firms and investors respond to such uncertainty related to climate change has implications for their adaptation effort. Uncertainty about future climate shocks affect investments in innovation and technologies as well as decisions regarding other aspects of production such as input choice, location of firm and the sourcing of materials (Jia et al., 2022).

Firms' expectations about future weather events or shocks influence their decisions concerning their choice of inputs, spatial sourcing of material inputs, location of production and so on which in turn affects their productivity. Expected risks affects a firm's finances. (Huang et al., 2018) uses Global Climate Risk Index to capture likelihood of losses from natural hazards at the country level is associated with lower and more volatile firm earnings and cash flows. These firms also tend to hold more cash and pay less cash dividends, suggesting that more exposed firms tend to hedge more against cash flow volatility and illiquidity due to higher climate risk. Increased climate uncertainty can also affect firms by increasing their insurance premiums. This can manifest through a decline in coverage agreements and, consequently, an increase in insurer exits because of limited revenue streams (Born and Viscusi, 2006), both will inevitably lead to higher insurance premiums.

Extreme events can trigger ripple effect in a firm's supply chains. In aggregate, this means that such shocks impact non-treated areas. If a supply chain is not diversified and

[3]Nevertheless, such climate-related financial risks are still mispriced and not fully reflected in asset valuations (Caselli and Figueira, 2020), although recently financial markets are increasingly recognizing such risks (Alsaifi et al., 2020) and firms are becoming more careful in embedding uncertainties in their overall risk management.

features a type of O-Ring such that a break in the chain shuts down production, then the whole network is sensitive to extreme disasters and weather events Carvalho et al. (2021). Access to geocoded micro data is creating new opportunities to study how firms adapt to extreme weather events. For example, geocoded microdata from Pakistan's Federal Board of Revenue on the near-universe of formal firm-to-firm monthly sales transactions over ten years in combination with GPS tracking on trucks can help understand the spillover effects of floods through production network (Balboni et al., 2023). This research finds that firms affected by major floods relocate to less flood prone areas, diversify their supplier base, and shift the composition of their suppliers towards those located in less flood-prone regions and reached via less flood-prone roads. Another recent study on India using new data on the universe of firm-to-firm transactions confirms that firms diversify sourcing locations, and that suppliers exposed to climate risk charge lower prices (Castro-Vincenzi et al., 2024). Such swift diversification of suppliers points to a forward-looking action that reduce future vulnerability to flood risk rather than direct effects of flooding are consistent with experience-based updating. It also supports the hypothesis that the impacts of climate change will be mediated as firms learn from the experience of increasingly frequent climate disasters.

In recent work, Lin et al. (2020) show that electricity providers increase investments in flexible power plants in response to long-term changes in local climate; (Li et al., 2020) document a negative effect of changes in long-term climate conditions on local employment; and Li et al. (2020) find that firms with high climate uncertainty increase their capital investments.

*Firm size and the supplier base*

Larger firms have lower exposure to risk as they can devote relatively more resources and have better abilities to sustain performance than smaller firms (Birkie et al., 2017). Firms that have a more *diverse supply base*, both in terms of numbers and geographic dispersion, and hence may better manage climate risk by ensuring faster recovery in the event of unexpected climate shock (Tokui et al., 2017). Sophisticated supply chains can also increase exposure to climate-related disruptions due to potential ripple effect (Gouda and Saranga, 2018) and managing such risk may require firms to have better capabilities.[4]

### Industry attributes and climate risk

*Climate sensitivity*

Firms in sectors that rely on certain *seasonal and climate conditions* (e.g., agriculture

[4] A number of factors such as size, customer base, firms' organizational setup, the breadth of the supply chain network, and diversification of product portfolio, are all sources of supply chain complexity (Birkie et al., 2017).

and related businesses), those that are vulnerable to the disruption of *infrastructure*, and those *located in areas* that are susceptible to physical climate change risks are particularly vulnerable (Weinhofer and Busch, 2013). Increased climate uncertainties can also increase price volatility in markets that have relatively higher dependence on moderate weather, such as agriculture and energy (including mining and oil extraction) (Fleming et al., 2006). The higher volatility of prices in these markets, which had been on the rise especially for agricultural products (Taghizadeh-Hesary et al., 2019), can deter investments and increase resource requirements for risk management that can be otherwise devoted to more productive activities. The exposure and the ability to mitigate climate risks vary by the sophistication of the sector.

# 4 How Does Government Policy Influence Firm Resilience Investment?

No government has the sole goal of maximizing a nation's climate resilience. Instead, many government officials are pursuing policies to increase national economic growth. Such pro-growth policies raise the likelihood that officials will stay in power and enhances their own reputations and influence. If such officials are concerned that weather risks do have a causal effect on slowing their nation's economic growth, then they have an incentive to consider adopting different policies to adapt to this anticipated impact. Future research should explore the political economy of when developing nation officials are willing to introduce new adaptation policies. For example, what role does international assistance play in encouraging developing nations to expand resilience efforts?

Policy makers focus on both place based and people based resilience policies. Place based policies consist of strategies for building up defensive infrastructure and infrastructure such as roads that facilitates trades and income growth. Person based policies focus on skill enhancement, poverty reduction and introducing incentives for private insurance markets to flourish.

Given that there are so many possible ways that government policy can influence firm resilience, we focus this section on a narrow set of themes. We note that a promising line of research here relates to the public finance of resilience public goods. In the developing world, governments often have limited access to revenue. Their ability to tax and to issue bonds plays a key role in determining their fiscal capacity to make resilience investments.

## 4.1 Place-Based Public Interventions

Over the next few decades, enormous investments will be made in durable infrastructure investment in the developing world. Nations will build new roads, sea walls, bridges, water treatment facilities, power generation plants, airports and many other pieces of location specific sunk capital. Such capital will last for decades and will be costly to retrofit.

Government investment in protective infrastructure can crowd out private investment in self-protection if the two are substitutes (Ehrlich and Becker, 1972). Public investment in place-based infrastructure (such as Sea Walls) could crowd out private self-protection as firms move to the risky area because it is a productive area that now faces less extreme weather risk. Infrastructure is long lived and this creates "lock in" effects such that if it is built in places that turn out to be risky then road infrastructure investments can simultaneously increase a firm's productivity (because it can ship goods at lower costs) while raising its short term climate risk exposure (Balboni, 2019). For instance, Hsiao et al. (2021) argues that sea wall investment in Jakarta that is financed by the nation as a whole is attracting too many people to live in this mega-city, implying that more people and firms face climate risks relative to a counter-factual where spatial sunk investment in sea walls had not taken place. International financing agencies have an incentive to anticipate this dynamic and to take into account the growth complementarities that will be caused by building the new infrastructure (Hsiao, 2023; Avner et al., 2021).

## 4.2 Firm-level Resilience Policies

The analogue to person-based resilience policies are programs that seek to help firms to adapt both ex-ante and ex-post to anticipated shocks. Some illustrative policy options are described below.

**Support to upgrade managerial capabilities**

The classical justification for the State to subsidize an activity rests on public goods and externality arguments. In the case of building up adaptation human capital, small firms managers may invest too little time and effort in building up these skills due to *information barriers*, where managers lack awareness of poor practices and benchmarks for improvement, *Information asymmetry* in the quality of consulting services or *uncertainty* in returns from such investments (Cusolito et al., 2020). When exposed to climate shocks, workers and supply chains of firms with lower managerial capabilities will be exposed to more risk. While competitive market forces will weed out inefficient firms that fail to adapt, this process imposes costs on the vulnerable.

Firms with low managerial capacities pay less attention to productivity-enhancing climate change adaptations and do not explore the new business opportunities offered by the changing environment. In fact, in anticipation of climate change, adjustments on the employment margins (layoffs) and firm exit margins (shutdowns) are more pronounced for firms with top managers believing climate change is a concern (Li et al., 2020). Further, risks of climate change are taken in isolation and not compounded with other risks such as financial, leading to significant underestimation of the total risks that firms actually face (Hoffmann et al., 2009).

Recent research demonstrating the importance of manager quality in adapting to disaster risks highlights a possible channel through which public policy can help to build up resilience Van Reenen and Keiller (2024). For instance, management training programs have been shown to be broadly effective in increasing the skills of managers (Bloom et al., 2013). General managerial quality and practices can help firms in the developing world anticipate emerging risks and plan out investments to self-protect against these risks (Bassi et al., 2021). Further research is also needed to explore the mechanisms underlying the connections between management practices, disasters, and firm outcomes, as well as the potential mediating role of national institutions and policies (Van Reenen and Keiller, 2024).

**Targeted Industry Subsidies**

In 2024, many nations are actively engaging in industrial policies intended to boost their economies. In the United States, the Biden Administration has used the Inflation Reduction Act to provide billions of dollars in subsidies to accelerate the pace of decarbonizing the U.S economy. Going forward, we anticipate that future targeted industrial subsidies will focus on reducing industrial risk exposure. Developing nations often prioritize expanding their manufacturing capacity due to the perceived link between manufacturing, economic growth, and job creation. This raises the question of whether going forward more nations will offer special incentives for helping the manufacturing firms adapt to climate change faster and at scale, and relative to other sectors. For example, evidence suggests that in response to climate shocks, manufacturing firms can receive more aid and have better access to government programs, allowing them to replace old capital and invest in newer, more productive capital (Noth and Rehbein, 2019). However, Juhász et al. (2023) review of industrial policies around the world suggests that these policies face multiple objectives and trade-offs, including promoting local supply chains, advancing job growth, addressing digitalization and the green transition, and navigating geopolitical challenges. These complexities highlight the need for diverse policy instruments and a more nuanced approach that goes beyond traditional economic perspectives focused on manufacturing.

**Encourage risk taking through the development of insurance markets**

Insurance markets play a key role in pooling risks. Even in advanced countries such as the United States, businesses' losses from hurricanes are not covered by insurance (Battisto et al., 2017; Swiss Re, 2018; Collier et al., 2020). Disasters can cause spatially concentrated loan defaults in the absence of insurance (Collier and Babich, 2019; Collier, 2020) and a reduction in the credit supply after the disaster that further delays the recovery of affected firms (Del Ninno et al., 2003). In developed and developing countries alike, getting businesses to insure remains a formidable challenge. The progress on expanding insurance coverage to SMEs in developing markets has been slow (Binswanger-Mkhize, 2012) due to (i) differences in perception of risks (Wagner, 2020); (ii) liquidity constraints; and (iii) presence of other types of risks (Cole et al., 2013) that may be more prevalent in developing countries (Collier, 2020). For instance, other risks that cannot be insured can affect the demand for insurance (e.g., Doherty and Schlesinger, 1983; Courbage et al., 2017; Hoffmann et al., 2009) because the burden of insurance premiums reduce the wealth of policyholders and hence increase their susceptibility to other shocks (Collier, 2020). Policymakers can assist in establishing new insurance arrangements for natural disasters or improve existing ones, possibly even being an insurer of last resort (Bruggeman et al., 2010).

**Reducing Information Frictions that Limit Insurance Market Growth**

Informational issues also affect the use of insurance. Firms tend to under-insure through markets not only due to ignorance about their risk, but also because of the complexity of coverage under different insurance products, and the strategic behavior that balances market insurance with mitigation and self-insurance (Kousky, 2019). For example, behavioral economists posit that economic agents tend to underestimate the probability of a climate risk if they have not recently experienced it ("availability bias"), which in turn discourages investments in crises preparation or insurance (Bin and Polasky, 2004; Kousky, 2010; Atreya et al., 2013; Bin and Landry, 2013).

An open research question here pertains to whether self-protection and and market insurance are substitutes. If they are, then the inability to buy market insurance is predicted to lead firms to invest more in self-protection. An empirical implication of this prediction is that weather shocks should cause less damage because uninsured firms are better prepared for these shocks.

**Financial Support for Rebuilding Firms**

Governments often provide financial support for helping to rebuild firms that have experienced a shock. A number of policy instruments exist to support firms in responding to climate shocks. For instance, grants or financial aid, which had been effective in the case of micro-enterprises in Sri Lanka post 2004 Tsunami (De Mel et al., 2008). Real profits among treated firms increased due to cash and in-kind grants compared to the control groups. The "build-back-better" experienced by firms in Germany after a major flood in 2013 was also partially attributed to the availability of government aid, and banks' willingness to fund re-investments (Noth and Rehbein, 2019). Manufacturing firms, which received the *most financial aid* post 1959 Ise Bay Typhoon in Nagoya City, Japan, had higher chances of remaining viable as opposed to those in retail and wholesale sectors (Okubo and Strobl, 2021).

Small firms face disproportionate financing challenges, even under normal conditions, as banks exhibit greater reluctance to lend to them due to perceived higher default risks and the associated costs of appraisal, monitoring, and asset liquidation. These difficulties are further amplified in developing countries, where weak financial institutions hinder access to credit information and operate within a fragile legal framework for collateralizing assets (Grover and Imbruno, 2020).

More research is needed on the moral hazard incentive effects induced by anticipated government disaster support. Do such expected transfers distort firm locational choices? Do firms under-invest in self-protection if they anticipate ex-post disasters transfers?

# 5 Empirical Benchmarking of Firm Adaptation Progress

At any point in time, each firm can calculate its expected present discounted value of profits lost from a given weather shock. If this loss declines over time for a given firm, then we define this to mean that the firm is making adaptation progress. In this case, the firm's willingness to pay to not face the shock is declining.

The empirical challenge here is how to operationalize such calculations given the current data researchers typically have access to. With the rise of nation level geocoded administrative data sets such as the Census of Manufacturers and the Census of Services, there is an increased capacity to track the economic performance of firms over time. By merging in data on the location specific weather events that have taken place, observational econometrics approaches can used to estimate "climate damage functions". These are reduced form regressions such as the one presented below.

$$\text{Damage}_{i,j,l,t} = \text{X}_{l,t+m} + \beta_{1,t}\text{Weather}_{l,t} + \beta_2\text{Expected Weather}_{l,t+m} + \text{U}_{i,j,l,t} \tag{1}$$

In this regression, the unit of observation is firm i in sector j located in city l at time t. The dependent variable is a measure of the flow damage (measured in dollars) suffered by a firm. Controlling for firm attributes, the key explanatory variables are measures of the firm's recent exposure to extreme weather and the firm's expectations of future weather conditions. Most empirical studies do not include this second term. Assuming that the error term is uncorrelated with the weather realization, this regression yields an estimate of the average effect of a weather shock on a firm specific outcome variable. It is important to note that this approach does not explicitly model the general equilibrium effects of how the weather shock affects market prices for output or labor. In these empirical studies, the prices are taken as given.

Estimates of this equation are useful but up until now they have not explicitly modeled the firm's locational choice. Imagine a case where firms update their beliefs about location j's future weather shocks as the climate scientists are predicting that location j faces medium term extreme weather risk. Forward looking firms will start to migrate to relatively safer locations over time. In this case, an econometrician who estimates equation (1) should be concerned that the firms who continue to locate in location j are not a representative sample of firms. One selection hypothesis would be to posit that better managers might locate in such areas if they have a risk adaptation edge. In this case, they can rent cheap land and still be productive. Another selection hypothesis would posit that worse managers will choose to locate in the riskiest areas because avoiding risk is a normal good.

In estimating equation (1), the researcher does not observe the costs that the firm has incurred to offset extreme weather. Such a regression does estimate the marginal cost to the firm of being exposed to extreme weather. If the firm has incurred upfront costs to adapt, then the econometrician is likely to estimate smaller marginal coefficients in equation (1). In an economy where firms are anticipating more extreme weather, firms will invest more in adaptation and the econometrician will actually estimate a smaller marginal damage coefficient over time.

The climate damage estimate literature relies on observational data as extreme weather provides the variation. Adaptation scholars can rarely implement field experiments here. A field experiment might consist of randomly distributing risk report cards to firms to educate them about the risks their geographic location faces. If firms trust the information source and were unaware of the risk, then this "new news" may affect their adaptation investment. Survey research and observational data on subsequent output can be used to study whether such an information nudge accelerates adaptation investment and lowers the marginal damage (B1 in equation 1) for the treated firms. Another field experiment research design would be to randomly assign different subsidies to firms for purchasing adaptation products. This price variation would trace out the demand curve for adaptation goods and this random variation could again be used to test whether the climate damage is less sensitive to extreme weather when firms have been induced (at random) to invest more in adaptation. As more firms seek to buy adaptation enhancing products, this provides an incentive for entrepreneurs to design these products. This dynamic innovation process will lead to higher quality products that sell for lower prices and this accelerates the global adaptation process Acemoglu and Linn (2004).

A final issue worth noting here is the timing of the observations. Most administrative data are annual data. Suppose a firm is exposed to fifteen extreme weather days over the last year. Ideally, the researcher would have daily data on the firm's output to observe the short run and the annual effects of the extreme weather. While the researcher can access daily weather data and thus know that this firm was exposed to fifteen extreme days, the researcher observes an annual economic outcome such as the average output per worker across the entire year. This averaging reduces the likelihood that the researcher can measure the standard deviation of firm output. This matters because if a firm fails to adapt to extreme weather it will be likely to go bankrupt and its workers will seek new employment. Given that weather shocks are spatially correlated, many nearby firms may simultaneously suffer and this reduces the likelihood that the displaced workers easily transition to another job paying the same wage. This example highlights how firm level research on adaptation will be improved by tracking the earnings dynamics for displaced workers who lost their job because of the extreme weather event.

# 6 Conclusion

Global carbon dioxide emissions continue to rise. While the annual International Conference of the Parties (COP) meetings have helped nations to co-ordinate decarbonization activities, the global growth in population and per-capita income raises greenhouse gas emissions. A fundamental global free rider problem lurks as developing nations are prioritizing economic growth over decarbonization. Every nation is hoping that every other nation bears the costs of decarbonization. As global fossil fuel consumption continues to rise, developing country nations face greater risks from climate change. Facing this reality, climate change adaptation takes on a prime importance especially in developing countries.

In this survey, we have presented a microeconomic approach that focused on the challenges that extreme weather poses for firms in the developing world. We surveyed research that studies the role of markets, information, and expectations in determining the pace of adaptation. The expectation that firms will lose profit if they fail to adapt motivates them to consider adopting adaptation strategies.

In this paper, we have not focused on the global Pareto problem of what is the optimal amount of investment in carbon mitigation versus climate change adaptation. Given our focus on firms, these firms are focused on their own profit maximization. If every firm faced a carbon tax, then global emissions would be lower and the adaptation challenge would be less severe. Throughout this study, we have implicitly assumed that the global free rider challenge continues such that global greenhouse gas emissions continue to rise and firms have to adapt to the emerging challenges posed by this global externality.

We close by highlighting several possible future research topics. First, there is a need to explore emerging data sources, such as geocoded data from smartphones, to provide more granular insights into firms' adaptation dynamics. These unconventional data sources can shed light on various aspects of adaptation, including the spatial and temporal dimensions of firms' responses to shocks. Secondly, there should be a focus on investigating firms' direct adaptation strategies, moving beyond the perception of firms as passive victims and recognizing their active experimentation with different approaches. Understanding the specific measures firms undertake, such as implementing heat protection measures for workers, can provide valuable insights into effective adaptation strategies. Attention should be given to government and societal action, through informal credit schemes or utilizing the diaspora's ability to transmit money using mobile platforms as efforts to support firms during shocks. Lastly, future research should also continue to study the strategic interactions between private and public sector investment. Ideally, these investments are complements in enhancing the developing nation's resilience, with government investments not crowding out private sector decision makers to locate in increasingly risky places that face flood and fire risk.

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