Flooded House or Underwater Mortgage? The Macrofinancial Implications of Climate Change and Adaptation

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This version: December 29, 2024
First version: March 15, 2023.

Abstract

I study the macrofinancial implications of climate change on housing markets and private adaptation efforts. Households are exposed to extreme weather events, which damage housing and degrade land which is in inelastic supply. While the exposure to climate risk weakens demand for housing, I show that the materialization of climate change raises house prices, as habitat becomes increasingly scarcer. This leads to a reallocation of credit in the economy towards households. In frictionless markets, price signals lead to efficient adaptation. However, credit-constrained households have weaker incentives to adapt to climate change, indicating that pricing alone may be insufficient. Unequal adaptation reinforces wealth inequality and leads to a further reduction in future habitat. Since this increases the importance of housing relative to future consumption, the private adaptation gap widens over time. I show that a societal shift from constrained homeownership to a rental model with unconstrained owners could lead to more efficient adaptation.

Keywords — Climate Change, Adaptation, Housing, Financial Assets, Financial Constraints, Extreme Weather Events, Wealth Inequality.

JEL codes — E44, G51, Q54.

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I. Introduction

The urgency of climate change adaptation is becoming increasingly evident as climatic impacts intensify across the globe, and mitigation efforts remain inadequate in preventing temperatures from rising by more than 1.5 degree Celsius (UNEP, 2023). This raises the question how to address rising physical climate risks. While mitigation efforts seek to prevent further climate change by limiting global emissions, adaptation measures are implemented to reduce our vulnerability to existing climate impacts, moderating potential economic losses and damages (IPCC, 2021). A growing macro-literature studies adaptation to climate change and its macroeconomic effects (see e.g. Burke et al., 2024; Bilal and Rossi-Hansberg, 2023; Hong et al., 2023; Fried, 2022), yet the role of finance remains underexplored. Physical climate risks may lead to significant economic losses (see e.g. Barrage and Nordhaus, 2024; Bilal and Känzig, 2024), but also have a direct impact on real estate markets. A substantial finance literature investigates whether these risks are priced into house values and factored into lending and insurance decisions (see e.g. Bernstein et al., 2019; Baldauf et al., 2020; Bakkensen and Barrage, 2021; Sastry, 2022; Ge et al., 2022). However, it remains unclear how these financial incentives shape private adaptation efforts.

In this paper, I study the broader macrofinancial implications of climate change and private adaptation. What is the direct effect of climate change on relative prices in housing and financial markets and credit allocation? Do households adapt efficiently given price signals? Are there indirect feedback effects, as financial constraints prevent the most vulnerable from reducing their exposure to climate risk, since income and wealth critically determine our ability to adapt? I take a long-term perspective and embed climate change in a general equilibrium framework with overlapping generations. In this economy, households have preferences over housing and a non-durable consumption good. Houses are traded across generations, with the young purchasing the the stock of houses from the old in each period. Housing is a risky investment, as the economy is exposed to physical climate risks from extreme weather events (e.g., floods, wildfires, hurricanes) or gradual changes like sea-level rise. Extreme weather events occur in each period and with a certain probability households suffer losses, indicating that all risk is idiosyncratic of nature. Climate impacts may not only destroy part of the housing stock but also degrade land, reducing its usability and long-term value (IPCC, 2019).[1] Since land is in inelastic supply due to geographic constraints (Saiz, 2010), this degradation renders habitable land increasingly scarce. Since houses are traded across generations, house prices are forward-looking and account for climate risks and damages. Climate change has two opposing effects on house prices. The exposure to climate risk weakens demand for housing, as future damages lower the expected resale value of housing. As a result, the future resale value of the house is discounted for the exposure to climate risk, which lowers house prices (see e.g., Bernstein et al., 2019; Bosker et al., 2019; Baldauf et al., 2020). However, due to the degradation of land, habitable land becomes increasingly scarcer. This leads to an endogenous reduction in the supply of inhabitable houses over time, which puts upwards pressure on house prices. If households are sufficiently risk-averse in their housing

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[1] This degradation includes increased soil salinity, erosion due to reduced canopy and weakened roots, and flooding, which can render previously habitable land unsuitable for development.

consumption, this scarcity effect dominates, causing house prices to rise in the long run.

I introduce private adaptation to climate change by allowing households to invest in self-protective measures that reduce their vulnerability to extreme weather events. There is a growing need for private adaptation, as individuals typically have a better understanding of the unique risks and vulnerabilities they face. Private adaptation measures can thus be tailored to meet the specific needs of individuals, which may not be adequately addressed by public policies. Private adaptation measures, such as storm-proof windows, or flood-proof floors, do not alter the probability of extreme weather events or the progression of climate risk, but reduce the idiosyncratic losses households suffer due to an extreme weather event. Hence, private adaptation investments directly affect the speed at which the housing supply shrinks.[2]

Adaptation investments are costly, however, and households trade off the present costs and future benefits of adaptation in the form of avoided climate change damage. The private adaptation choice increases in the economy's climate risk exposure, as households face higher expected damages. It also rises with house prices, since these reflect the value at risk to households. Since house prices are forward-looking, they prompt households to internalize the benefits of their adaptation investments for future generations. This prevents a "tragedy of the horizon" effect (Carney, 2015), and leads to efficient private adaptation in frictionless markets. However, price signals can only guide households to invest optimally in adaptation if climate risk is accurately capitalized into house prices.[3] Therefore, accurate climate risk pricing in housing markets is essential for incentivizing optimal adaptation. Moreover, the private optimum only coincides with the social optimum in the case in which the welfare of future generations is evaluated using markets discount rates. If greater social weight was placed on the welfare of future generations, house prices would fail to reflect the value of adaptation to future generations and households underinvest in adaptation from a social perspective. While determining the appropriate discount rate for mitigation efforts can be complex, a key implication is that using the market discount rate to evaluate the impact of private adaptation investments may serve as a useful starting point. This is because private adaptation measures protect households' assets, which are traded goods. Consequently, adaptation holds direct material value for households, and market incentives may guide effective decision-making.

In times of rising wealth inequality (Saez and Zucman, 2016; Zucman, 2019; Blanchet and Martínez-Toledano, 2023), it is essential to understand the heterogeneity in households' ability to respond to rising climate risk. The incentives for low-income households to adapt to climate change critically depend on their access to finance. Housing is pledged as collateral under the mortgage contract, but its liquidation value is affected by climate change. Borrowers can mitigate the losses by adapting to climate change, thereby protecting the liquidation value of the collateral. However, their adaptation investment is non-verifiable to mortgage creditors. Mortgage creditors thus form expectations about the private choice of adaptation of their borrowers and should rationally not allow the size of household debt to exceed the

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[2] While I focus on private adaptation by households to protect the housing stock, the model set-up is general, and can therefore be interpreted more broadly to reflect adaptation by farmers to prevent a loss in the productivity of their agricultural land, or investments in public adaptation infrastructure by local municipalities.

[3] If climate risk is mispriced — due to heterogeneity in beliefs about climate change (see e.g., Bakkensen and Barrage, 2021; Baldauf et al., 2020) or limited buyer sophistication (see e.g., Bernstein et al., 2019) — households underinvest in adaptation and remain vulnerable to climate impacts.

expected liquidation value of collateral (Kiyotaki and Moore, 1997; Sastry, 2022).

When credit constraints bind, those most vulnerable to climate risk are discouraged from investing optimally in adaptation. Constrained households become more short-sighted in their consumption choices, spending a larger share of their resources on housing. This is because households derive utility from housing in the present, while adaptation investments only benefits them in the future, when the extreme weather event occurs. As a result, credit constrained households end up protecting a smaller fraction of their housing wealth. This has redistributive implications, since credit constrained households face a disproportionately large reduction in their housing wealth once the extreme weather event occurs. The underinvestment also leads to a further reduction in the supply of housing, leaving future generations with less housing and therefore lower welfare. The private adaptation gap widens as the reduction in habitat increases the importance of housing relative to future consumption. This weakens the incentives of constrained households to invest in resilience even further. Credit constraints present a significant challenge to effective climate adaptation (IPCC, 2023; Havlinova et al., 2022), necessitating targeted policies to address the differential impacts of climate change. One such policy is to encourage credit-constrained households to rent rather than buy. I show that a societal shift from constrained homeownership to a rental model with unconstrained owners leads to more efficient adaptation when rental markets are perfectly competitive. In perfectly competitive rental markets, rental prices adjust for any house price appreciation and for the adaptation efforts undertaken by the landlord, since preventive measures increase the revenue from reselling housing in the future. As a result, price signals provide landlords, who have deep enough pockets, with the incentives to optimally invest in adaptation.

I introduce firms in the general equilibrium framework. Firms are established in each period by some households with entrepreneurial talent and operate for a single period. The firms produce the non-durable consumption good, using physical and intangible capital, alongside labour supplied by households. Households work in the firm when they are young and differ in terms of their skills, which are exogenously given. High-skilled workers are complementary to intangible capital, whereas low-skilled workers are complementary to physical capital (Krusell et al., 2000; Goldin and Katz, 2009; Eisfeldt et al., 2023). Extreme weather events damage the firms' physical capital (Bilal and Känzig, 2024; Acharya et al., 2022), leading to a capital loss that reduces output. This lowers the wages of both high- and low-skilled workers. However, the loss of physical capital has a direct, negative impact on the productivity of low-skilled workers. Moreover, firms scale back their investments in physical capital to a greater extent due to their exposure to climate risk. This leads to a larger decline in the wages of low-skilled workers than those of high-skilled workers, increasing wage inequality. Climate-related damages also affect the cost of capital, which is determined by the return on physical capital. Since climatic impacts destroy savings, capital becomes more scarce in the economy. This raises the cost of capital, which has redistributive implications. Specifically, as the cost of capital rises, households with positive savings accumulate wealth at a faster rate. In contrast, households with a mortgage face an increase in the costs of servicing their mortgage contract. This underscores the redistributive implications of climate change, even in the absence of binding financial constraints.

I provide a model extension in which I introduce an insurance market. Adaptation fundamentally differs from insurance, since adaptation aims at prevention, whereas insurance offers monetary compensation after losses occur. Hence, insurance does not moderate the decline in the supply of inhabitable houses. Rather, I show that insurance leads to moral hazard in adaptation (Fried, 2022). This is because insurance limits the downside from a disaster in a way which is relatively cheaper than investing in adaptation, thus reducing households' willingness to undertake those investments. The insurance choice affects the price of the insured good. In particular, the moral hazard in adaptation accelerates the reduction in the supply of houses, leading to a more rapid increase in house prices. This indicates that the choice of insurance is not separable from the portfolio decisions (Mayers and Smith Jr, 1983). While this home equity effect provides a countervailing force, by increasing the value at risk to households, it never dominates in equilibrium since the elasticity of prices with respect to the insurance coverage is less than unity. Consequently, private insurance leads to an underprovision of private adaptation. Since the underprovision of private adaptation leads to a further reduction in the supply of houses, this increases inequality across generations. However, a trade-off emerges since a higher insurance coverage reduces the rate at which wealth inequality rises within a given generation, due to the monetary compensation provided to compensate damages. This underscores the relevance of considering distributional consequences in designing effective climate insurance schemes.

Roadmap The remainder of this paper is structured as follows. I discuss the related literature in Section II. In Section III, I introduce the baseline framework with housing and climate risk. The conditions relevant for the definition of an equilibrium are derived in Section IV. In Section V, I introduce firms in the general equilibrium framework and solve for the general equilibrium in Section VI. Section VII provides a quantitative assessment of the evolution of the equilibrium over time. In Section VIII, I provide a number of model extensions and Section IX provides suggestive empirical evidence on the. Section X concludes.

II. Related literature

This paper relates broadly to the literature studying the effects of climate change. This literature can be divided into a stream focusing on quantifying the effect of a rise in temperatures on productivity, for example in agriculture, labour productivity or GDP growth more broadly (see e.g. Nordhaus, 1992, 1977; Mendelsohn et al., 1994; Deschênes and Greenstone, 2007; Schlenker and Roberts, 2009; Dell et al., 2012; Golosov et al., 2014; Burke et al., 2015; Barrage and Nordhaus, 2024; Cruz and Rossi-Hansberg, 2024; Bilal and Känzig, 2024) and a stream of literature studying the effect of sea level rise on real estate markets, which encompasses the pricing of physical climate risk in housing markets, and the effects of physical climate risk on mortgage - and insurance markets.

This paper contributes to this latter stream, particularly to the literature studying the pricing of physical climate risk in housing markets. These papers study empirically whether sea level rise risk is capitalized into housing markets in coastal areas. The majority of papers find evidence of a positive

’sea level rise discount’, indicating that houses exposed to sea level rise risk trade at a lower price in the market (see e.g., Harrison et al., 2001; Bin et al., 2008; Keenan et al., 2018; Gibson et al., 2017; Bosker et al., 2019; Bernstein et al., 2019; Hino and Burke, 2020; Keys and Mulder, 2020; Baldauf et al., 2020; Giglio et al., 2021; Bakkensen and Barrage, 2021). This literature finds that factors as - amongst others - buyers’ sophistication (Bernstein et al., 2019) and (heterogeneity in) climate change beliefs can explain (Baldauf et al., 2020; Murfin and Spiegel, 2020; Bakkensen and Barrage, 2021) variation in the sea level rise discount.Consistent with the aforementioned research, I show that demand for houses exposed to future climate risk is lower, which puts downwards pressure on current house prices. However, I demonstrate that the materialization of climate-related damages reduces the supply of habitable houses. I derive the conditions under which this scarcity effect dominates in the general equilibrium, showing that this is the case when households are sufficiently risk-averse with respect to their housing consumption.

The evolution of house prices matters for mortgage market dynamics. Hence, there is a growing literature studing the effect of physical climate risk on mortgage markets. Issler et al. (2019) show that mortgage delinquency and foreclosure rates significantly increase after a wildfire. Bakkensen et al. (2022) find that homeowners with a larger exposure to SLR-risk are more likely to be leveraged due to heterogeneity in beliefs about climate risk. Bakkensen et al. (2022) further find that the underlying mortgage contracts have a longer maturity, and climate change pessimists are more likely to trade their climate risk exposure with banks via long-term debt contracts. Ouazad and Kahn (2022) show that mortgage originators are more likely to approve mortgages that can be securitized after the occurrence of a natural disaster. The authors show that natural disasters lead to more securitization right below the conforming loan limit, suggesting that mortgage originators transfer climate risk rather than screening for them. Building on this insight, Kahn et al. (2024) show that financial institutions may adapt to rising climate risk by transferring such risk to securitizers that have the skill and expertise to build diversified pools. Sastry (2022) shows that mortgage originators further offload flood risk to the government through flood insurance contracts, and to under-insured households through higher down payments. This indicates that mortgage originators only screen for flood risk when they retain residual exposures to it. Building on this latter result, I consider endogenous credit constraints in my theoretical framework. Specifically, mortgage originators take into consideration the exposure to climate risk, as this reduces the expected liquidation value of collateral pledged to the mortgage contract (cf. Kiyotaki and Moore, 1997). While this reduces financial risks, I show that such credit constraints fundamentally hinder homeowners from optimally investing in adaptation, as this is private information.

As physical climate risk rises, so do the costs of insuring oneself against these risks. Keys and Mulder (2024) document that insurance premia have risen sharply due to an increase in local disaster risk and the pass-through of reinsurance costs. Ge et al. (2022) show that higher insurance premia reduce transaction prices, with the effect being strongest for homes exposed to long-term sea level rise. Ge et al. (2022) suggest that insurance pricing can accelerate the incorporation of climate risk into asset markets. Boomhower et al. (2024) document that high exposure to wildfire risk not only leads to higher prices, but also to limited participation in insurance markets. Sastry et al. (2023) also find that traditional insurers increasingly exit the Florida-market. Importantly, Sastry et al. (2023) find that lower quality insurers enter the market to fill this gap. Mortgage lenders respond to the decline in insurance quality by selling a large portion of exposed loans to government sponsored enterprises, who bear an increasing share of insurance counterparty risk. While it is essential to ensure that premia accurately reflect climate risk exposures, I show that climate risk insurance leads to moral hazard in adaptation, even if premia reflect the accurate climate risk exposure. This is because insurance limits the downside from a disaster in a way which is relatively cheaper than investing in adaptation, reducing households' willingness to undertake those investments.[4]

It is essential to consider adaptation when quantifying climate-related losses and their impact. Hence, a growing macro-literature studies adaptation to climate change. Bradt and Aldy (2023) and Hsiao (2023) focus on public adaptation. Bradt and Aldy (2023) estimate the magnitude and distribution of benefits from public adaptation infrastructure. Hsiao (2023) shows that public adaptation intervention hinders long-run resilience against flood risk by creating coastal moral hazard, which leads to lock-in and delays inland migration. Since public adaptation relies on collective efforts which require political support, and individuals typically have a better understanding of the unique risks and vulnerabilities they face, there is a growing need for private adaptation. Specifically, private adaptation measures can be tailored to meet the specific needs of individuals, which may not be adequately addressed by public policies. Fried (2022) develops a macro heterogeneous-agent model to quantify the interactions between adaptation, federal disaster policy, and climate change. Fried (2022) shows that moral hazard effects from disaster aid reduce adaptation in the U.S. economy, but federal subsidies for investment in adaptation more than correct for the moral hazard. Hong et al. (2023) analyze how private and public sectors should adapt to manage disaster risks to the capital stock when they learn about the adverse consequences of global warming for disaster arrivals. Hong et al. (2023) highlight that adaptation is more valuable under learning. In a similar spirit, Balboni et al. (2023) show that climate change impacts will be moderated as flood-affected firms in Pakistan learn from the experience of increasingly frequent disasters and increasingly relocate to safer areas.[5] However, Albert et al. (2021) show that spatial capital and labour market frictions constrain the reallocation process of capital and labour from agriculture to manufacturing in Brazil.

This paper contributes to the literature on climate change adaptation by taking into consideration the role of financial markets in driving private adaptation decisions. I show that the capitalization of climate risk in house prices influences the incentives of households to adapt to climate change. Specifically, in frictionless markets, price signals lead to efficient adaptation, as household internalize the effect of their adaptation investments on future generations. However, I show that pricing may not always be sufficient. Specifically, credit-constrained households have weaker incentives to adapt to climate change as they become more short-sighted in their consumption choices. This aligns with the findings of Rampini and

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[4] This is consistent with the findings of Fried (2022), who focuses on the effect of disaster relief policies on adaptation.

[5] I abstract from not migration as adaptation mechanism in this paper. Cruz and Rossi-Hansberg (2024); Bilal and Rossi-Hansberg (2023); Desmet and Rossi-Hansberg (2015); Muis et al. (2015) the adaptation incentives in dynamic spatial models. For example, Cruz and Rossi-Hansberg (2024) examine responses to local temperature changes through costly trade, migration, and technological innovations, while Bilal and Rossi-Hansberg (2023) focus on migration and capital investment decisions. These papers highlight that migration may reduce substantially the welfare impact of climate change.

Viswanathan (2013); Rampini (2019), who show that firms facing financing constraints are less likely to invest in durable assets. I highlight that credit constraints lead to a dynamic feedback effect in the context of climate change adaptation. Specifically, credit constraint households remain more exposed to climate risks as they underadapt. This reinforces wealth inequality and leads to a further reduction in future habitat. As habitat becomes increasingly scarcer in supply, housing becomes relatively more important relative to future consumption . This leads to a widening of the private adaptation gap over time. I propose that a societal shift from constrained homeownership to a rental model with unconstrained owners could overcome the dynamic underinvestment problem and lead to more efficient adaptation.

Finally, this paper relates to the literature studying the effects to climate change policies on inequality. Känzig (2023) shows that a carbon taxes disproportionately affects the poor, as these households have a high energy share within their consumption bundle, and tend to work in sectors which are more impacted by carbon pricing policies. Pedroni et al. (2022), Belfiori and Macera (2024) and Belfiori et al. (2024) study how inequality can be optimally accounted for in climate mitigation policies.

III. A Simple Framework of Housing and Climate Risk

Time is discrete and denoted by $t \in \{0, 1, ..., \infty\}$. The economy is characterized by two overlapping generations, each consisting of a unit mass of households. Households derive utility from consuming housing and a non-durable consumption good, which is in infinite supply (in Section VI, I introduce firms which produce this good). At the start of each period, an extreme weather event occurs. This extreme weather event hits a fraction of households, damaging their housing capital. All risk is idiosyncratic, and the economy's climate risk exposure rises deterministically over time.

A. Households

Households live for two periods. When young, households purchase housing capital, denoted by L, from the old generation at a relative price p (the price of the consumption good is normalized to 1).[6] Additionally, young households hold financial assets, and can invest in mortgage debt. Once old, households channel their savings, which consist of the proceeds from selling their house, as well as the return earned on their savings, to the purchase of the non-durable consumption good, denoted by c. There is an initial generation at $t = 0$, which is endowed with the supply of houses, $\bar{L}_0$.

*A.*1 Preferences

Households have preferences over housing and the non-durable consumption good, which are given by the following quasi-linear utility function

$$U\left(c_{i,t+1}, L_{i,t}\right) = c_{i,t+1} + v\left(L_{i,t}\right)$$

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[6] While I focus on owner-occupied housing, the model implicitly embeds a rental market. When the rental market is perfectly competitive, households are indifferent between renting and buying housing. I exploit this feature in Section V.D.3.

$v(L_{i,t})$ captures the utility that household i obtains in period t from owning $L_{i,t}$ housing capital. I assume that $v'(\cdot) > 0, v''(\cdot) < 0$. Households maximize expected lifetime utility.

A.2 Skills and Wages

Households have heterogeneous (and exogenous) skills, which determine household income. There are two skill levels. I denote high skills and income by h and low skills and income by l. A fraction ϕ of households is high-skilled, and is endowed with $\bar{h}$ high-skilled labour. The remaining households are low-skilled, denoted by l, and are endowed with $\bar{l}$ manual labour.
Young workers supply labour to the firm and earn an income of $y_{i,t} = \{q_t\bar{h}, w_t\bar{l}\}$, where q_t (w_t) denotes the high-skilled (low-skilled) wage per unit of labour.

B. Climate Risk and Housing Capital

The economy is exposed to climate risk and an extreme weather event occurs in each period. Let $\gamma_{t+1} \in [0,1]$ denote the probability that a given household is hit by an extreme weather event in period, $t+1$. This probability is common among households and increases deterministically over time. By the law of large numbers, γ_{t+1} corresponds to the fraction of households that suffer climate-related damages in any period $t+1$. I follow Fried (2022) by modeling idiosyncratic climate damages. Denote by $\xi_{i,t+1} \in [0,1]$ the idiosyncratic losses of a given household, i, in period, $t+1$. These losses follow some distribution, $F(\xi_{i,t+1})$, which is i.i.d. across households. This reflects that extreme weather events may hit certain households harder than others. However, as idiosyncratic risk can be diversified, the expectation of the losses matters for pricing. Denote by $\mu_L \in [0,1]$ the expected loss, as a fraction of housing capital, conditional on being hit by the extreme weather event. The expected idiosyncratic losses are given by:

$$\begin{aligned}\mathbb{E}(\xi_{i,t+1}) &= \mathbb{E}\left(\xi_{i,t+1}\middle|\text{Hit by Extreme weather event}\right)\cdot\mathbb{P}(\text{Hit by Extreme weather event})\\ &= \mu_L\gamma_{t+1}\end{aligned}$$

Climate-related damages reduce the amount of housing that can be resold after the extreme weather event. For a given household i, the housing capital remaining in period $t+1$ is given by:

$$L_{i,t+1} = (1-\xi_{i,t+1})\,L_{i,t}$$

Extreme weather events not only destroy part of the housing stock, but also degrade land, reducing its usability and long-term value (IPCC, 2019). Such degradation includes increased soil salinity, erosion due to reduced canopy and weakened roots, and flooding, which can render previously habitable land unsuitable for development. Denote the supply of houses (i.e., livable land, cf. Burzyński et al. (2019)) in a given period by $\bar{L}_t$, which is inelastic due to geographic constraints (Saiz, 2010).[7] As a result of land

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[7] For example, Saiz (2010) shows that the fraction of undevelopable land is particularly high in coastal cities, such as Miami, San Francisco, and New Orleans.

degradation, the supply of houses evolves dynamically over time and follows the law of motion:

$$\begin{aligned}\bar{L}_{t+1} &= \int_0^1 (1-\xi_{i,t+1})\, di \cdot \bar{L}_t \\ &\overset{\text{LLN}}{=} (1-\mu_L \gamma_{t+1}) \cdot \bar{L}_t\end{aligned}$$

Hence, by the law of large numbers, the supply of inhabitable houses falls in each period $t+1$ by a fraction $\mu_L \gamma_{t+1}$.[8]

C. *Housing Market Dynamics and Financial Markets*

There is one housing market on which all home purchases and sales take place. The market opens after the extreme weather takes place, which occurs at the start of the period. Define $S_{i,t}$ as the net savings of a young household, i in period t, after the purchase of housing capital:

$$S_{i,t} = y_{i,t} - p_t L_{i,t}$$

This can be positive or negative, depending on whether a given household i is a net lender or borrower:

$$S_{i,t} \begin{cases} \geq 0 & \text{net lender} \\ < 0 & \text{net borrower} \end{cases}$$

Households earn a rate of return of r on their savings, which is exogenously given. Households may lend to other households that needs to finance the purchase of their housing capital. Lending takes place against collateral, and the housing capital purchased that backs the mortgage contract. However, destroyed housing capital has zero liquidation value, indicating that borrowers risk default. Therefore, borrowers hence pay the risky rate of return, $\hat{r}_{t+1} > r$.

Default occurs when that mortgage is “under water”. That is, when the revenue from selling the undamaged housing capital is smaller than the value of the amount borrowed (including interest):

$$p_{t+1} L_{i,t+1} \leq (1+\hat{r}_{t+1})(-S_{i,t})$$

Define the loan-to-value ratio as

$$LTV_{i,t+1} = \frac{(1+\hat{r}_{t+1})(-S_{i,t})}{p_{t+1} L_{i,t}}$$

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[8] The supply of livable land remains constant over time in the absence of climate risk. Hence, it is the residual change in the supply of houses attributable to climate change which I model.

The condition implicitly defines a threshold on the climate damages above which a homeowner defaults:

$$\hat{\xi}_{i,t+1} = 1 - LTV_{i,t+1}$$

Accordingly, the probability of default is given by

$$\chi_{i,t} = \mathbb{P}\left(\xi_{i,t+1} \geq \hat{\xi}_{i,t+1}\right) = \left(1 - F\left(\hat{\xi}_{i,t+1}\right)\right)$$

IV. Equilibrium

A. Household Optimization Problem

Households maximize utility subject to the budget constraint and a limited liability constraint:

$$\begin{aligned} \max_{c_{i,t+1}, L_{i,t}, S_{i,t}} \quad & \mathbb{E}\left(U(c_{i,t+1}, L_{i,t})\right) = \mathbb{E}_t\left(c_{i,t+1}\right) + v\left(L_{i,t}\right) \\ s.t. \quad y_i &\leq p_t L_{i,t} + S_{i,t} \\ c_{i,t+1} &\leq \max\{p_{t+1}(1 - \xi_{i,t+1})L_{i,t} + (1 + \hat{r}_{t+1})S_{i,t}, 0\} \\ c_{i,t+1}, L_{i,t} &\geq 0. \end{aligned}$$

where $\mathbb{E}_t$ denotes expectations formed at date t.

*A.1 Optimal Demand for Housing Capital

The optimal demand for housing capital in a given period t determines its price:

Lemma IV.1. *The demand for housing capital of each household i in period t is given by*

$$L_t^* = v'^{-1}\left((1 + r)p_t - \left(1 - \mu_L \gamma_{t+1}\right)p_{t+1}\right)$$

Accordingly, the price of housing capital in a given period, t, becomes

$$p_t = \frac{(1 - \mu_L \gamma_{t+1})p_{t+1} + v'\left(L_t^*\right)}{(1 + r)}$$

This is a standard asset pricing equation, indicating that the price of housing capital today is equal to the discounted value of the benefits from owning housing. The benefits of owning housing consist of two parts. First, there are marginal benefit to owning housing capital, which is captured by $v'\left(L_t^*\right)$ (the 'dividend'). Second, the owner reaps the revenue from selling the undamaged housing capital at the start of the next period (the 'resale value'). The revenue per unit of housing capital owned is given by the future house price, p_{t+1}, which is discounted for the fraction of expected damages. As a result, demand for housing weakens and current house prices are thus discounted for the exposure to future climate risk (e.g., Bernstein et al., 2019; Baldauf et al., 2020; Bosker et al., 2019). Hence, house prices decline in *future* climate risk, γ_{t+1}.

A.2 Demand for Household Debt

Household debt follows residually. Households with net savings lend to others households while households with negative savings take out a mortgage.

B. Equilibrium and Market Clearing

A competitive equilibrium is an allocation $\{c_{t+1}, L_t, S_t\}_{t=0}^{T}$ and prices $\{p_t\}_{t=0}^{T}$, such that in each period, t, given prices, households maximize lifetime utility and all markets clear.

Housing market Total housing demand equals total housing supply, so that $\int_0^1 L_{i,t}^{*} di = \bar{L}_t$. Therefore, housing market equilibrium requires

$$\bar{L}_{t+1} = (1 - \mu\gamma_{t+1})\, \bar{L}_t.$$

The housing market clearing condition pins down the equilibrium price of housing capital:

$$p_t^{*} = \frac{(1 - \mu_L\gamma_{t+1})\, p_{t+1} + v'\left(\bar{L}_t\right)}{1 + r}$$

Forward substitution gives

$$p_t^{*} = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left[v'\left(\bar{L}_j\right)\right] \prod_{\iota=t}^{j-1} (1 - \mu_L\gamma_{\iota+1})$$

Hence, as the housing stock is traded across generations, and households have perfect foresight, house prices become forward-looking. The expression reveals that climate change influences house prices through an additional channel, which is the rising scarcity of housing. Households are risk averse with respect to housing consumption - which is considered a relatively more essential good than their non-durable consumption. This risk aversion is reflected by the concavity of $v(L)$ in housing, L. When the supply of housing decreases due to climate-related damages, the remaining housing supply becomes scarcer. This increases the value households place on the housing they own, as reflected by a rise in the marginal utility of owning housing. A higher marginal utility of owning housing raises the willingness to pay, thus driving up house prices. Hence, while houses exposed to climate *risk* face a price discount in the market, climate-related *damages* (i.e., the materialization of climate risk) drive up contemporaneous house prices.

Proposition 1. *Let climate risk increase in all future periods by a factor $\sigma > 1$ (i.e., future climate risk* *is given by* $\{\sigma\gamma_{t+1}, ..., \sigma\gamma_{\infty}\}$*). The price of housing capital rises in* σ *if*

$$\underbrace{-\frac{v''(\bar{L}_j)\cdot \bar{L}_j}{v'(\bar{L}_j)}}_{RRA} \geq 1 \tag{1}$$

Proof: See Appendix A.1

If households are sufficiently risk-averse with respect to their consumption of housing - that is, households are more risk-averse with respect to their housing consumption than their consumption of the non-durable consumption good -, the scarcity effect dominates in the general equilibrium.[9] This leads to a rise in house prices in the long run. While the initial loss of habitable land has a negligible effect on the utility households derive from owning housing, the ensuing reduction in the housing supply significantly increases the marginal utility of owning housing. As a result, the rise in house prices becomes stronger over time.

The two opposing effects on house prices can be interpreted intuitively in the context of geographical variation. For the sake of the argument, suppose there are two different types of housing stocks in the given region. That is, a fraction $f(\gamma_t)$ of all houses are located on high elevation (e.g., on a hill) and the expected loss conditional on being hit for these houses is given by $\underline{\mu_L}$. The remaining houses are located on low elevation (e.g., at the waterfront) and the expected loss conditional on being hit for these houses is given by $\bar{\mu_L}$, with $1 > \bar{\mu_L} > \underline{\mu_L} > 0$.

If the risk exposure is common across houses in the region and housing markets are unsegmented, house prices adjust in equilibrium to ensure that households are indifferent between purchasing housing in the region with a high or low risk exposure. Then, house prices in each respective region are given by

$$p_t^{low} = \frac{\left(1 - \underline{\mu}\gamma_{t+1}\right) p_{t+1} + v'(\bar{L}_t)}{(1+r)}$$
$$p_t^{high} = \frac{\left(1 - \bar{\mu}\gamma_{t+1}\right) p_{t+1} + v'(\bar{L}_t)}{(1+r)}$$

The differences in risk exposure results in implicit price segmentation, since houses with a higher risk exposure trade at lower prices than houses with a lower risk exposure. Intuitively, this implies that houses on higher elevation are a hedge against houses on lower elevation. In aggregate, house prices are given by

$$p_t = f(\gamma_t)\cdot p_t^{low} + (1 - f(\gamma_t))\cdot p_t^{high}$$

The supply of housing decreases faster in the region with a high climate risk exposure. Over time, this changes the composition of the housing stock in the region, as houses with a lower risk exposure have a higher likelihood to remain. As inhabitable land becomes increasingly scarce in the high-risk region, this

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[9] I provide suggestive evidence in the short-run that illustrates the mechanism of the theory model by leveraging data on house values at the ZIP-code level from Zillow and exploiting plausibly exogenous variation in house values in the Boulder-Colorado area after the Marshall Fires of December 2021. More details are provided in Appendix B.1.

shifts housing demand to the region with a lower risk exposure, pushing up prices for low-risk housing.

Corollary 1. *Within a region, houses on higher elevation trade at higher prices than those on lower elevation. Over time, aggregate house prices rise.*

In the remainder of this analysis, I focus on one type of housing stock within the given region.

Financial market Aggregate income of young households must in equilibrium equal the aggregate investment in housing. Hence,

$$\int_0^1 y_i di = p_t \bar{L}_t,$$

where the aggregate labour income of the young is:

$$\int_0^1 y_i di = \phi q + (1 - \phi) w.$$

In equilibrium, the total savings of labour income must be large enough to cover the purchase of the stock of houses. This indicates that at least one type of households must have positive savings. Since high-skilled households earn higher wages, these households are net lenders. Low-skilled are either net lenders or net borrowers and the volume of mortgage credit in the economy, m, is given by

$$m_t = \max \left\{ 0, (1 - \phi) \left(p_t \bar{L}_t - w \right) \right\}$$

i.e., the size of mortgage credit in the economy is equal to the value of the housing stock owned by low-skilled households, net of their income.

Corollary 2. *The volume of credit rises in climate risk.*

V. Adapting to Climate Change

In this Section, I introduce private adaptation to climate change, allowing households to invest in self-protective measures that increase their resilience and reduce vulnerability to extreme weather events. Private adaptation measures, such as storm-proof windows, flood-proof floors, or the fortification of one's home do not alter the probability of extreme weather events in a given period (γ_t) or the progression of climate risk ($\gamma_{t+1}, ..., \gamma_\infty$). Rather, by investing in adaptation, households reduce the idiosyncratic losses they suffer due to the extreme weather event. As a result, household's private adaptation measures directly influence the rate at which inhabitable land degradates, and thus the speed at which the housing supply shrinks.

A. Climate Change Adaptation

Households invest in climate change adaptation at the time they purchase housing capital. Denote by $x_{i,t} \in [0,1)$ the choice of adaptation of household i in period t. This investment comes at a cost. Specifically, the investment costs are given by $\psi(x_{i,t}, L_{i,t}) = \frac{1}{2}L_{i,t}(x_{i,t})^2$. The costs increase with the amount of housing capital, as larger houses require more significant investments, such as a greater number of storm-proof windows, to achieve the same level of protection (Fried, 2022). Moreover, the investment rise at an accelerating rate in the choice of adaptation, indicating that even the most ambitious investments cannot entirely prevent climate-related losses and damages (UNEP, 2022).

By adapting to climate change, households protect themselves against climate-related damages from extreme weather events in the next period. Let the choice of adaptation, $x_{i,t}$, represent the fraction of idiosyncratic losses which are prevented due to the investment in resilience. Adaptation thus leads to a leftward shift in the distribution of losses by $x_{i,t} \cdot \mu_L \gamma_{t+1}$. In expectation, the losses suffered by a given household, $\xi_{i,t+1}$, are given by:

$$\mathbb{E}\left(\xi_{i,t+1}\right) = \left(1 - x_{i,t}\right)\mu_L \gamma_{t+1}$$

A household with $x_{i,t} = 0$ does not undertake any measures to reduce idiosyncratic losses, while $x_{i,t} \to 1$ indicates that the household has perfectly adapted to climate change and has nearly eliminated all expected losses. Define x_t as the aggregate private investment in adaptation, i.e.

$$x_t = \int_0^1 x_{i,t} di$$

By its virtue of preserving housing capital, climate change adaptation reduces the rate at which the supply of inhabitable houses declines. More specifically, when households adapt to climate change, the supply of inhabitable houses evolves according to the following law of motion:

$$\begin{aligned} \bar{L}_{t+1} &= \int_0^1 \left(1 - \xi_{i,t}\right) di \cdot L_t \\ &\overset{\text{LLN}}{=} \left(1 - (1 - x_t)\mu_L \gamma_{t+1}\right) \bar{L}_t \end{aligned}$$

The investment in adaptation in period t prevents some of the reduction in the housing supply in the subsequent period, $t+1$. Therefore, adaptation constitutes an intertemporal investment, leaving the current housing supply, $\bar{L}_t$, unaffected. Consequently, adaptation does not increase the utility of owning housing capital, $v(L)$. Instead, by reducing the damage to housing, adaptation ensures that more of the housing stock stays intact and can be resold in the next period. This gives older households more resources to spend on non-durable goods. Adaptation also benefits future generations. By protecting the housing stock, it ensures that more houses remain available for them to live in and derive utility from. In this way, adaptation helps both current and future households by preserving economic resources and housing availability.

Note on Insurance Markets Investing in adaptation fundamentally differs from purchasing insurance, since adaptation aims at prevention, whereas insurance offers monetary compensation after losses occur. While purchasing insurance is an effective measure to reduces the impact of climate risk on household wealth, the ex-post compensation provided cannot alleviate the reduction in the supply of inhabitable houses. Demand for insurance is not separable from households' portfolio decision, however, as climate-related damages directly affect the value of the insured good (Mayers and Smith Jr, 1983). Hence, climate risk insurance affects the private choice of adaptation in the general equilibrium. I explore this in more detail in a model extension, in Section VIII.A.

B. *Unconstrained Private Choice of Adaptation*

*B.*1 Household Optimization Problem

When households adapt to climate change, the household maximization problem is given by

$$\begin{aligned} \max_{c_{i,t+1}, L_{i,t}, S_{i,t}, x_{i,t}} \quad & \mathbb{E}\left(U(c_{i,t+1}, L_{i,t})\right) = \mathbb{E}_t\left(c_{i,t+1}\right) + v\left(L_{i,t}\right) \\ s.t. \quad & y_i \leq \left(p_t + \frac{1}{2} x_{i,t}^2\right) L_{i,t} + S_{i,t} \\ & c_{i,t+1} \leq \max\left\{p_{t+1}\left(1 - \xi_{i,t+1}\right) L_{i,t} + \left(1 + \hat{r}_{t+1}\right) S_{i,t}, 0\right\} \\ & c_{i,t+1}, x_{i,t}, L_{i,t} \geq 0 \end{aligned}$$

where $\mathbb{E}_t$ denotes expectations formed at date t.

*B.*2 Optimal Demand for Housing and Adaptation

When households adaptation to climate change, this affects their demand for housing capital. First, by reducing vulnerability to climate risk, investments in adaptation ensure that a larger fraction of housing capital remains undamaged. This increases the per unit revenue of selling housing once households turns old, thus raising housing demand. However, the investment in adaptation absorbs part of households' savings, leaving less resources to be allocated to housing consumption.

Lemma V.1. *When households adapt to climate change, the demand for housing capital of a given household, i, in a given period, t, is given by*

$$L_t^* = v'^{-1}\left((1+r)\left(p_t + \frac{\theta}{2} x_{i,t}^{*2}\right) - \left(1 - (1 - x_{i,t}^*)\mu_L \gamma_{t+1}\right) p_{t+1}\right)$$

and the price of housing capital in a given period, t, is given by

$$p_t = \frac{\left(1 - (1 - x_{i,t}^*)\mu_L \gamma_{t+1}\right) p_{t+1} + v'(L_t^*)}{(1+r)} - \frac{\theta}{2} x_{i,t}^{*2}$$

The above expression indicates that the total amount spent per unit of housing capital, i.e., $p_t + \frac{\theta}{2}x_{i,t}^{*2}$, must equal the discounted value of the benefits from owning housing capital. This expression reveals the trade-off between the present costs and future benefits of adaptation, as adaptation requires an upfront investment cost while it only generates benefits to households once they sell their housing. This trade-off determines the private choice of adaptation in equilibrium, with households investing in adaptation as long as its marginal benefits outweigh its marginal cost.

Lemma V.2. *The optimal private choice of adaptation of a given household i is given by*

$$x_{i,t}^* = \frac{\mu_L \gamma_{t+1} \cdot p_{t+1}}{(1+r)}$$

The optimal private choice of adaptation increases in climate risk exposure (γ_{t+1}), as well as in the expected losses of housing capital when hit by an extreme weather event, μ_L, since both parameters increase the expected damages to the housing capital owned. Therefore, a rise in households' climate risk exposure strengthens their incentives to invest in adaptation over time.

The optimal private choice of adaptation is crucially influenced by house prices, as the house price reflects the value at risk from extreme weather events to households. Price signals, therefore, play a critical role in shaping private adaptation decisions, with significant implications. As discussed in Section IV.B., house prices are forward-looking. They not only reflect the reduction in households' climate risk exposure due to adaptation efforts but also incorporate the benefits adaptation provides for future generations. By investing in adaptation, households preserve more of the housing stock for the future, making housing less scarce over time. This reduced scarcity dampens the rise in the value households place on owning housing. Since these intergenerational benefits are capitalized into house prices, households—guided by price signals—effectively internalize the long-term benefits of their adaptation investments. Hence, price signals prevent the "tragedy of the horizon" effect, where short-term decision-making overlooks long-term climate risks and their impacts on future generations (Carney, 2015).

To illustrate this point, suppose that an unconstrained social planner maximizes utilitarian welfare , i.e.

$$\max_{x_{S,t}} \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t \left[-(1+r)\frac{1}{2}\bar{L}_t \cdot x_{S,t}^2 + v(\bar{L}_t)\right]$$

subject to

$$\bar{L}_j = \bar{L}_t \prod_{\iota=t}^{j-1} (1 - (1 - x_{S,\iota})\mu_L \gamma_{\iota+1})$$

This gives:

$$x_{S,t}^* = x_{i,t}^*$$

Proposition 2. *The optimal private choice of adaptation is efficient.*

Proof: See Appendix A.2

Households determine their private choice of adaptation based on market signals. Consequently, Proposition 2 is sensitive to two underlying assumptions. First, within this framework, climate risk is accurately capitalized into house prices. Although empirical studies show that climate risk is gradually being incorporated into house prices (see e.g., Baldauf et al., 2020; Bernstein et al., 2019; Bosker et al., 2019), it is crucial to assess whether prices in the housing market sufficiently reflect the actual climate risk exposure of a given region. If climate risk is not properly accounted for in market pricing — due to factors such as heterogeneity in beliefs about climate change (see e.g., Bakkensen and Barrage, 2021; Baldauf et al., 2020) or buyers' limited sophistication (see e.g., Bernstein et al., 2019) prices may fail to signal the risks faced by households. As a result, households would underinvest in adaptation, leaving them vulnerable to the impacts of climate change. The accurate pricing of climate risk in housing markets is therefore crucial to incentivize households to adapt optimally.

Second, Proposition 2 is highly sensitive to the choice of the social discount rate used to evaluate the welfare of future generations. If a social planner maximizes utilitarian welfare and weights the utility of different generations using market discount rates, the private optimum and social optimum coincide. However, if the social planner assigns a larger weight to the welfare of future generations (i.e., a discount rate lower than the market discount rate), the value of preserving an additional unit of housing would have a higher social value than market prices reflect. In this case, households would underinvest in adaptation from a social perspective.

Corollary 3. *If the social planner evaluates the welfare of future generations using a discount rate of* $r^{SP} \in [0,1]$ *with* $r^{SP} < r$*, unconstrained households* ***underinvest*** *in adaptation. Denote by* Ω *the social adaptation gap, which is defined as the difference between the private choice of adaptation and the social optimum. In a given period,* t*, the size of the social adaptation gap is given by*

$$\Omega_t = \frac{\mu\gamma_{t+1}}{(1+r)} \cdot \sum_{j=t+1}^{\infty} \left(\left(\frac{1}{1+r^{SP}} \right)^t - \left(\frac{1}{1+r} \right)^t \right) \left[-(1+r)\frac{1}{2}x_j^2 + v'(L_j) \right] \prod_{i=t+1}^{j-1} \left(1 - (1-x_i)\,\mu\gamma_{i+1}\right)$$

The choice of the appropriate social discount rate has received large attention in the climate change economics literature (see e.g., Stern, 2007; Nordhaus, 2007; Weitzman, 2007), yet disagreements remain at the heart of the climate policy debate (Nordhaus, 2013).[10] Determining the appropriate discount rate for mitigation efforts has been recognized as a complex challenge (Nordhaus, 2007). However, a key

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[10] Following the Ramsey rule, the relationship between the equilibrium real return on capital, r^*, and the growth rate of the economy, g^* is given by $r^* = \varrho + \zeta \cdot g^*$, where ϱ denotes the pure rate of time preference, g denotes the growth rate of per capita consumption and ζ denotes the elasticity of consumption (Nordhaus, 2007). Stern (2007) argues that it is immoral to evaluate the welfare of future generations using a social discount rate based on market discount rates. Rather, the author favours an a priori approach, with $\varrho = 0.1\%$, $\zeta = 1$ and $g^* = 1.3\%$. This gives a real return of capital equal to $r^* = 1.4\%$.. Nordhaus (2008) argues that economists have no particular expertise in what is morally right, but must ensure that models replicate reality. Therefore, Nordhaus (2007) advocates a market based approach with $\varrho = 1.5\%$, $\zeta = 2$, and $g^* = 2\%$. This gives a real return on capital equal to $r^* = 5.5\%$. Weitzman (2007) proposed his guess of consensus estimates among economists studying climate change. This gives $\varrho = 2\%$, $\zeta = 2$ and $g^* = 2\%$, translating into a real return on capital equal to $r^* = 6\%$. However, arguing that uncertainty is key to the climate problem, Weitzman (2007) favors a discount rate that declines sharply over time. While the difference in the proposed social discount rates may appear small, small differences lead to large disparities between the recommended intensity of climate change mitigation policies (Heal and Millner, 2014).

implication of Proposition 2 is that the market discount rate may provide a useful benchmark for private adaptation investments. This is because private adaptation directly protects households' assets, which are traded goods with measurable market value. As a result, adaptation holds direct material value for households, and market incentives thus guide effective, value-driven decision-making.

C. Equilibrium and Market Clearing

When households adapt to climate change, this changes the housing - and financial market clearing conditions.

Housing market Total housing demand equals total housing supply, so that $\int_0^1 L_{i,t}^* di = \bar{L}_t$. Therefore, housing market equilibrium requires

$$\bar{L}_{t+1} = \left(1 - (1 - x_t)\mu\gamma_{t+1}\right)\bar{L}_t.$$

with $x_t = \int_0^1 x_{i,t}^* di$
The housing market clearing condition pins down the equilibrium price of housing capital:

$$p_t^* = \frac{\left(1 - (1 - x_t)\mu_L\gamma_{t+1}\right)p_{t+1} + v'\left(\bar{L}_t\right)}{1 + r} - \frac{1}{2}x_t^2$$

Forward substitution gives

$$p_t^* = \sum_{j=t}^{\infty}\left(\frac{1}{1+r}\right)^{j-t+1}\left[-(1+r)x_t^2 + v'\left(\bar{L}_j\right)\right]\prod_{\iota=t}^{j-1}\left(1 - (1 - x_\iota)\mu_L\gamma_{\iota+1}\right)$$

Due to the forward-looking nature of house prices, adaptation efforts reduce the speed at which the housing supply declines. This reduced scarcity dampens the rise in the value households place on owning housing. If Condition (1) holds (see Proposition 1), this scarcity effect dominates in equilibrium. Then, adaptation helps mitigating the effect of climate risk on house prices.

Corollary 4. *Investments in adaptation reduces the rate at which house prices rise.*

Financial market Aggregate income of young households must in equilibrium equal the aggregate investment in housing and adaptation. Hence,

$$\int_0^1 y_i di = \left(p_t + x_t\right)\bar{L}_t,$$

In this case, the volume of mortgage credit in the economy, m, is given by

$$m_t = \max\left\{0, (1 - \phi)\left(\left(p_t + \frac{1}{2}x_t^2\right)L_t - w\right)\right\}$$

Corollary 5. *Investments in adaptation reduces the rate at which the volume of mortgage credit rises.*

D. Endogenous Credit Constraints

Borrowers are protected by limited liability, which can make it advantageous for those with high debt levels to strategically default on their mortgage. In the simple model, housing capital is collateralized to prevent this. However, an important consideration thus far overlooked is that households are exposed to climate risk. Extreme weather events directly affect both the quantity and value of housing capital pledged as collateral. Mortgage creditors, anticipating these potential losses, adjust their lending decisions accordingly due to the deterministic nature of climate risk. Rational creditors should thus never allow the size of household debt (gross of interest) to exceed the expected liquidation value of the *undamaged* housing capital in the next period (Kiyotaki and Moore, 1997; Sastry, 2022).

The expected liquidation value of the collateral depends on the economy's climate risk exposure and the adaptation efforts undertaken by borrowers. By investing in adaptation, borrowers can mitigate potential losses, thereby directly influencing the liquidation value of the collateral. However, adaptation investments are made privately. Mortgage creditors are unable to individually verify the investment households have made in adaptation and - even if creditors could - it is nearly impossible to verify that adaptation measures are maintained and remain functional at the time of an extreme weather event. This creates a prohibitively high cost for mortgage creditors to monitor borrowers' private adaptation choices after credit has been extended.[11] Mortgage creditors thus form expectations on the choice of adaptation of borrowers, denoted by $\mathbb{E}\left(\bar{x}_{l,t}\right)$. The credit constraint then becomes:

$$(1+\hat{r}_{t+1})(-S_{l,t}) \leq \left(1-\left(1-\mathbb{E}\left(\bar{x}_{l,t}\right)\right)\mu_L\gamma_{t+1}\right)p_{t+1}\cdot L_{l,t}$$

where

$$S_{l,t} = w - \left(p_t + \frac{1}{2}x_{l,t}^2\right)L_{l,t} < 0$$

The left-hand side of the equation represents the mortgage credit demanded by borrowers, which depends on current house prices, p_t, borrowers' choice of adaptation, $x_{l,t}$, and their demand for housing, $L_{l,t}$. The right-hand side reflects the expected liquidation value of the undamaged collateral. This liquidation value is influenced by the economy's climate risk exposure, γ_{t+1}, the expected choice of adaptation of borrowers, $\mathbb{E}\left(\bar{x}_{l,t}\right)$, and future house prices, p_{t+1}. Since there is no aggregate uncertainty, mortgage creditors have perfect foresight on future house prices.

Climate change impacts the credit constraint through multiple channels. Consider first the expected liquidation value of the collateral. While future house prices rise due to the reduced housing supply, enhancing borrowing capacity, these damages also reduce the amount of housing capital with positive liquidation value, tightening the credit constraint. Adaptation serves as a countervailing force against

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[11] If a contract could be written that mandated optimal adaptation investments as a precondition for obtaining a mortgage, the problem would be alleviated. However, enforcement in difficult, as an underinvestment in adaptation only poses a problem for creditors in the event of default. Once damages occur and default is triggered, borrowers cannot be penalized as the damage is done, and the verification of the original efforts is nearly impossible.

this tightening of the credit constraint, by mitigating expected climate-related damages. Climate change also affects the demand for mortgage credit. The forward-looking nature of house prices implies that an increase in climate risk raises current house prices (see Proposition 1). Additionally, higher climate risk exposure increases the need for adaptation measures, driving up investment costs. Consequently, higher climate risk leads to an increase in the down payment required from borrowers.[12]

D.1 Equilibrium with Credit Constraints

As indicated in Section IV.B., high-skilled households are net lenders in equilibrium. Low-skilled households are either net lenders or net borrowers. When these households borrowers, they maximize expected utility subject to the budget constraint, limited liability constraint, and the credit constraint:

$$\begin{aligned} \max_{c_{l,t+1},L_{l,t},S_{l,t},x_{l,t}} \mathbb{E}\left(U(c_{l,t+1},L_{l,t})\right) &= \mathbb{E}_t\left(c_{l,t+1}\right) + v\left(L_{l,t}\right) \\ s.t. \quad w &\leq \left(p_t + \frac{1}{2}x_{l,t}^2\right)L_{l,t} + S_{l,t} \\ c_{l,t+1} &\leq \max\left\{p_{t+1}\left(1-\xi_{l,t+1}\right)L_{l,t} + \left(1+\hat{r}_{t+1}\right)S_{l,t}, 0\right\} \\ -(1+\hat{r}_{t+1})S_{l,t} &\leq \left(1-\left(1-\mathbb{E}\left(\bar{x}_{l,t}\right)\right)\mu_L\gamma_{t+1}\right)p_{t+1}L_{l,t} \\ c_{l,t+1}, L_{l,t}, x_{l,t} &\geq 0 \end{aligned}$$

D.2 Optimal Demand for Housing and Adaptation

Due to credit constraints, low-income households have limited financial resources to finance the purchase housing capital and their investment in adaptation. In equilibrium, low-income households borrow up to the point where the constraint binds:

Lemma V.3. *The demand for housing capital of credit constrained, low-income households is given by:*

$$L_{l,t}^* = \frac{(1+r_{t+1})w_t}{(1+r_{t+1})\left(p_t+\frac{1}{2}x_{l,t}^2\right) - \left(1-\left(1-\mathbb{E}(\bar{x}_{l,t})\right)\mu_L\gamma_{t+1}\right)p_{t+1}}$$

where $\mathbb{E}(\bar{x}_{l,t}) = x_{l,t}^*$ *in a symmetric equilibrium. The choice of adaptation of credit constrained, low-skilled households,* $x_{l,t}^*$*, is given by*

$$x_{l,t}^* = \frac{\mu_L\gamma_{t+1}\cdot p_{t+1}}{(1+r_{t+1})(1+\lambda_t)}$$

with $\lambda_t \geq 0$ *the shadow price of the credit constraint.*

The shadow price of the credit constraint, λ_t, represents the increase in the optimal level of utility when the constraint is loosened by one unit. The shadow price of the constraint is strictly positive. When credit constraints bind, the quantity of housing capital consumed by credit-constrained households is

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[12] Sastry (2022) documents empirically that lenders screen for flood risk and, when they retain residual exposures to it, require higher down payments.

strictly below the optimal consumption level. As a result, the marginal utility an additional unit spent on housing capital is strictly higher than the marginal utility an additional unit spent on the non-durable consumption good. In other words, credit-constrained households would benefit more from reallocating spending—reducing adaptation investments to free up resources for housing consumption. Consequently, they allocate a relatively larger share of their (limited) budget to purchasing housing capital, while investing a relatively smaller share in protecting their housing through adaptation measures. The intuition behind this lies in the short-term focus of credit-constrained households. Housing, which is an essential good, provides immediate utility, while adaptation is an investment that enhances resilience against future climate risks. For credit-constrained households, the immediate utility derived from housing outweighs the delayed benefits of adaptation. As a result, the private adaptation choice of credit-constrained households is strictly lower than that of unconstrained households.[13][14]

Proposition 3. *Credit constrained, low-income households adapt relatively less to climate change than high-income households:*

$$x_l^* < x_h^*$$

Proof: See Appendix A.3

Proposition 3 has several key implications. Since $x_{l,t}$ represents the *fraction* of idiosyncratic losses prevented, the underinvestment in adaptation by credit-constrained households implies that these households protect a smaller fraction of their housing capital. Consequently, these households remain relatively more vulnerable to climate risks. When extreme weather events occur, then, credit constrained households experience a disproportionately larger reduction in their housing wealth in expectation, which reinforces wealth inequality. Second, the underinvestment in adaptation by credit-constrained households accelerates the decline in the housing supply as climate impacts materialize. This exacerbates housing scarcity, leaving future generations with less housing and reducing their overall welfare. Denote by Λ_t the private adaptation gap, which is defined as the optimal private choice of adaptation relative to the constrained choice of adaptation:

$$\Lambda_t = \frac{x_{h,t}^*}{x_{l,t}^*} = (1 + \lambda_t)$$

Proposition 4. *When the utility function of housing ($v(L)$) is characterized by constant relative risk aversion, the private adaptation gap rises in climate risk.*

Proof: See Appendix A.4

The private adaptation gap widens over time as habitat becomes increasingly scarce. As a result, households place an increasingly high value on owning housing. In essence, future generations become

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[13] This finding is consistent with Rampini and Viswanathan (2013); Rampini (2019), who show that credit-constrained firms are less likely to invest in durable assets.

[14] Appendix C shows that this result holds more generally under fully homothetic household preferences. Using Cobb-Douglas preferences, I demonstrate that the choice of adaptation increases with household income.

endogenously more credit constrained over time due to the underinvestment in adaptation by previous households. This dynamic is reflected by a rise in the marginal utility of owning housing, which further increases the shadow price of the credit constraint. For credit-constrained households, this weakens incentives to invest in resilience. Specifically, as the importance of owning housing grows relative to future consumption, credit constrained households allocate an increasingly larger share of their (progressively smaller) budget to housing rather than adaptation investments over time.

D.3 Rental Markets and Effective Adaptation

Credit constraints prevent households from adequately reducing their vulnerability to climatic impacts, leading to underinvestment in adaptation. This raises the question whether the economy as a whole would benefit if credit-constrained households relied on households with deeper pockets individuals to mitigate climate impacts? Specifically, I explore whether it is more efficient for credit-constrained households to rent housing capital, rather than purchasing it. Recall that the price of housing capital is given by:

$$p_t + \frac{\theta}{2}{x_t}^2 = \frac{\left(1-(1-x_t)\mu_L\gamma_{t+1}\right)p_{t+1} + v'(\bar{L}_t)}{(1+r_{t+1})}$$

In a perfectly competitive rental market, the rental price (per unit of housing L_t), Υ_t, must be such that (unconstrained) households are indifferent between renting or buying housing. Then, the rental price satisfies

$$\Upsilon_t = v'\left(\bar{L}_t\right)$$

The model implicitly incorporates a rental market, where $v'\left(\bar{L}_t\right)$ represents the imputed rent. This suggests that credit-constrained households are better off renting housing capital rather than purchasing it. By renting, these households no longer need a mortgage to finance their housing consumption, thereby bypassing credit constraints. As a result, they can consume the optimal amount of housing capital. Furthermore, rental prices adjust dynamically to reflect any house price appreciation, preventing wealth transfers between landlords and renters

Landlords' investment in adaptation is driven purely by financial incentives. Adaptation ensures that a larger fraction of the housing capital remains undamaged and can be resold in the future. In a perfectly competitive rental market, rental prices adjust to reflect the adaptation efforts undertaken by landlords. This creates strong incentives for landlords to invest optimally in adaptation. Consequently, in perfectly competitive rental markets, landlords effectively shield credit-constrained households from the climatic impacts they would otherwise face. A key implication is that optimal adaptation investments are made across all houses in the economy, not just those owned by unconstrained households. This benefits future generations by preserving a larger supply of housing capital. Furthermore, unconstrained households are equally well-off in expectation when they become landlords, as the probability of being affected by extreme weather events is independent and identically distributed (i.i.d.) across households.

Proposition 5. *A societal shift from constrained homeownership to a rental model with unconstrained owners leads to more efficient adaptation as long as rental markets are perfectly competitive.*

Proof: See Appendix A.5

VI. General Equilibrium with Firms

In this Section, I introduce a general equilibrium framework that incorporates firms. Firms are established in each period by some households with entrepreneurial talent. Firms operate for a single period and produce the non-durable consumption good, using physical and intangible capital, alongside labour supplied by households. Extreme weather events occur in each period and damage the firms' physical capital, hindering its production.[15] In addition to endogenizing wages, the interest rate, and the production of the non-durable consumption good, the purpose of introducing firms is to show that heterogeneity in the vulnerability of different types of capital can amplify the redistributive effects observed on the household side.

A. Households

The characterization of household preferences is equivalent to the one provided in the simple model (see Section III.A.1). Extreme weather events destroy the housing capital of households (following Section III.B) and households adapt to climate change (following Section V.A). In the general equilibrium framework, wages are endogenous and are equal to the marginal productivity of the respective labour type. Skill levels remain exogenously given. However, the general equilibrium framework features a third type of household, high-skilled workers who have some entrepreneurial talent.

*A.*1 Innovators

A fraction $\varepsilon \in (0,1)$ of high-skilled workers has some entrepreneurial talent. Each 'innovator' establishes $\frac{1}{\phi\varepsilon}$ firms, f, indicating that innovators jointly set up a unit mass of firms. Each firm operates with some intangible capital, H, which is created by innovators when they are young (Döttling and Perotti, 2017). Intangible capital lacks any physical presence and rather represents information (cf. Corrado et al., 2009; Corrado and Hulten, 2010; Crouzet et al., 2022a). Intangibles can thus be regarded as knowledge capital and are created through investments like research and development or human capital and skill accumulation (Crouzet et al., 2022a). The investment is given by $I_{H,t}$, where $I_{H,t} = H_{t+1}$, and requires an effort cost:

$$C\left(I_{H,t}\right) = \frac{1}{2} I_{H,t}^2$$

I assume that intangible capital is fully non-rival in use (Crouzet et al., 2022a,b). That is, innovators invest in intangible capital once, and deploy the intangible capital within all their firms.

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[15] Adaptation by firms is covered in a model extension, in Section VIII.C.

B. *Firms*

There is a unit mass of firms in the economy, which operate a single period and maximize profits.

B.1 Production Technology

Firm produce the non-durable consumption good, using physical capital and intangible capital in the production process. Physical capital (K) is complementary to low-skilled labour (l; see e.g., Krusell et al. (2000), Goldin and Katz (2009), Eisfeldt et al. (2023)), while intangible capital (H) is complementary to high-skilled labour (h). Output, Y_t, is produced according to the following constant elasticity of substitution production technology:

$$\begin{aligned} Y_t &= A\mathcal{F}(H_t, h_t, K_t, l_t) \\ &= A\left[\eta\left(H_t^{\alpha} h_t^{1-\alpha}\right)^{\rho} + (1-\eta)\left(K_t^{\alpha} l_t^{1-\alpha}\right)^{\rho}\right]^{\frac{1}{\rho}} \end{aligned}$$

with A a technology parameter, $\rho \in [0,1)$ the substitution parameter, and η a distribution parameter reflecting the relative productivity of intangible capital and high-skilled labour.[16]

B.2 Capital Investments

While intangible capital is created through the effort of innovators, physical capital is created upon (monetary) investment, with $I_{f,K,t} = K_{f,t+1}$. Tangible, as well as intangible capital, depreciate fully after the production period (i.e. $\delta_K = \delta_H = 1$). Firms operating in $t = 0$ are endowed with an initial stock of physical capital, K_0, and the old innovators at $t = 0$ are endowed with an initial stock of intangible capital, H_0.

B.3 Appropriation of Intangibles

Intangible capital is utilized exclusively by high-skilled workers in the production process. The value of intangible inputs may be captured and privately appropriated (Crouzet et al., 2022a,b). Key, high-skilled workers can hold up the firm, for example, by threatening to withdraw their human capital (Hart and Moore, 1994). This hinders the firm's production. To overcome this, innovators allocate shares of the firm to these workers, enabling them to appropriate part of the value generated by its intangible capital (Eisfeldt and Papanikolaou, 2014; Eisfeldt et al., 2023). Let $\omega \in (0,1]$ represent the innovator's bargaining power over the returns generated by intangible capital (Döttling and Perotti, 2017). Accordingly, shareholders capture a fraction $(1-\omega)$ of the value of intangible capital, while the innovator receives the remaining fraction as income in period $t+1$.

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[16] To ensure that wages of high-skilled workers are higher than those of low-skilled workers, I assume that high-skilled labour is relatively scarce (see Döttling and Perotti, 2017), i.e.,

$$\frac{\phi}{1-\phi} \leq \frac{\eta}{1-\eta}$$

$B.4$ Climate Risk and Firm Capital

Firms are exposed to climate change, as extreme weather events destroy its physical capital (Bilal and Känzig, 2024; Acharya et al., 2022).[17] Let $\gamma_{t+1} \in [0,1]$ capture the probability that a given firm is hit by an extreme weather event in period, $t+1$. This probability is common among firms and, by the law of large numbers, corresponds to the fraction of firms that suffer climate-related damages in any period $t+1$. Denote by $\xi_{f,t+1} \in [0,1]$ the losses of a given firm, f, in period, $t+1$. These losses follow some distribution, $G(\xi_{f,t})$, which is i.i.d. across firms. The losses are idiosyncratic, reflecting that extreme weather events may hit certain firms harder than others. However, as idiosyncratic risk can be diversified, it is the expected losses that matter to investors. Denote by $\mu_K \in [0,1]$ the expected losses, as a fraction of physical capital, conditional on being hit by an extreme weather event. The expected idiosyncratic losses are given by:

$$\begin{aligned} \mathbb{E}\left(\xi_{f,t+1}\right) &= \mathbb{E}\left(\xi_{f,t+1}\middle|\text{Hit by Extreme weather event}\right) \cdot \mathbb{P}\left(\text{Hit by Extreme weather event}\right) \\ &= \mu_K \gamma_{t+1} \end{aligned}$$

Climate-damages reduce the amount of physical capital which has productive value:

$$\tilde{K}_t = \left(1 - \xi_{f,t}\right) K_t$$

Climate-related damages thus hinder production[18]:

$$\tilde{Y}_t = A\mathcal{F}(H_t, h_t, \tilde{K}_t, l_t), \qquad \mathcal{F}'_\gamma(H_t, h_t, \tilde{K}_t, l_t) \leq 0$$

and reduce the firm's output. In contrast to damages to the housing stock, climate-related damages to the physical capital stock affect a firm's output only within the given period, as the firms' capital stock depreciates fully after each production period. Consequently, climate-related damages affect firms on a *flow* basis. In contrast, in the housing market, the supply of habitable houses experiences a permanent decline over time, indicating that climate-related damages have a *stock* effect.

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[17] While intangible capital, which may represent system-wide infrastructure can also be affected by physical climate risk, I take physically localized view and abstract from damages to intangible capital. This is in accordance with Acharya et al. (2022), who show that tangible industries (e.g., construction, mining, oil & gas, utilities, manufacturing and forestry & fishery) are more exposed to physical climate risk than service industries.

[18] In the environmental economics literature climate-related damages to production are modeled using a damage function (see e.g., Golosov et al., 2014; Nordhaus, 1992). Specifically, a damage function, which rises in temperatures, reduces TFP. While I model climate-related damages to production as a physical capital loss of fraction $\xi_{f,t}$, the production function can be rewritten as

$$\tilde{Y}_t = A\left[\eta\left(H_t^\alpha h_t^{1-\alpha}\right)^\rho + (1-\eta)\left(1-\xi_{f,t}\right)^{\alpha\rho}\left(K_t^\alpha l_t^{1-\alpha}\right)^\rho\right]^{\frac{1}{\rho}}$$

This function reflects that climate-related damages reduce firm's overall productivity of physical inputs (i.e. low-skilled labour and physical capital). This specification also captures a decline in the productivity of manual labour due to, e.g., heat-stress (Acharya et al., 2022).

C. Firm Financing and Financial Markets

Each firm, f, issues corporate debt to finance the investment in physical capital. Corporate debt, which has a face value of $D_{f,t}$, is funded by households with positive savings. The corporate debt held by household i in firm f in period t is denoted by $D_{i,f,t}$ and the total holdings of corporate debt of a given household are denoted by $D_{i,t} = \int_0^1 D_{i,f,t} df$. Lending to firms occurs against collateral, and the firm's physical capital backs its corporate debt. While physical capital is also exposed to climate-related risks, I abstract from corporate default in the model. This simplify the analysis and maintains the focus on the allocation of resources and the economic consequences of climate risks, while avoiding the complexities of modeling default and bankruptcy. Hence, corporate debt earns a risk-free rate of return, r_t, and is repaid each period.

Innovators also issues equity, which is backed by the value of the share of intangible capital appropriated by equity holders. I denote the equity held by shareholder i in firm f in period t by $s_{i,f,t}$ and the total equity holdings of a given household are denoted by $s_{i,t} = \int_0^1 s_{i,f,t} df$. I normalize the quantity of shares of each firm to 1. The price of a share of firm f is denoted by $e_{f,t}$, and shares receive a dividend payment, $d_{f,t}$, at the end of the period.

VII. General Equilibrium

A. Household Optimization Problem

Households maximize utility subject to the budget constraint and limited liability constraint:

$$\begin{aligned}
\max_{c_{i,t+1}, L_{i,t}, s_{i,t}, S_{i,t}, x_{i,t}} \quad & \mathbb{E}\left(U(c_{i,t+1}, L_{i,t})\right) = \mathbb{E}_t\left(c_{i,t+1}\right) + v\left(L_{i,t}\right) \\
s.t. \quad & y_{i,t} \leq \left(p_t + \frac{1}{2}x_{i,t}^2\right) L_{i,t} + s_{i,t}e_t + S_{i,t} \\
& c_{i,t+1} \leq \max\{y_{i,t+1} + p_{t+1}(1 - \xi_{i,t+1})L_{i,t} + d_{t+1}s_{i,t} + (1 + \hat{r}_{t+1})S_{i,t}, 0\} \\
& c_{i,t+1}, L_{i,t}, x_{i,t} \geq 0,
\end{aligned}$$

where $\mathbb{E}_t$ denotes expectations formed at date t.

A.1 Optimal Demand for Housing and Adaptation

Within the general equilibrium framework, the optimal demand for housing and adaptation matches that of the simple framework, as outlined in Section V.B.2. In the general equilibrium framework, the risk-free rate is time-variant.

A.2 Optimal Demand for Shares and Corporate Debt

The share price follows from households' demand for share holdings, $s_{i,t}$ and is equal to the discounted value of the dividend payment, d_{t+1}

$$e_t = \frac{d_{t+1}}{(1+r_{t+1})}$$

Investments in corporate and household debt follow as residual. Households with net savings lend to others households and firms, while households with negative savings take out a mortgage.

B. Firm Optimization problem

Firms maximize the value to its equity holders. Since firms only operate for one period, and pay out all profits, the maximization problem is given by:

$$\max_{H_t, h_t, K_t, l_t} \pi_{f,t} = \tilde{Y}_t(A, H_t, h_t, \tilde{K}_t), l_t) - \omega R_t H_t - q_t h_t - (1+r_t)D_{t-1} - w_t l_t$$

B.1 Wages

Labour markets are perfectly competitive, which implies that high-skilled and low-skilled workers earn their marginal productivity.

Lemma VII.1. *Wages of high- and low-skilled workers,* q_t *respectively* w_t *are equal to*

$$\begin{aligned} q_t^* &= A^\rho (1-\alpha)\eta \cdot \frac{\tilde{Y}_t^{1-\rho}}{h_t^{1-(1-\alpha)\rho}} \cdot H_t^{\alpha\rho} \\ w_t^* &= A^\rho (1-\alpha)(1-\eta) \cdot \frac{\tilde{Y}_t^{1-\rho}}{l_t^{1-(1-\alpha)\rho}} (1-\mu_K \gamma_t)^{\alpha\rho} \cdot K_t^{\alpha\rho} \end{aligned}$$

The wage ratio is defined as $\frac{q_t^*}{w_t^*}$ *and is given by:*

$$\frac{q_t^*}{w_t^*} = \frac{\eta}{1-\eta} \cdot \left(\frac{H_t}{(1-\mu_K \gamma_t) K_t} \right)^{\alpha\rho} \cdot \left(\frac{l_t}{h_t} \right)^{1-(1-\alpha)\rho}$$

Climate-related damages lead to a decline in income, reducing wages of high- and low-skilled workers. However, the damages to physical capital have a direct, negative impact on the productivity of low-skilled workers. As a result, the wages of low-skilled workers fall to a larger extent than those of high-skilled workers, leading to a rise in wage inequality. The wage ratio also depends on the balance of intangible and physical capital used in production. As income declines, firms (and innovators) cut back their investment in both physical and intangible capital. However, since tangible capital is more vulnerable to climate risks, firms scale back their investments in physical capital to a greater extent, further suppressing the wages of low-skilled workers relative to high-skilled workers over time.[19]

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[19] This result also holds if intangible capital were exposed to climate risk, as long as the elasticity of tangible capital to

Proposition 6. *Wage inequality rises in climate-related damages.*

Proof: See Appendix A.6

B.2 Return on Physical Capital

Firms are financially unconstrained and borrow up to the point where the marginal cost of capital is equal to its marginal productivity

Lemma VII.2. *The return to physical capital is given by*

$$(1+r_t^*) = A^\rho \alpha (1-\eta) \cdot \frac{\tilde{Y}_t^{1-\rho}}{\left(\left(1-\mu_K\gamma_t\right)K_t\right)^{1-\alpha\rho}} \cdot l_t^{(1-\alpha)\rho}$$

and firms fully finance the investment in physical capital by debt in each period, $I_{K,t}^* = D_t$.

The return on physical capital determines the cost of capital. While redistributive technological change (reflected by a rise in η) produced a decline in interest rates due to excess savings (Döttling and Perotti, 2017)[20], climatic impacts destroy these excess savings. The decline in income reduces investment and consumption, which reduces capital demand and suppresses the cost of capital. Again, supply adjust as well due to the climate-related damages. Climate-related damages cause physical capital to becomes more scarce in the economy, which raises the cost of capital. Since the elasticity of physical capital to climate-related damages is higher than the elasticity of income to climate-related damages (that is, income is produced using two types of capital - one of which is not exposed to climate risks), the scarcity effect dominates in equilibrium. Consequently, the cost of capital rises in climate-related damages.

Proposition 7. *The cost of capital rises in climate-related damages.*

Proof: See Appendix A.7

The rise in the cost of capital has redistributive implications. Specifically, as the rate of return rises, households with positive savings accumulate wealth at a faster rate. In contrast, households that finance the purchase of housing capital by issuing household debt face an increase in the costs of servicing their mortgage contract. Hence, through the costs of borrowing channel, savings act as an *unequalizing* force, increasing wealth inequality.

B.3 Dividends and Share Prices

Shareholders capture a fraction $(1-\omega)$ of the return to intangibles capital. In equilibrium, dividends are given by:

$$\begin{aligned} d_t^* &= \tilde{Y}_t(H_t, \tilde{K}_t, h_t, l_t) - (\omega R_t^* H_t + q_t^* h_t + (1+r_t^*)K_{t-1} + w_t^* l_t) \\ &= (1-\omega) R_t^* \cdot H_t \end{aligned}$$

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climate-related damages is larger than the elasticity of intangible capital to climate-related damages.

[20] Excess savings arise as technological change increases the reliance of the economy on intangible capital, reducing demand for physical capital and corporate debt.

where the return on intangible capital is given by[21]

$$R_t^* = A^\rho \alpha \eta \cdot \frac{\tilde{Y}_t^{1-\rho}}{H_t^{1-\alpha\rho}} \cdot h_t^{(1-\alpha)\rho}$$

Share prices are given by the discounted value of the dividend payment:

$$e_t^* = \frac{(1-\omega)R_{t+1} \cdot H_{t+1}}{1+r_{t+1}}$$

Lemma VII.3. *Climate-related damages reduce dividends.*

Since climate-related damages hinder the firm's production, the firm experiences a decline in its output and therefore its profitability. This reduces the dividend payment. The simultaneous reduction in dividends and rise in the firm's borrowing costs triggers a revaluation of the firm's equity, which suppresses equity prices.

Proposition 8. *Share prices decline in climate risk.*

Proof: See Appendix A.8

The decline in equity prices reduces the financial wealth of shareholders. Therefore, financial asset price changes act as an *equalizing* force for the wealth distribution.[22]

C. Equilibrium and Market Clearing

A competitive equilibrium is defined as an allocation $\{c_t^l, c_t^h, L_t^l, L_t^h, s_t^l, s_t^h, D_t^l, D_t^h, K_t, H_t, l_t, h_t\}_{t=0}^T$ and prices $\{p_t, e_t, r_t, R_t, w_t, h_t\}_{t=0}^T$ such that in each period, t, given prices

1. Households maximize lifetime utility;
2. Firms maximize profits;
3. Innovators optimally choose intangible investment;

and all markets clear.

Housing market Within the general equilibrium framework, the housing market clearing condition and the expression for the price of housing capital, p_t, are similar to those of the simple framework, as outlined in Sections V.C. In the general equilibrium framework, the risk-free rate becomes time-variant.

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[21] Competitive firms pay a return on intangible capital equal to its marginal productivity. Given the return, innovators create an amount of intangible capital equal to:

$$I_t^* = \frac{\omega}{\phi\varepsilon} R_{t+1}^* = \tilde{\omega} R_{t+1}^*$$

where $I_t^* = H_{t+1}^*$ (Döttling and Perotti, 2017).

[22] Bauluz et al. (2022) study the rise of global saving and wealth between 1980-2018. One of the authors' finding is that saving were an unequalizing force for the wealth distribution, while capital gains were an equalizing force.

Labour markets Total labour demand equals total labour supply, so that

$$\int_0^1 \left[h_{f,t}^d, l_{f,t}^d\right] df = [h^s, l^s]$$

Households supply their entire labour endowment since the marginal product of labour is strictly positive. Therefore, $[h^s, l^s] = \{\phi\bar{h}, (1-\phi)\bar{l}\}$ and the labour market equilibrium requires:

$$\int_0^1 \left[h_{f,t}^d, l_{f,t}^d\right] df = \{\phi\bar{h}, (1-\phi)\bar{l}\}$$

Financial markets Aggregate income of young households must equal the value of assets that carry savings over time. This consists of the aggregate investment in housing, corporate debt and shares:

$$(1-\alpha)\tilde{Y}_t - p_t\bar{L}_t = e_t + D_t$$

where $(1-\alpha)\tilde{Y}_t = q_t\phi\bar{h} + w_t(1-\phi)\bar{l}$. For equity markets to clear, the total share holdings must equal the total supply of shares:

$$\int_0^1 s_{i,t}^* di = 1$$

Recall that the investment in physical capital is fully financed by corporate debt, i.e. $D_t = K_t$. Hence, the financial market clearing condition provides an expression for the supply of physical capital:

$$K_t = (1-\alpha)\tilde{Y}_t - p_t\bar{L}_t - e_t$$

VIII. Quantitative Assessment and Counterfactual Analysis

To illustrate the equilibrium effects of rising climate risk and adaptation on the economy, I quantitatively assess the implications of the model. I provide a parameterization based on the U.S. economy in the year 2010 and I simulate the model from 2000 to 2150 for Florida's coastal area.[23] Given the overlapping generation structure of the model, each time period equals 30 years. I conduct counterfactual analysis to demonstrate the evolution of the economy under different climate change scenarios as projected by IPCC (2023).[24] Specifically, I simulate the model under low greenhouse gas emission-scenarios (SSP1-1.9, SSP1-2.6), under an intermediate greenhouse gas emission-scenario (SSP2-4.5) and a high greenhouse gas emission-scenario (SSP3-7.0).[25]

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[23] The projections of climate change used are relative to a 1995-2014 baseline. Hence, the climate risk parameter has a value of 0 between 2000 and 2010.

[24] Bilal and Känzig (2024); Cruz and Rossi-Hansberg (2024); Bilal and Rossi-Hansberg (2023) also use projections to measure future impacts of climate change. The authors focus on temperature projections, which closely match the projections of the IPCC under a business-as-usual (i.e. the high greenhouse gas emission) scenario.

[25] The SSP$x-y$ scenarios describe different climate futures depending on socio-economic trends underlying the scenario (x) and the approximate level of radiative forcing (in watts per square meter) resulting from the scenario in the year 2100 (y).Under SSP1-1.9 (SSP1-2.6), global warming remains approximately below 1.5 (2.0) degrees Celsius above 1850-1900 in the year 2100, which is the target of the Paris Agreement. This scenario requires net zero CO2 emissions by 2050 (in the second half of the century). SSP2-4.5 is in line with the aggregate Nationally Determined Contribution emission levels by

A. The Evolution of Climate Risk

To determine the evolution of climate risk, I assume that γ_t represents the fraction of homes in Florida's coastal area which are at risk of flooding due to future sea level rise.[26] Florida is a low-lying state at the east coast of the United States, and is at high risk of flooding due to sea level rise. Within the next 30 years, approximately 64,000 homes in Florida will be at risk of chronic flooding and 12,000 of those homes are located in the Miami Beach area. The number of homes that are at risk from sea level rise is expected to rise rapidly, to more than 1 million by the end of the century. This implies that Florida alone would account for more than 40 percent of the houses at risk in the United States as a whole (Dahl et al., 2018).

To evaluate property-level exposure to sea level rise in Florida's coastal areas, I rely on the estimates provided by Bernstein et al. (2019). These authors use geographic mapping software to assess each property's vulnerability to sea level rise. Specifically, Bernstein et al. (2019) combine the geolocation data of individual properties with projections from the National Oceanic and Atmospheric Administration (NOAA) sea level rise calculator, which identifies regions expected to be underwater under different sea level rise scenarios. I focus on aggregate exposure estimates, which measure the total number of properties at risk of flooding for varying levels of future sea level rise.[27] These estimates provide the fraction of properties expected to be flooded for different levels of future sea level rise.

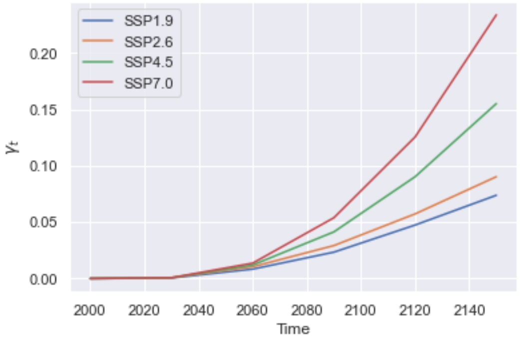

Figure 1: The evolution of γ_t under the SSP1-1.9, SSP1-2.6, SSP2-4.5 and SSP3-7.0 scenario.

To approximate the evolution of the fraction of houses at risk of flooding due to future sea level rise, γ_t, under different scenarios of sea level rise, I use the NASA Sea Level Projection Tool (Garner et al., 2021; Fox-Kemper et al., 2021; Garner et al., in prep.). This tool visualizes the median projections of global and regional sea level rise, relative to a 1995-2014 baseline. These projections are based on IPCC (2023). Projections are provided for various regions and cities in Florida. As there is relatively little variability in their projection, I focus on the projections for the Miami-beach area. By the end of

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2030. Under this scenario, global warming reaches approximately 2.7 degrees Celsius above 1850-1900 by the end of the century. SSP3-7.0 is a medium to high climate change scenario. Under this scenario, global warming reaches approximately 3.6 degrees Celsius above 1850-1900 by the end of the century.

[26] Specifically, I focus on properties that would be flooded for 10 feet of sea level rise.

[27] The estimates cover scenarios from 1 to 10 feet of sea level rise. For example, Bernstein et al. (2019) find that 7.2 percent of properties in Florida's coastal areas would be flooded under 3 feet (0.914 meters) of sea level rise, while 50.7 percent would be flooded under 6 feet (1.83 meters).

Table 1: Parameter Values

Parameter	Description	Value	Source/Target
A	TFP in final-good production	1	Normalization
$\tilde{h}$	Inelastic supply of high-skilled labour	35	Credit allocation target
$\tilde{l}$	Inelastic supply of low-skilled labour	20	Credit allocation target
$\bar{L}$	Initial stock of houses	1	Normalization
α	Capital share in final-good production	0.32	BEA (2010)
η	Relative productivity of intangible inputs	0.67	Credit allocation target
μ_L	Fraction of damages to housing capital	1	Complete losses due to SLR
μ_K	Fraction of damages to tangible capital	0.7	$\mu_L/\mu_K = 0.7$ (Fried, 2022)
ρ	Substitution parameter	0	Cobb-Douglas Production
ϕ	Fraction of high skilled labour	0.3	U.S. Census Bureau (2010)
$\tilde{\omega}$	Bargaining power of innovators (scaled)	0.58	Capital structure target

the century, this region is expected to experience a sea level rise of 0.71 meters under an intermediate greenhouse gas emission scenario (SSP2-4.5).[28] The evolution of the fraction of houses at risk of flooding due to future sea level rise, γ, is depicted in Figure 1 under the different SSP$x - y$ trajectories.

B. *Other Parameters and Functional Form Specifications*

Other parameter values are specified in Table 1. I use a number of internally and externally calibrated parameters. Externally calibrated parameters are reported as of 2010 for the Unites States. The capital share in final-good production is based on net capital share of gross domestic income. The net capital share is 0.32 and is calculated as gross domestic income less consumption of fixed capital, taxes on production and imports less subsidies, less compensation of employees, divided by gross domestic income less consumption of fixed capital, taxes on production and imports less subsidies. All values are reported by the Bureau of Economic Analysis (BEA). The fraction of high-skilled labour is 0.3 and is measured as the fraction of U.S. citizens of 25 years and that have completed at least 4 years of college education. This data is provided by the U.S. Census bureau.

Since I am interested in the effect of climate change on credit allocation, I internally calibrate the supply of labour and the relative productivity of intangible capital. Specifically, I choose the value of these parameters to target the ratio of household to (non-financial) corporate debt in the U.S. economy in 2010, which is 0.68 (Federal Reserve Board, 2010).[29] The bargaining power of the innovators is set to match an aggregate capital structure target of the U.S. economy, given by the size of the (non-financial) corporate debt market relative to the market value of equity plus (non-financial) corporate debt is 0.26 (Fred, 2010).[30]

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[28] Projections are provided for Virginia Key, Lake Worth Piert, Trident Pier (Port Canaveral), Dayone Beach, Mayport (Bar Pilots Doc), Fernandina Beach, Vace Key, Key West, Naples, Fort Myers, St. Petersburg, Clearwater Beach, Cedar Key, Apalachicola, Panama City, St. Andrews Bay, and Pensacola. By the end of the century, these regions are expected to experience a sea level rise between 0.64 and 0.73 meters by the end of the century under an intermediate greenhouse gas emission scenario (SSP2-4.5).

[29] Data on the financial accounts of the United States for non-financial sectors is available via the Federal Reserve Board. See `https://www.federalreserve.gov/releases/z1/dataviz/z1/nonfinancial_debt/table/`.

[30] Data on non-financial corporate debt as a percentage of the market value of corporate equities in the United States is

Table 2: Targeted Moments

Target	Description	Data	Model
Credit allocation target	Household debt/(Household + corporate debt)	0.68	0.65
Capital structure target	Corporate debt/(Corporate debt + equity)	0.26	0.29

The supply of houses is equal to 1 at the start of the simulation. I choose the expected idiosyncratic damages, μ_L, equal to 1 - since the model simulation focuses on sea level rise - and target a ratio of damages to housing relative to productive capital of 0.7, which is based on Fried (2022). Finally, I set ρ equal to zero, such that the production technology is Cobb-Douglas, and the functional form of the utility of housing is $v(L) = ln(L)$.

C. The Evolution of Private Adaptation

To solve the model, I assume a steady state is reached by 2150, which is last year for which sea level rise projections are available. That is, I assume that climate risk remains constant after this period and The solve the model backwards from this point. I compare the simulations of an economy with climate change to those of an economy where households endogenously adapt to climate change. Figure 2 shows the evolution of the optimal private choice of adaptation, x_t, which increases in the economy's climate risk exposure. The fraction of idiosyncratic losses prevented remains relatively modest. Under the most severe climate change scenario and by the end of the century, households invest to reduce approximately 10 percent of the idiosyncratic losses. This rises vastly, reaching about 35 percent by 2150.

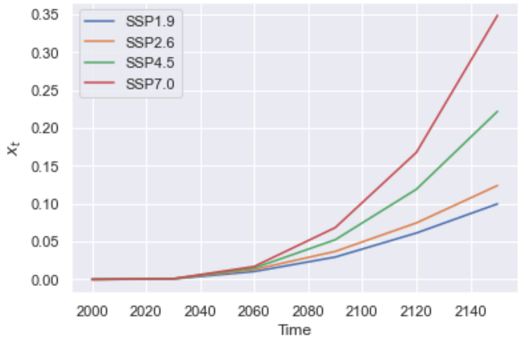

Figure 2: The evolution of the choice of adaptation, x (right), under the SSP1-1.9, SSP1-2.6, SSP2-4.5 and SSP3-7.0 scenario.

D. The Evolution of the Relative Prices

The supply of inhabitable houses declines endogenously in the model with climate risk. In line with Proposition 1, this leads to a rise in house prices over time. This is illustrated in Figure 3, which plots the ratio of house prices relative to income. Specifically, in the model with climate risk only (left panel), the ratio of house prices to income increases by 30-50 percent under the medium climate change scenarios.

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available via the Federal Reserve bank of St. Louis. See `https://fred.stlouisfed.org/series/NCBCMDPMVCE`.

The right panel of Figure 3 illustrates the effect of adaptation by households on the evolution of house prices. Adaptation to climate change endogenizes the rate at which the supply of inhabitable houses declines, as households can invest in measures that limit damages to their housing capital. This reduces the rate at which the supply of housing declines over time, weakening the scarcity effect on house prices. Consequently, when households adapt to climate change, house prices rise at a slower pace, moderating the rise in house prices relative income to 20-40 percent.

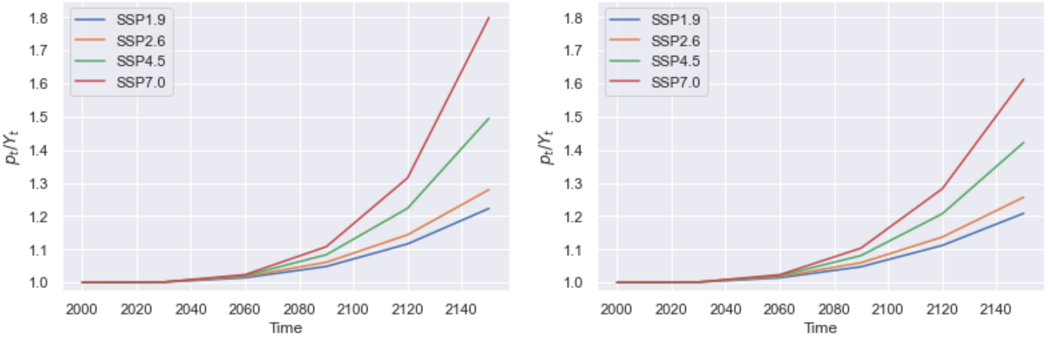

FIGURE 3: THE EVOLUTION OF HOUSE PRICES TO INCOME (INDEXED TO 1 IN 2000) UNDER THE DIFFERENT SSP$x-y$ SCENARIOS, FOR THE MODEL WITH CLIMATE CHANGE (LEFT) AND THE MODEL WITH ADAPTATION TO CLIMATE CHANGE (RIGHT).

Due to climate-related damages, physical capital becomes more scarce in the economy. Following Proposition 7, this raises the costs of borrowing. Figure 4 demonstrates that the cost of capital rises in the exposure to climate risk. Specifically, the cost of capital rises between 11-37 percent, depending on the severity of the climate change scenario (left panel). While adaptation by household only reduces losses to housing capital, their efforts have broader implications in the general equilibrium. By limiting damages to the housing stock, households moderate the rise in house prices. This reduces the aggregate investment in housing, allowing a larger part of savings to be allocated to corporate debt. As a result, the cost of capital rises by approximately 10-26 percent when households adapt to climate change.

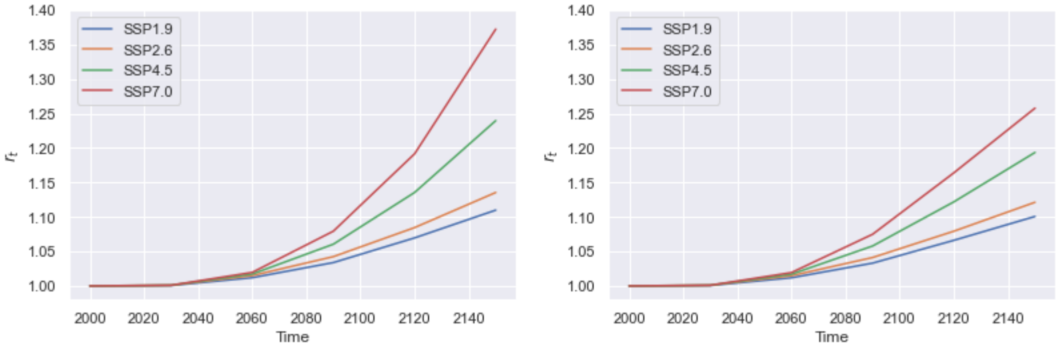

FIGURE 4: THE EVOLUTION OF THE COST OF CAPITAL (INDEXED TO 1 IN 2000) UNDER THE DIFFERENT SSP$x-y$ SCENARIOS, FOR THE MODEL WITH CLIMATE CHANGE (LEFT) AND THE MODEL WITH ADAPTATION TO CLIMATE CHANGE (RIGHT).

E. The Evolution of the Credit Allocation

The rise in house prices and the subsequent increase in interest rates has implications for credit allocation. Specifically, capital is reallocated away from firms and towards households. This is visualized in Figure 5, which plots the share of capital that is allocated to households and firms over time under the most extreme climate change scenario. As housing becomes more expensive, households demand more credit to finance the purchase of their homes. On the other hand, as interest rates rise, firms to reduce investment in physical capital and therefore demand less corporate debt. These dynamics raise the fraction of capital that is allocated towards households from 65 to 70 percent over time. Climate change adaptation reduces the increase in relative prices, potentially moderating the shift in credit allocation. However, adaptation investments also increase capital demand of households. Consequently, the fraction of capital allocated to households continues to rise even when households adapt to climate change.

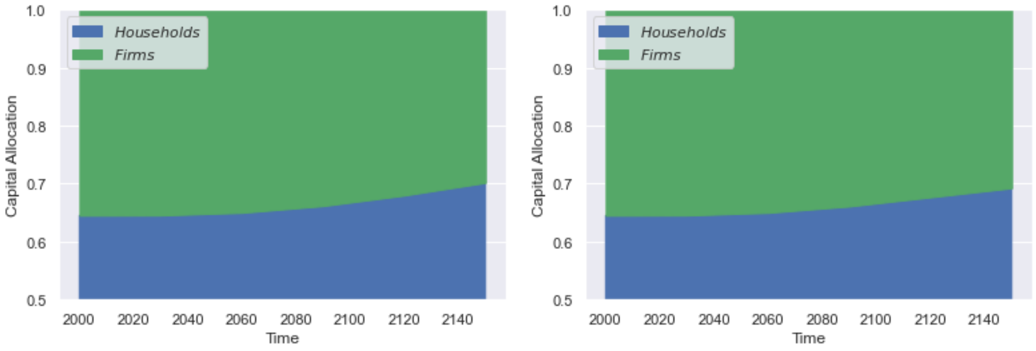

Figure 5: The evolution of credit allocation under the SSP-3-7.0 scenarios, for the model with climate change (left) and the model with adaptation to climate change (right).

F. The Evolution of the Wealth Inequality

The rise in the cost of capital, alongside the growth in household debt, leads to greater consumption inequality. Specifically, households with positive savings accumulate wealth at a faster rate, while those who borrow become increasingly indebted as capital costs continue to rise. Define Δc_{t+1} as the difference between the time $t+1$ consumption of high-skilled households and low-skilled households. Figure 6 demonstrates that (consumption equivalent) wealth inequality has risen as household debt becomes larger. This is consistent with Mian et al. (2020). Specifically, consumption inequality rises by 3-9 percent absent climate change adaptation. Adaptation reduces the rise in (consumption equivalent) wealth inequality to at most 5 percent. This is achieved by shielding households from climate-related damages, indicating that adaptation is a crucial to moderate the redistributive consequences of climate change.

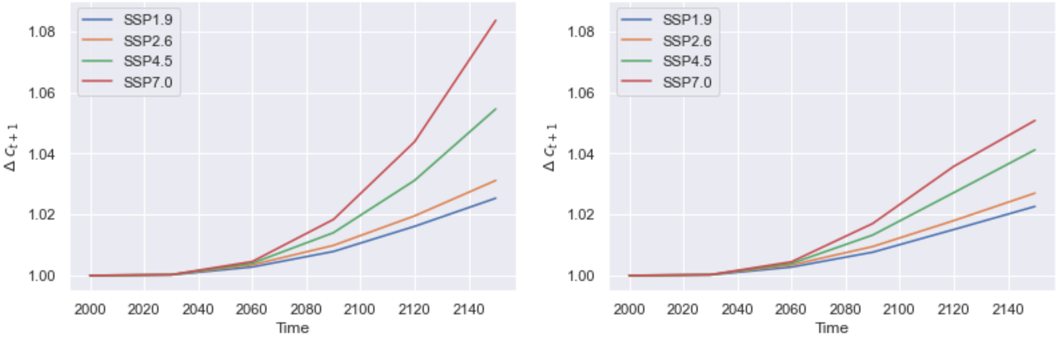

FIGURE 6: THE EVOLUTION OF CONSUMPTION INEQUALITY, Δc_{t+1} (INDEXED TO 1 IN 2000), UNDER THE DIFFERENT SSP$x-y$ SCENARIOS, FOR THE MODEL WITH CLIMATE CHANGE (LEFT) AND THE MODEL WITH ADAPTATION TO CLIMATE CHANGE (RIGHT).

IX. Model Extension: Insurance Markets

Insurance plays a key role in mitigating the impact of climate change on household wealth, since households can privately insure climate related damages to their home with home insurance. In the context of climate change, a challenge arises as multiple households face similar climate-related risks, leading to the correlation of losses. This complicates the insurance landscape.

A. *Institutional Context*

In Florida, homeowners are not legally required to have flood insurance. However, mortgage lenders often require it to protect against the risk of physical damage to the property that serves as collateral, as this could lead to a decline in its value.[31] Government-backed lenders further mandate flood insurance for properties located in areas designated as "Special Flood Hazard Areas" by the Federal Emergency Management Agency (FEMA).[32] Flood damage, caused by storms, heavy rain, or overflowing water bodies, are typically not covered by home insurance policies. Therefore, homeowners who live in a flood zone must obtain separate flood insurance.

Flood insurance is offered through the National Flood Insurance Program (NFIP), a federally-backed initiative administered by the government for homeowners, renters, and businesses. Eligibility for NFIP coverage depends on the property's flood zone and the community's participation in the program. The NFIP covers physical damages directly caused by flooding, up to a limit of 250,000 US dollars for building coverage.[33] In Florida, the average annual cost of NFIP flood insurance is 760 US dollars, and the average claim payout is approximately 29,000 US dollars. Homeowners can also apply for FEMA disaster assistance in addition to an insurance claim. This is available only for properties in areas that have received a Presidential Disaster Declaration.[34] The average FEMA disaster relief payment in Florida is

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[31] For simplicity, I do not model the contractual relationship between the insurance and mortgage contract.

[32] FEMA's flood maps are regularly updated. Consequently, many areas are being reclassified over time.

[33] The mean value of a typical home in Florida was 431,534 US dollars in July, 2024 (Zillow, 2024).

[34] Homeowners in flood zones who have previously received federal disaster aid are required to maintain flood insurance to remain eligible for future aid.

about 5,100 US dollars. Additional flood coverage is available through private insurers. However, private insurance providers are increasingly exiting the Florida market due to the high risks associated with climate change (Sastry et al., 2023; Nicholson et al., 2020). Also Citizens, a state-backed insurer of last resort for those who cannot find affordable coverage through private insurers, potentially brings forward a role for the state in providing coverage as private options fail, does not provide flood insurance.[35]

B. *Climate Risk Insurance*

Households may insure damages to their housing capital at the time of purchase. Denote by $\pi_{i,t} \in [0,1]$ the insurance choice variable of household i, at time t per unit of housing capital, $L_{i,t}$. Thus, $\pi_{i,t} = 1$ indicates that the household purchases full coverage for the insured loss, $\pi_{i,t} < 1$ indicates that the household chooses fractional coverage. The coverage provided by private insurers has already seen a decline empirically, as a result of rising climate risk (Sastry et al., 2023; Boomhower et al., 2024).[36] Since multiple households face similar climate-related risks, and losses thus are correlated, providing coverage will become increasingly challenging as climate risks continue to rise. I therefore assume that insurance is partial, with insurers only covering a fraction $\theta \in [0,1]$ of losses. Hence, the coverage is given by $\theta \cdot \pi_{i,t}$.

The expected payout that insured households receive per unit of housing capital insured equals the future price times the expected losses covered by insurance, i.e., $\theta \cdot \mathbb{E}\left(\xi_{i,t+1}\right) \cdot p_{t+1}$. Insurers have perfect foresight on the climate risk exposure of the economy, and on future house prices since there is no aggregate uncertainty. However, since it is prohibitively costly to verify individual households' private adaptation choices (and their maintenance, see Section V.D), insurance intermediaries also form expectations on the choice of adaptation of a given household, denoted by $\mathbb{E}\left(\bar{x}_{i,t}\right)$. Denote the insurance premium for full coverage by z_t. Insurance is actuarially priced, that is, the premium reflects the discounted expected payout per unit of housing capital insured.[37] Then, the insurance premium is given by

$$z_t = \frac{\theta \cdot (1 - \mathbb{E}(\bar{x}_{i,t}))\mu\gamma_{t+1} \cdot p_{t+1}}{(1+r)}$$

The rise in climate risk leads to larger expected damages. Simultaneously, the rise in house prices increases the value of the insured asset. These factors lead to higher expected payouts, raising insurance premia over time.[38] This is illustrated in Figure 7, in which I plot the evolution of the insurance premium under a low and high coverage. The larger the fraction of losses covered (θ), the higher the expected payout and thus the higher the insurance premium.

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[35] Citizens is gradually introducing flood insurance requirements for its home insurance customers. Specifically, in 2023, customers in high-risk flood zones were required to have flood insurance, regardless of mortgage status. By January 2027, all Citizens home insurance customers will need to have flood insurance.

[36] Sastry et al. (2023) documents this in the context of flood risk and Boomhower et al. (2024) for wildfire risk.

[37] In the U.S., insurance premia are heavily subsidized, preventing full risk pricing. This is also the case in government-provided insurance programs as the NFIP. This provides an implicit subsidy to homeowners living in high risk areas and hinders price signals. While I abstract from mispricing in this framework, this would strengthen the moral hazard effect and further reduce investments in adaptation.

[38] This aligns with the findings of Keys and Mulder (2024), who study homeowner insurance. The authors document an increase in the average insurance premium between 2020-2023, which is the result of a stronger relationship between premiums and local disaster risk.

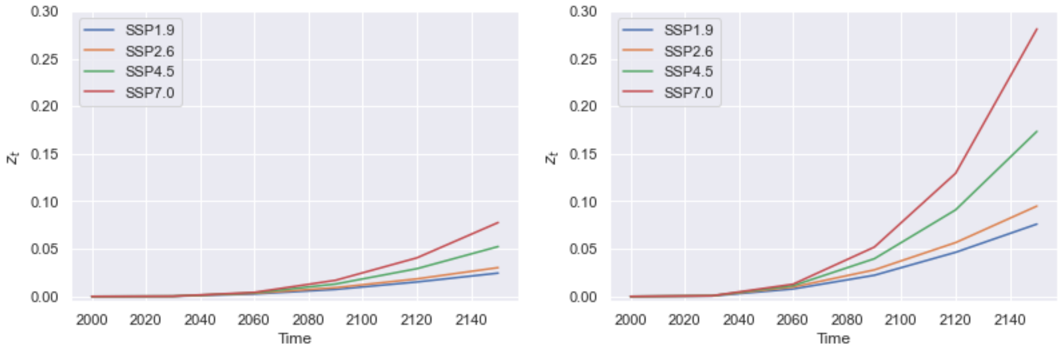

FIGURE 7: THE EVOLUTION OF THE INSURANCE PREMIUM, z_t, FOR $\theta = 0.25$ (LEFT) AND $\theta = 0.75$ (RIGHT), UNDER THE DIFFERENT SSP$x - y$ SCENARIOS.

C. *Optimal Demand for Adaptation with Insurance*

Since households are risk-neutral with respect to their consumption of the non-durable good, there is no demand for insurance, i.e., $\pi^*_{i,t} = 0$. Nevertheless, even without a strictly positive demand for insurance, its implications on house prices and the private choice of adaptation can be studied - which is the main purpose of this model extension. When households can insure the losses due to extreme weather events, the household maximization problem is given by:

$$\begin{aligned}
\max_{c_{i,t+1}, L_{i,t}, S_{i,t}, x_{i,t}, \pi_{i,t}} \quad & \mathbb{E}_t\left(c_{i,t+1}\right) + v(L_{i,t}) \\
s.t. \quad y_{i,t} \leq & \left(p_t + z_t\pi_{i,t} + \frac{1}{2}x^2_{i,t}\right) L_{i,t} + \ +S_{i,t} \\
c_{i,t+1} \leq & \max\left\{p_{t+1}(1 - (1 - \theta\pi_{i,t})\xi_{i,t+1})L_{i,t} + (1 + \hat{r})S_{i,t}, 0\right\} \\
c_{i,t+1}, L_{i,t}, x_{i,t}, \pi_{i,t} \geq 0. &
\end{aligned}$$

Lemma IX.1. *When households can insure against losses due to extreme weather events, the optimal private choice of adaptation is given by:*

$$x_{i,t} = \frac{(1 - \theta\pi_{i,t}) \cdot \mu_L\gamma_{t+1} \cdot p_{t+1}}{(1 + r)}$$

Climate risk insurance leads to moral hazard in adaptation. Due to the non-verifiability of the private efforts undertaken, insurance allows households to limit the downside from a disaster in a relatively cheaper way than when they invest in adaptation. Specifically, the marginal costs of insurance are constant, while the marginal costs of adaptation - which is an investment which is increasingly costly as one wants to prevent a larger fraction of damages - are rising. Hence, the availability of insurance reduces households' willingness to undertake adaptation investments. The private adaptation investment falls by a fraction $\theta\pi_{i,t}$ in response. Households thus invest in adaptation to mitigate uninsured damages to their housing only. This occurs even if there is is no mispricing regarding the economy's climate risk exposure. The choice of insurance is not separable from the portfolio decisions (Mayers and Smith Jr, 1983), however, since insurance coverage affects the price of the insured good. That is, even though the premium is actuarial, in insurance provision affects the price of housing capital the general equilibrium.

Lemma IX.2. *When households can insure against losses due to extreme weather events, the price of housing capital is given by:*

$$p_{t+1} = \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-(t+1)} \left[-(1+r)\left(z_j\pi_j + \frac{1}{2}x_j^2\right) + v'(\bar{L}_j)\right] \cdot \prod_{i=t+1}^{j-1} (1-(1-\theta\pi_i)(1-x_i)\mu\gamma_{i+1})$$

where $\pi_t = \int_0^1 \pi_{i,t} di$.

The provision of insurance reduces incentives for households to invest in adaptation, leading to a faster decline in the housing supply. This accelerates the rise in house prices. As households' adaptation choices depend on house prices — which reflect the value at risk — the "home equity effect" provides a countervailing force against the moral hazard effect. However, as there is moral hazard, the home equity effect never dominates in equilibrium. More specifically, this is because the elasticity of future house prices with respect to the choice of insurance remains less than unity. Figure 8 illustrates this, and highlights that the private choice of adaptation declines in the fraction of losses covered by insurance.[39] Therefore, climate risk insurance provision leads to underinvestments in adaptation.

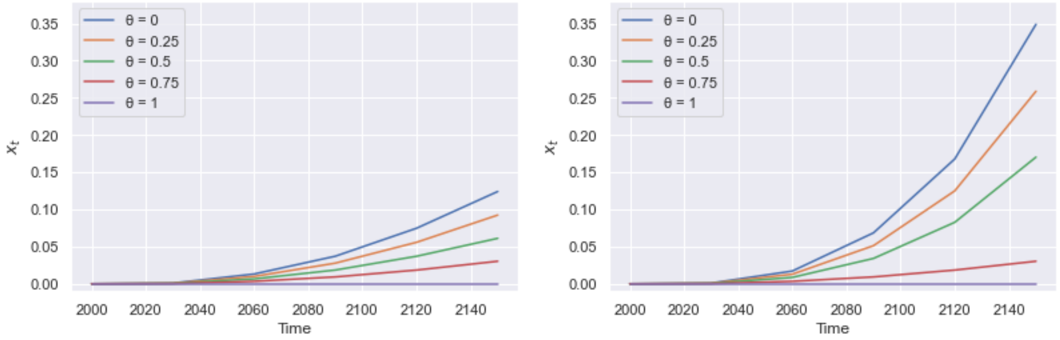

Figure 8: The evolution of the private choice of adaptation, x_t, for $\pi_t = 1$ and for various values of θ, under SSP2-4.5 (left) and SSP3-7.0 (right).

Proposition 9. *The provision of climate risk insurance leads to an underinvestment in private adaptation.*

Proof: See Appendix A.9

While encouraging partial coverage (i.e., altering quantities) could reduce moral hazard (Stiglitz and Weiss, 1981), a trade-off emerges between reducing inequality across generations and reducing inequality within generations. Since the underprovision of private adaptation leads to a faster reduction in the supply of houses, less houses remain available for future generations to live in and derive utility from. Hence, wealth inequality rises *across* generations due to the provision of climate risk insurance. However,

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[39] In the case in which $\theta = 0$ (i.e., private insurers do not cover any losses due to extreme weather events), the private choice of adaptation is equal to the solution in the absence of insurance markets.

a higher insurance coverage reduces wealth inequality *within* a given generation, due to the monetary compensation provided for damages. This latter effect is illustrated in Figure 9, which shows that wealth inequality rises at a slower rate within a generation as the insurance coverage is higher.

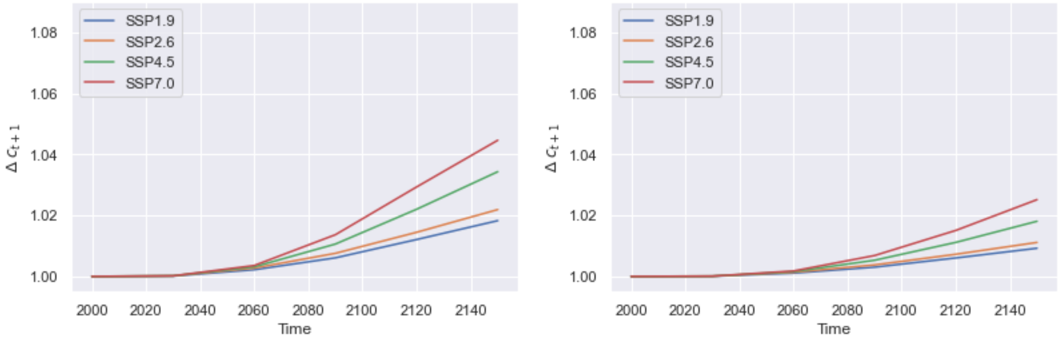

FIGURE 9: THE EVOLUTION OF CONSUMPTION INEQUALITY, Δc_t, FOR $\pi_t = 1$ AND FOR VARIOUS VALUES OF θ, UNDER SSP2-4.5 (LEFT) AND SSP3-7.0 (RIGHT).

This has implication for the optimal design of climate risk insurance, which should account for its distributional consequences - both across and within generations. While a higher coverage would reduce the redistributive effects of climate change within generations, the moral hazard in adaptation discourages investments in resilience to climate risks when coverage is too high, which increases wealth inequality across generations. Policymakers must carefully navigate the challenge of balancing this trade-off in designing effective insurance schemes.

X. Conclusion

This paper explores the broader macro-financial implications of climate change and adaptation, by embedding climate risk in a general equilibrium framework. Households and firms are exposed to extreme weather events, which damage the housing - and physical capital stock. This has redistributive implications. Climate-related damages reduce the productivity of low-income households disproportionately, while the rise in the scarcity of capital increases the costs of borrowing. This means that households with positive savings accumulate wealth at a faster rate, whereas those with a mortgage face an increase in the costs of servicing their mortgage. While the exposure to climate risk weakens demand for housing, I show that the materialization of climate change raises house prices, as habitat becomes increasingly scarcer. This leads to an rise in household debt and a reallocation of credit in the economy towards households.

I analyze the changing incentives of households to invest in climate change adaptation against the backdrop of rising climate risk. Although in frictionless markets price signals lead to efficient adaptation, credit-constrained households have weaker incentives to adapt to climate change, indicating that pricing alone may be insufficient. This reinforces wealth inequality and leads to a further reduction in future habitat. Consequently, housing becomes more important in the consumption bundle as climate change unfolds. This further weakens the incentives of credit constrained households to invest in future resilience, leading to a widening of the private adaptation gap. Credit constraints present a significant challenge to effective climate adaptation (IPCC, 2023; Havlinova et al., 2022) necessitating targeted policies to address the differential impacts of climate change. One such policy is to encourage credit constraint households to rent rather than buy housing. I demonstrate that a societal shift from constrained homeownership to a rental model with unconstrained owners could lead to more efficient adaptation.

The results in this paper indicate that low-income households do not need to live in a riskier area to be more exposed to climatic impacts. A potential limitation of the analysis is that migration is not considered. Cruz and Rossi-Hansberg (2024); Bilal and Rossi-Hansberg (2023); Desmet and Rossi-Hansberg (2015); Muis et al. (2015). Sastry (2022) show that migration is a key adaptation mechanism, as it reduces substantially the welfare impact of climate change. However, migration is costly (Desmet and Rossi-Hansberg, 2015). Therefore, while high income households may have at present a higher residual exposure to climate risk, migrating only offers an alternative to investing in self-protective measures to those who are able to afford it. For example, Varela Varela (2023) shows that post-flood migration patterns reinforce neighborhood segregation, thus increasing preexisting spatial inequities.

Finally, this paper has focused on analyzing household incentives to adapt to climate change, abstracting from mitigation strategies. Given the non-linear nature of climate change, it is important to recognize that adaptation alone cannot completely prevent potentially large economic losses (see also Bilal and Rossi-Hansberg, 2023). Indeed, the extent to which we succeed in mitigating climate change directly affects the necessity for adaptation measures. Adaptation and mitigation strategies both involve substantial costs. Therefore, a trade-off between these may emerge, especially when decisions are made when financial resources are scarce. The interplay between adaptation and mitigation strategies is left as a fruitful avenue for future research.

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Appendix A: Proof of Propositions

A.1 Proof of Proposition 1

Suppose climate risk rises in all future periods by some factor $\sigma > 1$, i.e. $\{\sigma\gamma_{t+1}, ..., \sigma\gamma_{\infty}\}$. Then, the price of house capital is given by

$$p_t^* = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left[v'\left(\bar{L}_j\right)\right] \prod_{\iota=t}^{j-1} \left(1 - \mu_L \sigma \gamma_{\iota+1}\right)$$

Then, the FOC of p_t with respect to σ is given by

$$\frac{\partial p_t}{\partial \sigma} = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left[\frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j} \cdot \frac{\partial \bar{L}_j}{\partial \sigma} \cdot \prod_{\iota=t}^{j-1}(1 - \mu_L \sigma \gamma_{\iota+1}) + v'\left(\bar{L}_j\right) \cdot \frac{\partial}{\partial \sigma}\left(\prod_{\iota'=t}^{j-1}\left(1 - \mu_L \sigma \gamma_{\iota'+1}\right)\right)\right]$$

Remark that

$$\bar{L}_j = \bar{L}_t \prod_{\iota=t}^{j-1} \left(1 - \mu_L \sigma \gamma_{\iota+1}\right)$$

and

$$\frac{\partial \bar{L}_j}{\partial \sigma} = -\mu_L \bar{L}_t \sum_{\iota=t}^{j-1} \gamma_{\iota+1} \prod_{\iota'=t, \iota' \neq \iota}^{j-1} \left(1 - \mu_L \sigma \gamma_{\iota'+1}\right)$$

then

$$\frac{\partial p_t}{\partial \sigma} = \sum_{j=t}^{\infty} \left(\frac{1}{1+r}\right)^{j-t+1} \left[-\frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j} \cdot \bar{L}_j - v'\left(\bar{L}_j\right)\right] \cdot \mu_L \sum_{\iota=t}^{j-1} \gamma_{\iota+1} \prod_{\iota'=t, \iota' \neq \iota}^{j-1} \left(1 - \mu_L \sigma \gamma_{\iota'+1}\right)$$

This is positive if

$$-\frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j} \cdot \bar{L}_j - v'\left(\bar{L}_j\right) \geq 0$$

or, equivalently if

$$-\frac{\frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j} \cdot \bar{L}_j}{v'\left(\bar{L}_j\right)} \geq 1$$

A.2 Proof of Proposition 2

The unconstrained social planner maximizes utilitarian welfare, i.e.

$$\max_{x_t} \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t \left[-\frac{1}{2}(1+r)\bar{L}_t \cdot x_t^2 + v(\bar{L}_t)\right]$$

subject to

$$\bar{L}_j = \bar{L}_t \prod_{\iota=t}^{j-1} (1 - (1 - x_\iota)\mu_L \gamma_{\iota+1})$$

The first order condition for x_t is

$$\left(\frac{1}{1+r}\right)^t \cdot (1+r)x_t \cdot \bar{L}_t = \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^j \left[-(1+r)\frac{1}{2}x_j^2 + v'(\bar{L}_j)\right] \frac{\partial \bar{L}_j}{\partial x_t}$$

Using that

$$\frac{\partial \bar{L}_j}{\partial x_t} = \mu_L \gamma_{t+1} \cdot \bar{L}_t \prod_{\iota=t+1}^{j-1} (1 - (1 - x_\iota)\mu_L \gamma_{\iota+1})$$

this becomes

$$(1+r)x_t = \mu_L \gamma_{t+1} \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-t} \left[-(1+r_{j+1})\frac{1}{2}x_j^2 + v'(\bar{L}_j)\right] \prod_{\iota=t+1}^{j-1} (1 - (1 - x_\iota)\mu_L \gamma_{\iota+1})$$

The first-order condition of the unconstrained household is

$$(1+r)x_t = \mu_L \gamma_{t+1} \cdot p_{t+1}$$

and the first-order condition of the unconstrained social planner is

$$(1+r)x_t = \mu_L \gamma_{t+1} \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-t} \left[-\frac{1}{2}(1+r)x_j^2 + v'(\bar{L}_j)\right] \prod_{\iota=t+1}^{j-1} (1 - (1 - x_\iota)\mu_L \gamma_{\iota+1})$$

A necessary and sufficient condition for the privately optimal level of investment to be efficient is

$$p_{t+1} = \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-t} \left[-\frac{1}{2}(1+r)x_j^2 + v'(\bar{L}_j)\right] \prod_{\iota=t+1}^{j-1} (1 - (1 - x_\iota)\mu_L \gamma_{\iota+1})$$

which holds. Therefore, under the condition that the social planner discounts the welfare of future generations using the market-implied discount rate, the first-order condition of the unconstrained social planner is equivalent to the first-order condition of the unconstrained household. This implies that the market outcome is efficient.

A.3 Proof of Proposition 3

The first-order condition for L_l^* is derived from the constrained household problem as

$$-(1+r)(1+\lambda)\left(\frac{1}{2}x_{l,t}^{*,2}(\lambda)+p_t\right)+(1+\lambda)\left(1-\left(1-x_{l,t}^*\right)\mu_L\gamma_{t+1}\right)p_{t+1}+v'\left(L_{l,t}^*\right)=0$$

This condition defines an implicit expression for λ_t, i.e.

$$\lambda_t=\frac{\left(1-\left(1-x_{l,t}^*(\lambda_t)\right)\mu_L\gamma_{t+1}\right)p_{t+1}+v'\left(L_{l,t}^*\right)-(1+r)\left(\frac{1}{2}x_{l,t}^{*,2}(\lambda_t)+p_t\right)}{(1+r)\left(\frac{1}{2}x_{l,t}^{*,2}(\lambda_t)+p_t\right)-p_{t+1}\left(1-\left(1-x_{l,t}^*(\lambda_t)\right)\mu\gamma_{t+1}\right)}$$

Since λ_t denotes the change in the optimal level of utility for loosening the constraint (and the marginal utility of owning housing is strictly positive), it holds by construction that $\lambda_t \geq 0$. What remains to be determined, is under which condition $\lambda_t = 0$.

As the denominator is strictly positive (see Proof of Lemma 8), the following condition must hold:

$$p_t=\frac{\left(1-\left(1-x_{l,t}^*(0)\right)\mu_L\gamma_{t+1}\right)p_{t+1}+v'\left(L_{l,t}^*\right)}{1+r}-\frac{1}{2}x_{l,t}^{*,2}(0)$$

In this case, $\lambda_t = 0 \implies x_{l,t}^* = x_{h,t}^*$. Recall that the price of housing capital is defined as

$$p_t=\frac{\left(1-(1-x_{h,t}^*)\mu_L\gamma_{t+1}\right)p_{t+1}+v'\left(L_{h,t}^*\right)}{1+r}-\frac{1}{2}x_{h,t}^{*,2}$$

Then, a necessary and sufficient condition for the above condition to hold is that $v'\left(L_{l,t}^*\right)=v'\left(L_{h,t}^*\right)$. This implies that $L_{l,t}^*=L_{h,t}^*$, which means that the constraint doesn't bind. However, in the presence of binding credit constraints, $L_{l,t}^*<L_{h,t}^* \implies v'\left(L_{l,t}^*\right)>v'\left(L_{h,t}^*\right)$. By contradiction, it must then be the case that $\lambda_t > 0$.

A.4 Proof of Proposition 4

To evaluate the effect of a rise in γ_{t+1} on λ_t, the expression for λ_t is first rewritten as:

$$(1+\lambda_t)=\frac{v'\left(L_{l,t}^*\right)}{v'\left(L_{h,t}^*\right)+\frac{1}{2}(1+r)\cdot x_{l,t}^{*2}(\lambda_t)\cdot\lambda_t^2}$$

Then, the FOC becomes

$$\frac{\partial \lambda_t}{\partial \gamma_{t+1}} = \frac{\frac{\partial v'\left(L^*_{l,t}\right)}{\partial L^*_{l,t}} \cdot \frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}} \cdot \left[v'\left(L^*_{h,t}\right) + \frac{1}{2}(1+r) \cdot x^{*2}_{l,t} \cdot \lambda^2_t\right]}{\left(v'\left(L^*_{h,t}\right) + \frac{1}{2}(1+r) \cdot x^{*2}_{l,t}(\lambda_t) \cdot \lambda^2_t\right)^2}$$

$$- \frac{v'\left(L^*_{l,t}\right) \cdot \left[\frac{\partial v'\left(L^*_{h,t}\right)}{\partial L^*_{h,t}} \cdot \frac{\partial L^*_{h,t}}{\partial \gamma_{t+1}} + (1+r) \cdot \left(\frac{\partial x^*_{l,t}}{\partial \lambda_t} \cdot \frac{\partial \lambda_t}{\partial \gamma_{t+1}} \cdot x^*_{l,t}\lambda^2_t + x^{*2}_{l,t}\lambda_t \cdot \frac{\partial \lambda_t}{\partial \gamma_{t+1}}\right)\right]}{\left(v'\left(L^*_{h,t}\right) + \frac{1}{2}(1+r) \cdot x^{*2}_{l,t}(\lambda_t) \cdot \lambda^2_t\right)^2}$$

This FOC is positive if

$$\frac{\partial \lambda_t}{\partial \gamma_{t+1}} \left[1 + v'\left(L^*_{l,t}\right) \cdot (1+r) \cdot \left(\frac{\partial x^*_{l,t}}{\partial \lambda_t} \cdot x^*_l \cdot \lambda^2_t + x^{*2}_{l,t} \cdot \lambda_t\right)\right] \geq$$
$$\frac{\partial v'\left(L^*_{l,t}\right)}{\partial L^*_{l,t}} \cdot \frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}} \cdot \left[v'\left(L^*_{h,t}\right) + \frac{1}{2}(1+r)x^{*2}_{l,t} \cdot \lambda^2_t\right] - v'\left(L^*_{l,t}\right) \cdot \left[\frac{\partial v'\left(L^*_{h,t}\right)}{\partial L^*_{h,t}} \cdot \frac{\partial L^*_{h,t}}{\partial \gamma_{t+1}}\right]$$

Using that

$$\frac{\partial x^*_{l,t}}{\partial \lambda_t} = -\frac{x^*_{l,t}}{(1+\lambda_t)}$$

the LHS is rewritten

$$\frac{\partial \lambda_t}{\partial \gamma_{t+1}} \underbrace{\left[1 + \lambda_t \cdot v'\left(L^*_{l,t}\right) \cdot (1+r) \cdot x^2_{l,t} \cdot \left(1 - \frac{\lambda_t}{(1+\lambda_t)}\right)\right]}_{\geq 0}$$

which is positive. Hence, the RHS remains to be evaluated. The RHS is rewritten as

$$\underbrace{\frac{\partial v'\left(L^*_{l,t}\right)}{\partial L^*_{l,t}}}_{\leq 0} \cdot \underbrace{\frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}}}_{\leq 0} \cdot \underbrace{\frac{1}{v'\left(L^*_{l,t}\right)}}_{\geq 0} - \underbrace{\frac{\partial v'\left(L^*_{h,t}\right)}{\partial L^*_{h,t}}}_{\leq 0} \cdot \underbrace{\frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}}}_{\leq 0} \cdot \underbrace{\frac{1}{v'\left(L^*_{h,t}\right)}}_{\geq 0} + \underbrace{\frac{\left(\frac{1}{2}(1+r_{t+1})x^{*2}_{l,t}\lambda^2_t\right)}{v'\left(L^*_{h,t}\right)}}_{\geq 0} \cdot \underbrace{\frac{\partial v'\left(L^*_{l,t}\right)}{\partial L^*_{l,t}}}_{\leq 0} \cdot \underbrace{\frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}}}_{\leq 0} \cdot \underbrace{\frac{1}{v'\left(L^*_{l,t}\right)}}_{\geq 0}$$

Then, in order for $\partial \lambda_t / \partial \gamma_{t+1}$ to be positive, it must hold that

$$\frac{\partial v'\left(L^*_{l,t}\right)}{\partial L^*_{l,t}} \cdot \frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}} \cdot \frac{1}{v'\left(L^*_{l,t}\right)} - \frac{\partial v'\left(L^*_{h,t}\right)}{\partial L^*_{h,t}} \cdot \frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}} \cdot \frac{1}{v'\left(L^*_{h,t}\right)} \geq 0$$

Suppose the utility function is characterized by CRRA with relative risk aversion coefficient ς. Then, the expression becomes

$$-\varsigma \left(\underbrace{\frac{\partial L^*_{l,t}}{\partial \gamma_{t+1}}}_{\leq 0} \cdot \frac{1}{L^*_{l,t}} - \underbrace{\frac{\partial L^*_{h,t}}{\partial \gamma_{t+1}}}_{\leq 0} \cdot \frac{1}{L^*_{h,t}}\right) \geq 0$$

which holds as the elasticity of the demand for housing of credit constrained, low-income households is larger than the elasticity for housing of unconstrained households in the presence of binding financial constraints. In conclusion, λ_t rises in γ_{t+1} if the utility function for housing is characterized by CRRA with RRA coefficient ς.

A.5 Proof of Proposition 5

If the rental market is perfectly competitive, it must be that (unconstrained) households are indifferent between renting and buying, i.e.

$$\begin{aligned}\mathbb{E}(U(\text{buy})) &= -\left(p_t + \frac{1}{2}{x_{i,t}}^2\right) \cdot L_{i,t} + \frac{\left(1-(1-x_{i,t})\mu_L\gamma_{t+1}\right)p_{t+1} \cdot L_{i,t}}{(1+r)} + v(L_{i,t}) = \\ \mathbb{E}(U(\text{rent})) &= v\left(L_{i,t}\right) - \Upsilon_t \cdot L_{i,t}\end{aligned}$$

with Υ_t the rental price price per unit of housing capital. This gives:

$$\Upsilon_t = \left(p_t + \frac{1}{2}{x_{i,t}}^2\right) - \frac{\left(1-(1-x_{i,t})\mu_L\gamma_{t+1}\right)p_{t+1}}{(1+r)}$$

Recall that with adaptation, the house price is given by

$$p_t + \frac{1}{2}{x_t}^2 = \frac{\left(1-(1-x_t)\mu_L\gamma_{t+1}\right)p_{t+1} + v'(\bar{L}_t)}{(1+r)}$$

where $\bar{L}_t = \int_0^1 L^*_{i,t}di$ and $x_t = \int_0^1 x^*_{i,t}di$. Hence, the rental price per unit of housing capital is given by:

$$\Upsilon_t = v'(\bar{L}_t)$$

The investment in adaptation is purely driven by financial motives. Hence, landlords have the incentive to invest optimally in adaptation, i.e.

$$x^*_{i,t} = \frac{\mu_L\gamma_{t+1} \cdot p_{t+1}}{(1+r)}$$

Consequently, if credit constrained households rent, the optimal investment in adaptation is made for all houses in the economy, not just those owned by unconstrained household.

Since the probability of being hit by an extreme weather event is i.i.d. across households, unconstrained households remain equally well-off in expectation when they become landlords, i.e.

$$\mathbb{E}(U_h(\text{landlord})) = \mathbb{E}(U_h(\text{no landlord}))$$

where

$$\begin{aligned}\mathbb{E}(U_h(\text{landlord})) &= 2\left[-\left(p_t + \frac{1}{2}{x_{i,t}}^{*2}\right) \cdot L^*_t + \frac{\left(1-(1-x^*_{i,t})\mu_L\gamma_{t+1}\right)p_{t+1} \cdot L^*_t}{(1+r)}\right] + v(L^*_t) + \text{Rent} \cdot L^*_t \\ \mathbb{E}(U_h(\text{no landlord})) &= -\left(p_t + \frac{1}{2}{x_{i,t}}^{*2}\right) \cdot L^*_t + \frac{\left(1-(1-x^*_{i,t})\mu_L\gamma_{t+1}\right)p_{t+1} \cdot L^*_t}{(1+r)} + v(L^*_t)\end{aligned}$$

Finally, constrained households are better off if they rent, as this allows them to consume the optimal level of housing capital:

$$\mathbb{E}(U_l(\text{rent})) = -\left(p_t + \frac{1}{2}{x_{i,t}}^{2*}\right) \cdot L_t^* + \frac{\left(1-(1-x_{i,t}^*)\mu_L\gamma_{t+1}\right)p_{t+1} \cdot L_t^*}{(1+r)} + v(L_t^*)$$

This gives them a higher than in the case in which they buy housing (see Proof of Proposition 3):

$$\mathbb{E}(U_l(\text{buy})) = -\left(p_t + \frac{1}{2}{x_{l,t}}^2\right) \cdot L_{l,t} + \frac{(1-(1-x_{l,t})\mu_L\gamma_{t+1})\,p_{t+1} \cdot L_{l,t}}{(1+r)} + v(L_{l,t})$$

A.6 Proof of Proposition 6

Wage inequality increases with climate-related damages when

$$\frac{\partial\,(q_t/w_t)}{\partial\gamma_t} = \frac{\eta}{(1-\eta)} \cdot \left(\frac{(1-\phi)\tilde{l}}{\phi\tilde{h}}\right)^{1-(1-\alpha)\rho} \cdot \frac{\partial}{\partial\gamma_t}\left(\frac{H_t}{(1-\mu_K\gamma_t)\,K_t}\right)^{\alpha\rho} \geq 0$$

For this to hold, it must be that

$$\frac{\mu_K}{(1-\mu_K\gamma_t)} + \frac{\partial H_t/\partial\gamma_t}{H_t} - \frac{\partial K_t/\partial\gamma_t}{K_t} \geq 0$$

or equivalently

$$\frac{\mu_L}{(1-\mu_K\gamma_t)} \geq \frac{\partial}{\partial\gamma_t} ln\left(\frac{K_t}{H_t}\right)$$

Hence, the losses of tangible capital (*i.e. the direct effect*) must be larger than the change in the investment in tangible capital relative to the investment in intangible capital in response to climate-related damages *(i.e. the indirect effect).* To proof this, it suffices to show that

$$\frac{\partial}{\partial\gamma_t} ln\left(\frac{K_t}{H_t}\right) \leq 0$$

Note first that

$$H_t = I_{t-1}^* = \omega \cdot A^\rho \alpha\eta \cdot \frac{Y_t^{(1-\rho)}}{H_t^{1-\alpha\rho}} \cdot h_t^{(1-\alpha)\rho}$$

Using logarithmic differentiation, the derivative of H_t to γ_t becomes

$$(2-\alpha\rho)\frac{\partial}{\partial\gamma_t} ln(H_t) = (1-\rho)\frac{\partial}{\partial\gamma_t} ln(Y_t)$$

The derivative of Y_t to γ_t is given by

$$\begin{aligned}\frac{\partial}{\partial \gamma_t} Y_t &= \frac{\partial Y_t}{\partial H_t} \cdot \frac{\partial H_t}{\partial \gamma_t} + \frac{\partial Y_t}{\partial K_t} \cdot \frac{\partial K_t}{\partial \gamma_t} \\ &= R_t \cdot \frac{\partial H_t}{\partial \gamma_t} + (1 + r_t) \cdot \frac{\partial K_t}{\partial \gamma_t}\end{aligned}$$

This equation provides a relation between the partial derivatives of capital to climate-related damages:

$$\frac{\partial K_t}{\partial \gamma_t} = \frac{\frac{(2-\alpha\rho)\cdot Y_t}{H_t\cdot(1-\rho)} - R_t}{(1 + r_t)} \cdot \frac{\partial H_t}{\partial \gamma_t}$$

It remains to be verified that:

$$\frac{\partial}{\partial \gamma_t} ln \left(\frac{K_t}{H_t}\right) \leq 0 \Leftrightarrow \frac{1}{H_t} \cdot \frac{\partial H_t}{\partial \gamma_t} \geq \frac{1}{K_t} \cdot \frac{\partial K_t}{\partial \gamma_t}$$

There are two cases:

1. $\partial H_t/\partial \gamma_t \leq 0$. The relation between the partial derivatives of capital to climate-related damages gives:

   $$R_t H_t + (1 + r_t) K_t \leq \frac{(2 - \alpha\rho) Y_t}{(1 - \rho)}$$

   Recall that:

   $$\alpha Y_t = R_t H_t + (1 + r_t) K_t$$

   Then, rewriting gives:

   $$\alpha \leq 2$$

   which is always satisfied. Therefore,

   Lemma A1. *The elasticity of tangible capital to climate-related damages is higher than the elasticity of intangible capital, i.e.*

   $$\frac{1}{K_t} \cdot \left|\frac{\partial K_t}{\partial \gamma_t}\right| \geq \frac{1}{H_t} \cdot \left|\frac{\partial H_t}{\partial \gamma_t}\right|$$

   Consequently. wage inequality increases in climate-related damages if $\partial H_t/\partial \gamma_t \leq 0$.

2. $\partial H_t/\partial \gamma_t \geq 0$. Lemma A1 ensures that:

   Corollary A1. *The partial derivatives of H_t, K_t and Y_t to γ_t have the same sign, i.e.*

   $$\frac{\partial H_t}{\partial \gamma_t} \geq 0 \implies \frac{\partial K_t}{\partial \gamma_t} \geq 0 \implies \frac{\partial Y_t}{\partial \gamma_t} \geq 0$$

Then, $\partial H_t/\partial\gamma_t \geq 0 \implies \partial Y_t/\partial\gamma_t \geq 0$. This is a contradiction, since $\mathcal{F}_\gamma \leq 0$. Therefore, Case 2 is ruled out and wage inequality increases in climate-related damages.

A.7 Proof of Proposition 7

The return to tangible capital is given by

$$(1+r_t^*) = A^\rho \alpha(1-\eta)\frac{\tilde{Y}_t^{1-\rho}}{\left(\left(1-\mu_K\gamma_t\right)K_t\right)^{1-\alpha\rho}} l_t^{(1-\alpha)\rho}$$

Using logarithmic differentiation, the derivative of r_t^* to γ_t becomes

$$\frac{\partial r_t^*}{\partial \gamma_t} = \frac{(1-\rho)}{Y_t}\cdot\frac{\partial Y_t^{net}}{\partial\gamma_t} - (1-\alpha\rho)\left[\frac{1}{K_t}\cdot\frac{\partial K_t}{\partial\gamma_t} - \frac{\mu_K}{(1-\mu_K\gamma_{t+1})}\right]$$

For $\rho = 0$, this derivative becomes

$$\left.\frac{\partial r_t^*}{\partial\gamma_t}\right|_{\rho=0} = \frac{1}{Y_t^{net}}\cdot\frac{\partial Y_t}{\partial\gamma_t} - \frac{1}{K_t}\cdot\frac{\partial K_t}{\partial\gamma_t} + \frac{\mu_K}{(1-\mu_K\gamma_{t+1})}$$

Recall that

$$\begin{aligned}\frac{\partial}{\partial\gamma_t}\tilde{Y}_t &= \frac{\partial\tilde{Y}_t}{\partial H_t}\cdot\frac{\partial H_t}{\partial\gamma_t} + \frac{\partial\tilde{Y}_t}{\partial K_t}\cdot\frac{\partial K_t}{\partial\gamma_t}\\ &= R_t\cdot\frac{\partial H_t}{\partial\gamma_t} + (1+r_t)\cdot\frac{\partial K_t}{\partial\gamma_t}\end{aligned}$$

and that

$$\left.\frac{\partial K_t}{\partial\gamma_t}\right|_{\rho=0} = \frac{\frac{2\cdot\tilde{Y}_t}{H_t} - R_t}{(1+r_t)}\cdot\frac{\partial H_t}{\partial\gamma_t} \Leftrightarrow \left.\frac{\partial H_t}{\partial\gamma_t}\right|_{\rho=0} = (1+r_t)\cdot\frac{\partial K_t}{\partial\gamma_t}\cdot\frac{H_t}{2\tilde{Y}_t - R_tH_t}$$

then

$$\begin{aligned}\left.\frac{\partial r_t^*}{\partial\gamma_t}\right|_{\rho=0} &= \frac{\partial K_t}{\partial\gamma_t}\cdot\left[(1+r_t)\cdot\left(\frac{2}{2\tilde{Y}_t - R_tH_t}\right) - \frac{1}{K_t}\right] + \frac{\mu_K}{(1-\mu_K\gamma_{t+1})}\\ &= \frac{\partial K_t}{\partial\gamma_t}\cdot\frac{2}{K_t\cdot(2\tilde{Y}_t - R_tH_t)}\cdot\Big((1+r_t)K_t + R_tH_t - \tilde{Y}_t - 1/2R_tH_t\Big) + \frac{\mu_K}{(1-\mu_K\gamma_{t+1})}\end{aligned}$$

Recall that

$$\alpha\tilde{Y}_t = R_tH_t + (1+r_t)K_t$$

Then

$$\left.\frac{\partial r_t^*}{\partial\gamma_t}\right|_{\rho=0} = \underbrace{\frac{\partial K_t}{\partial\gamma_t}}_{\leq 0}\cdot\underbrace{\frac{2}{K_t\cdot(2\tilde{Y}_t - R_tH_t)}}_{\geq 0}\cdot\underbrace{\Big((\alpha-1)\tilde{Y}_t - 1/2R_tH_t\Big)}_{\leq 0} + \underbrace{\frac{\mu_K}{(1-\mu_K\gamma_{t+1})}}_{\geq 0} \geq 0$$

Note that $\frac{\partial r_t^*}{\partial \gamma_t}$ falls in ρ:

$$\begin{aligned}\frac{\partial r_t^*/\partial\gamma_t}{\partial\rho} &= -\frac{1}{Y_t}\cdot\frac{\partial Y_t}{\partial\gamma_t}+\frac{\alpha}{K_t}\cdot\frac{\partial K_t}{\partial\gamma_t}-\frac{\alpha\mu_K}{(1-\mu_K\gamma_t)}\\ &= \frac{\partial K_t}{\partial\gamma_t}\cdot\left[\frac{\alpha}{K_t}-\frac{2(1+r_t)}{2Y_t-R_tH_t}\right]-\frac{\alpha\mu_K}{(1-\mu_K\gamma_t)}\\ &= \underbrace{\frac{\partial K_t}{\partial\gamma_t}}_{\leq 0}\cdot\underbrace{\left[\frac{2}{K_t(2Y_t-R_tH_t)}\right]}_{\geq 0}\cdot\underbrace{[\alpha Y_t-(1+r_t)K_t-\alpha R_tH_t+\alpha/2\cdot R_tH_t)]}_{\geq 0}-\underbrace{\frac{\alpha\mu_K}{(1-\mu_K\gamma_t)}}_{\geq 0}\leq 0\end{aligned}$$

Nevertheless, for $\rho = 1$, the derivative remains positive, i.e.

$$\left.\frac{\partial r_t^*}{\partial\gamma_t}\right|_{\rho=1}=(1-\alpha)\Bigg[-\frac{1}{K_t}\cdot\underbrace{\frac{\partial K_t}{\partial\gamma_t}}_{\leq 0}+\underbrace{\frac{\mu_K}{(1-\mu_K\gamma_{t+1})}}_{\geq 0}\Bigg]\geq 0$$

Since $\rho \in [0, 1)$, it holds that the cost of capital *rises* is climate-related damages.

A.8 Proof of Proposition 8

Share prices are given by

$$e_t^* = \frac{(1-\omega)R_{t+1}H_{t+1}}{1+r_{t+1}}$$

i.e.

$$e_t^* = (1-\omega)\cdot\frac{\eta}{(1-\eta)}\cdot\left(\frac{\tilde{h}}{\tilde{l}}\right)^{(1-\alpha)\rho}\cdot H_{t+1}^{\alpha\rho}\cdot((1-\mu_K\gamma_{t+1})\,K_{t+1})^{(1-\alpha\rho)}$$

Using logarithmic differentiation, the derivative of e_t^* to γ_{t+1} becomes

$$\frac{\partial e_t^*}{\partial\gamma_{t+1}}=\frac{\alpha\rho}{H_{t+1}}\cdot\frac{\partial H_{t+1}}{\partial\gamma_{t+1}}+(1-\alpha\rho)\left[\frac{1}{K_{t+1}}\cdot\frac{\partial K_{t+1}}{\partial\gamma_{t+1}}-\frac{\mu_K}{(1-\mu_K\gamma_{t+1})}\right]$$

For $\rho = 0$, this derivative becomes

$$\left.\frac{\partial e_t^*}{\partial\gamma_{t+1}}\right|_{\rho=0}=\frac{1}{K_{t+1}}\cdot\underbrace{\frac{\partial K_{t+1}}{\partial\gamma_{t+1}}}_{\leq 0}-\underbrace{\frac{\mu_K}{(1-\mu_K\gamma_{t+1})}}_{\geq 0}\leq 0$$

Note that $\frac{\partial e_t^*}{\partial\gamma_{t+1}}$ increases in ρ, as

$$\frac{\partial e_t^*/\partial\gamma_{t+1}}{\partial\rho}=\alpha\left[\frac{\mu_K}{(1-\mu_K\gamma_{t+1})}+\frac{1}{H_{t+1}}\cdot\frac{\partial H_{t+1}}{\partial\gamma_{t+1}}-\frac{1}{K_{t+1}}\cdot\frac{\partial K_{t+1}}{\partial\gamma_{t+1}}\right]$$

Following Proof of Proposition 5, this derivative is positive and increases monotonically in climate risk.

Since the derivative remains negative for $\rho = 1$, i.e.

$$\left.\frac{\partial e_t^*}{\partial \gamma_{t+1}}\right|_{\rho=1} = \frac{\alpha}{H_{t+1}} \cdot \underbrace{\frac{\partial H_{t+1}}{\partial \gamma_{t+1}}}_{\leq 0} + (1-\alpha)\left[\frac{1}{K_{t+1}} \cdot \underbrace{\frac{\partial K_{t+1}}{\partial \gamma_{t+1}}}_{\leq 0} - \underbrace{\frac{\mu_K}{(1-\mu_K \gamma_{t+1})}}_{\geq 0}\right] \leq 0$$

and $\rho \in [0, 1)$, it holds that share prices *decline* is climate risk.

A. A.9 Proof of Proposition 9

Future house price rises in choice of insurance if and only if insurance accelerates the rate at which the housing stock falls:

$$\frac{\partial p_{t+1}}{\partial \pi_t} = \sum_{j=t+1}^{\infty} \left(\frac{1}{1+r}\right)^{j-(t+1)} \left[\underbrace{\frac{\partial v'(\bar{L}_j)}{\partial \bar{L}_j}}_{<0} \cdot \frac{\partial \bar{L}_j}{\partial \pi_t}\right] \cdot \prod_{i=t+1}^{j-1} \underbrace{(1-(1-\theta\pi_i)(1-x_i)\mu_L \gamma_{i+1})}_{>0}$$

which requires that

$$\frac{\partial \bar{L}_j}{\partial \pi_t} = \bar{L}_t \cdot \sum_{i=t}^{j-1} \mu_L \gamma_{i+1} \left(\frac{\partial x_i}{\partial \pi_t}\right) \prod_{i'=t, i' \neq i}^{j-1} \underbrace{(1-(1-x_{i'})\mu_L \gamma_{i'+1})}_{>0} < 0$$

where

$$\frac{\partial x_t}{\partial \pi_t} = -\frac{\mu_L \gamma_{t+1} p_{t+1}}{(1+r)} + \frac{(1-\pi_t)\mu_L \gamma_{t+1}}{(1+r)} \cdot \frac{\partial p_{t+1}}{\partial \pi_t}$$

For this derivative to be negative, it must be that the elasticity of future house prices, p_{t+1} with respect to the choice of insurance, π_t is less than unity, i.e.

$$\frac{\partial p_{t+1}}{\partial \pi_t} \cdot \frac{1}{p_{t+1}} < 1$$

Suppose this condition does *not* hold. Then, insurance fosters private adaptation, i.e., $\frac{\partial x_t}{\partial \pi_t} > 0$, which implies that insurance reduces the rate at which the housing supply falls, i.e., $\frac{\partial \bar{L}_j}{\partial \pi_t} > 0$. Then, since the supply of housing falls at a slower rate, it must be that $\frac{\partial p_{t+1}}{\partial \pi_t} < 0$.
However, this implies that the home equity effect is negative. Consequently, the choice of adaptation must fall in the choice of insurance, i.e., $\frac{\partial x_t}{\partial \pi_t} < 0$. This implies that the supply of housing falls at a faster rate, i.e., $\frac{\partial \bar{L}_j}{\partial \pi_t} < 0$, which is a contradiction. Hence, demand for insurance crowds out private adaptation.

Appendix B: Marshall Fires and House Prices

The theoretical analysis takes a long-run perspective of the effect of climate-related damages on house prices. While the described impacts can thus only be expected to occur as climate change materializes over time, I provide some suggestive evidence to illustrate the effect of climate change on house prices. To this end, I exploit plausibly exogenous variation in house prices in the Boulder-area in Colorado (CO) after the Marshall Fires of December 2021.

The Marshall Fires is the most destructive wildfire event in the history of Colorado. The Fires was a result of two fires, that eventually merged in the Boulder-area, in Colorado on December 30th, 2021. The first was a lit intentionally by residents in the Eldorado Springs area in order to dispose of old materials and junk (Dougherty and Johnson, 2023). Due to high winds and the drought during the months prior (NOAA, 2024), this lead to a grass fire. Another fire was ignited as a result of hot particles discharged from a power line (Dougherty and Johnson, 2023). The two fires eventually merged, and hurricane-fore winds caused the fire to evolve into a suburban firestorm (NOAA, 2024). Around 50,000 people were evacuated and more than 6,000 acres (24 km^2) of land was burned as a result of the wildfire. The fire ended on January 1st, 2022, as a result of heavy snowfall over night. At that time, the wildfire had lead to two fatalities, 6 non-fatal injuries and destroyed more than a 1000 homes and dozens of commercial structures in the area of Boulder, Superior and Louisville (Dougherty and Johnson, 2023). The associated damages of the Marshall Fires have been estimated at more than 2 billion dollars, making the event one of 20 billion-dollar climate-related disasters in the U.S. in 2021 (NOAA, 2024).

To determine the effect of the Marshall Fires on the house prices in the affected area, I leverage housing data from Zillow. Specifically, I use the Zillow Home Value Index (ZHVI). The ZHVI measures the "typical home" value for a given region and housing type, where the typical home is defined as a mid-tier home (35th to 65th percentile range). Data is available at the ZIP-code level. The measure is smoothed and seasonally adjusted. The ZHVI is available for all (typical) homes, as well as separately for all single-family residences, condos, and all homes with 1, 2, 3, 4 and 5 or more bedrooms.

The time window I consider is from 2 years prior to the wildfire and two years after the wildfire, that is, January 2020 until December 2023. The annual growth rate of home values in a specific ZIP-code i at time t is defined as

$$\text{Growth}_{i,t} = \frac{ZHVI_t - ZHVI_{t-12}}{ZHVI_{t-12}} * 100\%$$

with data reported at month-end.

I consider the Boulder, Superior, and Louisville area as treatment group.[40] As control group, I consider all unaffected areas in the direct proximity of the wildfire zone.[41] This results in 756 observations, of which approximately one-third is in the treatment group. To assess the impact of the Marshall Fires on

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[40] Specifically, the zip-codes 80026, 80027, 80028, 80301, 80302, 80303, 80304, 80305, 80306, 80307, 80308, 80309, 80310, 80314 are in the treatment group.

[41] Zip-codes 80003, 80004, 80005, 80007, 80020, 80021, 80023, 80030, 80031, 80221, 80234, 80241, 80260, 80516 are in the control group.

Table 3: House Value Growth in Colorado After Marshall-Fires

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Typ. Home	Sing.-Fam.	Condo	1 Bedr.	2 Bedr.	3 Bedr.	4 Bedr.	5+ Bedr.
Treat_i*Post_t	3.821***	3.000***	4.482***	3.929**	5.067***	3.574***	2.782***	2.226**
	(0.737)	(0.673)	(0.607)	(1.385)	(0.907)	(0.746)	(0.775)	(0.834)
Year-Month FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ZIP-Code-FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	756	756	707	504	756	756	756	756
R-squared	0.975	0.974	0.970	0.929	0.974	0.973	0.975	0.968

Note: OLS estimation results with and time- and location-fixed effects. The dependent variable in each regression in the annual house value growth (measured using monthly data) in a ZIP-code area (i) for a specific year-month (t). Treat is an indicator variable equal to 1 if the ZIP-code is in the Colorado Marshall Fire Wildfire zone, and 0 for ZIP-codes in unaffected areas just around the wildfire zone. Post is an indicator variable equal to 1 for periods after 12/2021 and 0 for those periods prior. Data is used from 01/2020 - 12/2023. Standard errors are reported in parentheses and are clustered at the ZIP-code level. *** p<0.01, ** p<0.05, * p<0.1.

house value growth in the affected region, I estimate the following relationship:

$$\text{Growth}_{i,t} = \beta \text{Treat}_i \cdot \text{Post}_t + \eta_i + \mu_t + \epsilon_{i,t}$$

where $Treat_i$ is an indicator variable equal to 1 if the ZIP-code is in the Marshall Fire Wildfire zone, and 0 for ZIP-codes in the control group. Post is an indicator variable equal to 1 for periods after (the end of) December, 2021 and 0 for all periods prior. I include both ZIP-code fixed effects, η_i, as well as year-month fixed effects, μ_t. The idiosyncratic error term is denoted by $\epsilon_{i,t}$ and I cluster standard errors at the ZIP-code level. The coefficient of interest is β, which measures the effect of the wildfire on house value growth in affected ZIP-codes after the wildfire event. I hypothesize that this coefficient is positive, as the Marshall Fires put even more pressure on the housing market in the Colorado Boulder-area, which was already facing a severe housing shortage prior to the wildfire event.

The results are reported in Table 3. The first column reports the results for all typical homes. In the subsequent columns, I consider all single-family residences, condos, and all homes with 1, 2, 3, 4 and 5 or more bedrooms. I find that the growth rates in house values is significantly higher in areas affected by the wildfire in the period after its occurrence. Specifically, the growth rate in house values in the area affected by the wildfire was approximately 2.3 to 5.1 percent higher compared to the area just outside of the wildfire zone. This relationship is statistically significant at the 1 percent significance level across most categories. These findings show that the wildfire event put more pressure on the housing market in the affected region due to the loss in housing supply, illustrating the prediction of the theoretical model.

Appendix C: Homothetic Preferences

In the theoretical framework, I assume that preferences of households are quasi-linear. Due to the quasi-linearity of the utility function, households' income does not play a role in determining their choice of housing consumption, as this is the concave part of the utility function. This changes once financial constraints are introduced, as the housing consumption of constrained households depends directly on the resources at their disposal. In Proposition 3, I show that this affects the choice of adaptation as well, leading to underinvest in adaptation by financially constrained households. In this Section, I show that this results holds more generally with fully homothetic households' preferences. Specifically, using Cobb-Douglas preferences, I show that the choice of adaptation increases directly in households' income. When preferences are Cobb-Douglas, the household maximization problem is given by:

$$\begin{aligned}
\max_{c_{i,t+1}, L_{i,t}, S_{i,t}, x_{i,t},} \quad & U(c_{i,t+1}, L_{i,t}) = c_{i,t+1}^{o} L_{i,t}^{\kappa} \\
s.t. \quad & y_i \leq \left(p_t + \frac{1}{2} x_{i,t}^2\right) L_{i,t} + S_{i,t} \\
& c_{i,t+1} \leq \max\left\{p_{t+1}\left(1 - \xi_{i,t+1}\right) L_{i,t} + \left(1 + \hat{r}_{t+1}\right) S_{i,t}, 0\right\} \\
& c_{i,t+1}, x_{i,t}, L_{i,t} \geq 0
\end{aligned}$$

where $o > 0, \kappa > 0$ and $o + \kappa < 1$.

The equilibrium is characterized by a system of equations. Specifically, the optimal demand housing is given by

$$L_{i,t}^{*} = \frac{\kappa \cdot c_{i,t+1}^{*}}{o\left[(1+r)\left(p + \frac{1}{2} x_{i,t}^{*2}\right) - \left((1 - (1 - x_{i,t})\mu_L \gamma_{t+1}) p_{t+1}\right)\right]},$$

where the private choice of adaptation of a given household i in period t is given by

$$x_{i,t}^{*} = \frac{\mu_L \gamma_{t+1} \cdot p_{t+1}}{(1+r)},$$

and demand for the non-durable consumption good follows from the time $t+1$-spending constraint:

$$c_{i,t+1}^{*} = (1+r)\left(y_i - \left(p + \frac{1}{2} x_{i,t}^{*2}\right) L_{i,t}^{*}\right) + \left((1 - (1 - x_{i,t})\mu_L \gamma_{t+1}) p_{t+1}\right) \cdot L_{i,t}^{*}.$$

I solve this system of equation numerically, setting γ_{t+1} equal to its value under the SSP4-7.0 scenario in 2100 and fixing μ_L to one. The variables r and L are assigned their model-implied values from the simulations in Section VIII. For income, I select a grid ranging from 0.1 up to 0.9 with increments of 0.1. In Figure 10, I plot the choice of adaptation as a function of income for different values of the Cobb-Douglas parameters, o, κ.

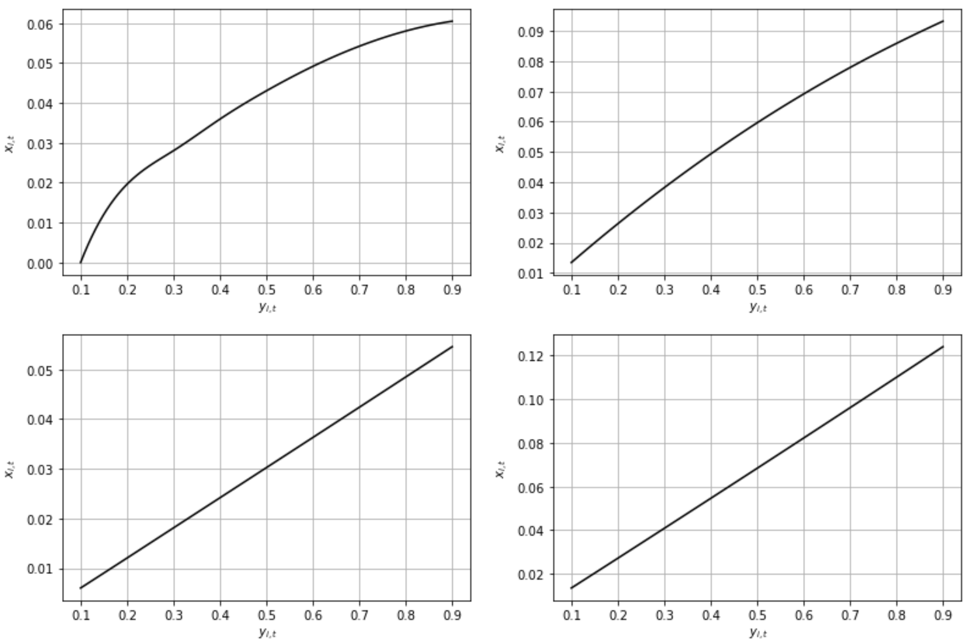

FIGURE 10: THE CHOICE OF ADAPTATION, $x_{i,t}$ AS A FUNCTION OF INCOME, $y_{i,t}$ FOR VARIOUS VALUES OF THE COBB-DOUGLAS PARAMETERS. THE LEFT (RIGHT) UPPER PANEL PLOTS THE RESULTS FOR $o = 0.1, \kappa = 0.5$ ($o = 0.4, \kappa = 0.5$). THE LEFT (RIGHT) BOTTOM PANEL PLOTS THE RESULTS FOR $o = 0.5, \kappa = 0.1$ ($o = 0.5, \kappa = 0.3$)

Appendix D: Other Model Extension

B. Endogenous Supply of Adaptation Capital

Households invest in adaptation by channeling part of their resources to adaptation capital. Thus far, the supply of adaptation capital was considered exogenous. The supply can be endogenized by requiring households to sacrifice part of their labour endowment. Specifically, households must use some of their time to take preventive measures that protect their housing capital. Denote the amount of high-skilled respectively low-skilled labour that a household must sacrifice, for a given choice of adaptation $x_{i,t}$ and housing consumption $L_{i,t}$, by h_x respectively l_x, where

$$l_x, h_x = f(x_{i,t}, L_{i,t}), \quad f'_x > 0, f''_{xx} > 0, \quad f'_L > 0, f''_{LL} = 0$$

When adaptation is labour-based, the income of high- respectively low-skilled households is given by:

$$y_l = w \cdot \left(\tilde{l} - l_x\right)$$
$$y_h = q \cdot \left(\tilde{h} - h_x\right)$$

For simplicity, assume that

$$l_x = \frac{1}{2} \cdot \frac{x_l^2 L_l}{w} \qquad h_x = \frac{1}{2} \cdot \frac{x_h^2 L_h}{q}$$

Then, labour-based adaptation reduces the income of households by an amount equal to what they would have spent on adaptation in monetary terms. Hence, the private choice of adaptation is equivalent to the solution derived in Section V.B.2. However, since labour-based adaptation reduces the amount of labour that can be used in production, this negatively affects output. This is shown in Figure 11, which demonstrates that labour-based adaptation strengthens the negative effect of climate change on output, the more so if climate risk rises.

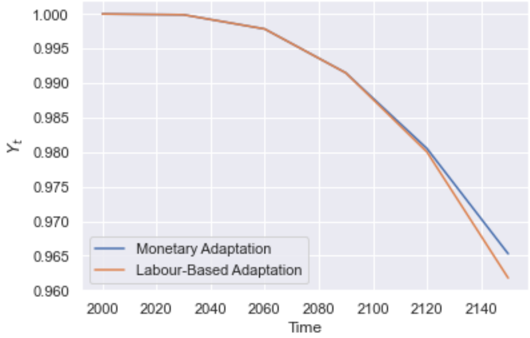

FIGURE 11: THE EVOLUTION OF INCOME, Y (INDEXED TO 1 IN 2000) UNDER SSP3-7.0 IN THE MODEL WITH MONETARY ADAPTATION (BLUE LINE) AND LABOUR-BASED ADAPTATION (ORANGE LINE).

C. Adaptation by Firms

The general equilibrium framework abstracted from adaptation by firms. In this extension, I study the effect of adaptation by firms on output and the costs of capital.[42] Suppose firms invest in climate change adaptation at the same time they invest in physical capital. Denote by $x_{f,t} \in [0, 1)$ the choice of adaptation of firm f in period t. This investment comes at a cost. Specifically, the investment costs are given by $\psi(x_{f,t}, K_{f,t}) = \frac{1}{2} K_{f,t}(x_{f,t})^2$. Similarly as to the household-setting, the costs increase linearly in the amount of physical capital protected, and the investment costs rise at an accelerating rate in the choice of adaptation.

By adapting to climate change, firms reduce protect themselves against climate-related damages from extreme weather events in the next period. Specifically, for a given choice of adaptation, $x_{f,t}$, the firm prevents a fraction $x_{f,t}$, of the idiosyncratic losses. Hence, adaptation leads to a leftward shift in the

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[42] Acharya et al. (2023) document that firms in the United States respond to heat stress by reducing employment in the affected locations and increasing it in unaffected locations, preventing heat-related decline in labour productivity. Balboni et al. (2023) find that flood-affected firms in Pakistan are more likely to relocate to safer areas, and shift purchases towards suppliers in less flood- prone regions. Bilal and Rossi-Hansberg (2023) model adaptation through migration and capital investment decisions in a spatial macroeconomic model, finding that anticipation of future climate damages amplifies climate-induced worker and investment mobility.

distribution of losses by $x_{f,t} \cdot \mu_K \gamma_{t+1}$. In expectation, the losses suffered by a given firm, $\xi_{f,t+1}$, are:

$$\mathbb{E}\left(\xi_{f,t+1}\right) = \left(1 - x_{f,t}\right) \mu_K \gamma_{t+1}$$

By reducing damages to physical capital used in production, adaptation reduces the decline in output:

$$Y_{t+1} = A\left[\eta\left(H_{t+1}^{\alpha} h_{t+1}^{(1-\alpha)}\right)^{\rho} + (1-\eta)\left(\left[\left(1-(1-x_{f,t})\mu_K \gamma_{t+1}\right) K_{t+1}\right]^{\alpha} l_{t+1}^{(1-\alpha)}\right)^{\rho}\right]^{\frac{1}{\rho}}$$

I assume that firms can pledge the adaptation capital as collateral. Then, firms borrow to finance the investment in adaptation capital and the firm maximization problem is given by:

$$\max_{H_t, h_t, K_t, l_t, x_{f,t}, \gamma_t} \pi_{f,t} = \tilde{Y}_t(A, H_t, h_t, \tilde{K}_t, l_t) - \omega R_t H_t - q_t h_t - (1+r_t)\left(1 + \frac{1}{2} x_{f,t}^2\right) K_t - w_t l_t$$

Lemma A2. *The optimal choice of adaptation by firms is implicitly defined as:*

$$x_{f,t}^{*} = A^{\rho} \alpha (1-\eta) \cdot \frac{\tilde{Y}_{t+1}^{1-\rho}}{\left((1-(1-x_f)\mu_K \gamma_{t+1})K_{t+1}\right)^{1-\alpha\rho}} \cdot l_{t+1}^{(1-\alpha)\rho} \cdot \frac{\mu_K \gamma_{t+1}}{(1+r_{t+1})}$$

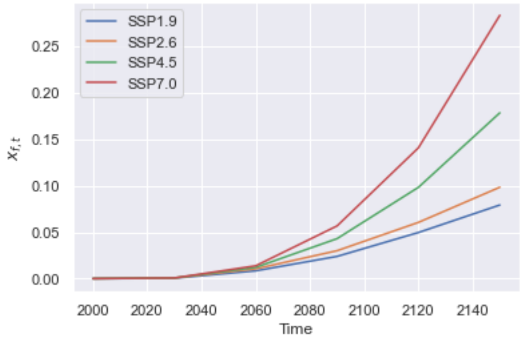

FIGURE 12: THE EVOLUTION OF THE FIRM'S CHOICE OF ADAPTATION, $x_{f,t}$, UNDER THE SSP1-1.9, SSP1-2.6, SSP2-4.5 AND SSP3-7.0 SCENARIO.

Figure 12 plots the evolution of the firm's choice of adaptation over time, showing that the firm's choice of adaptation rises as climate change worsens. Under the most severe climate change scenario, firms invest to reduce more than 25 percent of idiosyncratic losses by the end of the century. The left panel of Figure 13 demonstrates the extent to which this reduces the fall in output, which remains modest.

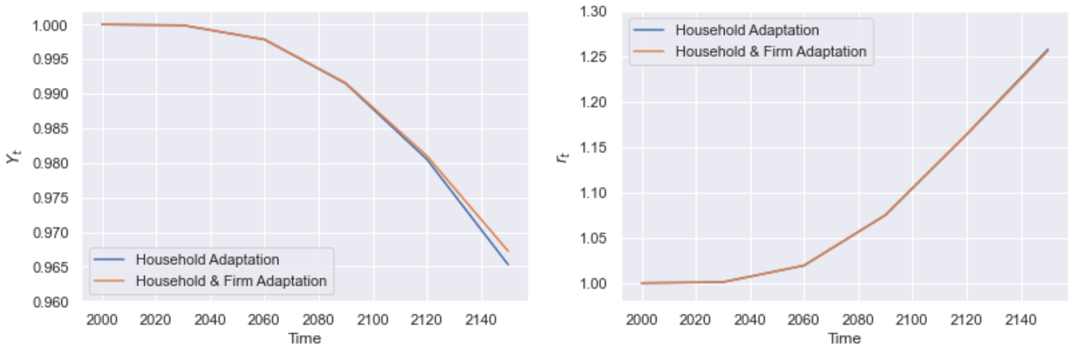

Figure 13: The evolution of income, Y (indexed to 1 in 2000, left) and the evolution of the cost of capital (indexed to 1 in 2000, right) in the model with household adaptation (blue line) and household- and firm adaptation (orange line).

Adaptation by firms is neutral on the cost of capital. By adapting to climate change, firms reduce the decline in aggregate income. This increases the supply of capital in the economy compared to the case in which firms do not adapt, thus reducing the cost of capital. However, firms finance their investment in adaptation by issuing corporate debt. This raises demand for capital, thus increasing the cost of capital. In equilibrium, these two effects fully offset one another, as is shown in the right panel of Figure 13.