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The Impact of Emerging Climate Risks on Urban Real Estate Price Dynamics

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Abstract

In the typical asset market, an asset featuring uninsurable idiosyncratic risk must offer a higher rate of return to compensate risk-averse investors. A home offers a standard asset's risk and return opportunities, but it also bundles access to its city's amenities—and to its climate risks. As climate change research reveals the true nature of these risks, how does the equilibrium real estate pricing gradient change when households can sort into different cities? When the population is homogeneous, the real estate pricing gradient instantly reflects the "new news". With population heterogeneity, an event study research design will underestimate the valuation of climate risk for households in low-risk cities while overestimating the valuation of households in high-risk areas.

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1 Introduction

In the absence of a global agreement on reducing world greenhouse gas emissions, climate change risk continues to be exacerbated by ongoing population and per-capita income growth. Rising greenhouse gas production increases atmospheric concentrations of carbon dioxide and this increases the probability of extreme climate events. Researchers working at the intersection of macro and environmental economics have evaluated the ex-ante social costs of "fat tail" disaster events (Barro, 2013; Costello et al., 2010; Pindyck, 2013; Pindyck and Wang, 2013; Weitzman, 2009, 2011). Macro models of climate changes consequences have often implicitly assumed away any spatial adaptation possibilities.[1]

Recent research on climate change adaptation has studied how changing climate conditions affects regional comparative advantage (Desmet and Rossi-Hansberg, 2013; Costinot et al., 2012). The former present a general equilibrium model featuring free trade across regions and study the welfare consequences of climate change when the location of both production and households can shift as climate conditions shifts while the latter analyze the likely macro effects of micro-scale reallocations of cropland in the face of a changing climate.

Empirical studies have estimated cross-city real estate hedonic pricing regressions to predict how climate change is likely to impact the value of real estate in different locations (Albouy et al., 2013; Kahn, 2009). Intuitively, in the year 2050 will the current real estate price differential between San Francisco and Detroit narrow if Detroit's climate is predicted to improve (i.e. warmer winters) relative to San Francisco?

In this paper, we analyze the spatial implications of emerging climate risk within a system of cities, each of which may face different risks. Within a nation such as the United States or a trading bloc such as the European Union, both labor and capital can move to any location. This potential for spatial arbitrage imposes cross-restrictions across real estate prices and local wages across space. In spatial equilibrium, both heterogeneous households and firms cannot raise their utility and profits by moving to another location. Cross-city real estate prices and wages adjust to support such that the local land market and the local labor market clear (Rosen, 2002).

We introduce a system of cities model to consider the economic incidence of an emerging new catastrophic risk (i.e., climate change). Throughout this paper, we assume that a known subset of cities face the most severe risk due to their

[1] Early work introducing a multi-region economy such as the Nordhaus and Yang (1996) RICE model did not allow for migration of labor across borders. In their model, regions differ with respect to their sectoral shares (i.e some regions have an agricultural focus while others specialize in manufacturing). They assume that the damage function from climate change is identical for each industry across different regions, and then conduct a shift-share calculation to determine how a region is affected by climate change. For example, if a region's economy specializes in agriculture and if climate change impacts agriculture then this region will be sharply impacted by climate change.

coastal geography. As climate scientists make progress and reveal the "new news" that cities such as Miami, New Orleans and New York City face increased risk of large-scale disasters, we seek to understand how equilibrium real estate prices across cities evolve. We embed the future risk of climate change into a classic Rosen/Roback (Rosen, 1979; Roback, 1982; Rosen, 2002) compensating differentials model. Climate change risk is a tied local public bad that (in expected value) poses future costs.

We contrast two main cases. In the first case, the population has homogenous preferences over coastal amenity attributes, climate, and avoiding low probability risks. The hedonic pricing gradient for homes immediately reflects the "new news" of the increased risk that cities such as Miami face due to rising greenhouse gas emissions.

In the second case, we introduce population heterogeneity along several dimensions. The population can differ with respect to income, tastes for amenities, the ability to engage in self protection against emerging risks (see Ehrlich and Becker, 1972), and location-specific networks and knowledge. Together these factors create a wedge between the willingness to pay among coastal incumbent home owners to remain in risky places versus the willingness to pay of outsiders considering moving to at risk cities. In this case, home prices in affected cities may not decline when the "new news" about climate risk becomes common knowledge. This result can be derived even when everyone agrees about the serious risk that the coastal cities face. An econometrician conducting an event study is likely to underestimate the average person's willingness to pay to avoid climate risk.

The key intuition here is to recognize that the marginal household, whose willingness to pay to live in the risky city sets the market price, may have a comparative advantage in coping with local risk or may have built up city specific capital (both social capital and local knowledge) such that this household effectively faces a higher migration cost for leaving the city. As we discuss below, this endogenous differential valuation of the same city by "insiders" and "outsiders" has implications for considering the merits of place based disaster insurance such as government FEMA programs.

In the literature on the fat tails of rare disasters, households within the model are aware of risks of which the econometrician is ignorant. In our model, the situation is different: both households and the econometrician are fully aware of the objective risks facing different cities. In this paper, the econometrician is unaware of the type and degree of household heterogeneity. This limits the extent to which prices of real estate—determined by marginal agents—reflect the willingness to pay of the average household. This limitation, due to residential sorting based on observed and unobserved attributes of both the city and the migrant, bears a similarity to the work of Shogren and Crocker (1991) on the attributes incorporated into hedonic pricing functions. Our findings concerning the information embedded in the hedonic gradient build on recent work by Kuminoff and Pope (forthcoming) in studying the economic incidence of changes in local public goods (in this case coastal safety).

Our findings build on past work in local public finance by scholars such as Starrett (1981), who examined the conditions under which local public goods will be capitalized completely, partially, or not at all. In that context, Lind (1973) and Kanemoto (1988) provide guidance on the interpretation of capitalization studies as providing bounds on the heterogeneous population's willingness to pay for location specific attributes.

In the last section of the paper, we discuss how essential heterogeneity (see Heckman et al., 2006) affects inferences from standard hedonic real estate event studies where the event in question is the realization that specific cities face severe climate change risk. Our findings have a similar flavor as the Shogren and Stamland (2002, 2005) analysis of hedonic wage regressions seeking to recover statistical value of life estimates in the presence of essential heterogeneity.

2 Will Miami Vanish?

The motivating example for this paper is Miami. The Miami metropolitan area is home to six million people. The city itself is located six feet above sea level. In summer 2013, Rolling Stone magazine published a long front page article focusing on the claim that Miami is doomed because of imminent sea level rise (Goodell, 2013). This salient case study highlights the coming challenge that the U.S coastal population faces. Rappaport and Sachs (2003) document that a majority of the nation's population and income is located in coastal and Great Lakes areas. In the case of Miami, urban planning documents highlight that Miami-Dade County is planning for sea level rise (Miami-Dade County, 2010). The housing crisis notwithstanding, Miami home prices have increased nearly as rapidly as those of far-inland Denver over the last thirty years, showing no stark decline as climate research has progressed.[2]

The apparent non-responsiveness of Miami real estate to changing climate risk poses a puzzle: why aren't holders of Miami real estate assets compensated for this risk with a price discount? This puzzle is almost the inverse of the equity premium puzzle, where risk-averse investors hold bonds despite the low returns. The answer of Barro (2006) is that the fat-tails of consumption disasters, unobserved to the econometrician, lead investors to hold safer assets. In our puzzle, people pay apparently large sums to hold risky assets—Miami real estate—whose risk profile has increased with the advent of climate change. In our case, unobserved household heterogeneity means that only the households most willing or capable of dealing with these risks choose to hold Miami real estate, limiting the price impacts of emerging climate risks.

[2]See Figure 1 in the appendix. Data from Trulia indicates that Miami coastal areas such as Coral Gables and Miami Beach experienced an even more pronounced recent boom.

In considering the Miami case as a leading motivating example, we seek to focus attention to the damage natural disasters pose to the place-based capital stock rather than to human longevity. Cross-country research has documented that natural disasters are killing fewer people over time and that richer nations suffer fewer deaths from natural disasters (Kahn, 2005). We recognize that extreme natural disasters such as Hurricane Katrina which is estimated to have killed roughly 1,850 people in 2005 can be deadly. Valuing each life lost at $6 million yields a total value of life lost at $11.1 billion. Estimates for the property damage from Hurricane Katrina are in the range of $100 billion (Knabb et al., 2005). An alternative way to look at the damage caused by Katrina is to recall that in the year 2000 that New Orleans had a population of 490,000. This means that the 1,850 deaths from Katrina represented 0.0038 of the area's total population; for comparison there were 210 homicides in New Orleans in the same year (Van Landingham, 2007).

In the case of Hurricane Sandy in 2012, this storm caused 117 deaths and a total of $65 billion dollars of damage (Mulvihill, 2013; Newman, 2012). This example highlights that the damage risk to physical property swamps the total death risk. We believe that the ratio of total value of lives lost to climate change disasters divided by the total damage to physical capital will only decline over time. With the rise of smart phones and emergency warnings, we predict that the footloose coastal population (facing mandatory evacuations) will become more responsive to disaster alerts so that fewer people die in disaster events while buildings and infrastructure are highly immobile and subject to extreme damage. This discussion motivates some of the modeling assumptions we make below.

3 A Model of Rare Disasters with Variable Risk Across Cities

3.1 The Model with Homogeneous Households

Consider a model of household location choice where households maximize lifetime utility. To choose a location $j(t) \in J$ requires ownership of an asset h_j (i.e., a home) that provides access to city j's amenity a_j and also its idiosyncratic maintenance shocks. The first maintenance shock is a small but regular depreciation shock δ_j and the second is a rare but large catastrophic shock κ_j.[3] Both are i.i.d. across time, and independent across space.[4]

[3] In addition to housing capital, public capital is also at risk, and κ_j can be interpreted as including the risk that local homeowners will be compelled to rebuild damaged public capital. We discuss private capital in a later section.

[4] The same climatic pressures may create drought in one area and flooding in another, and a hurricane may impact multiple locales; the i.i.d assumption is a simplification. However, given that households choose one city at a time and they choose this city prior to the observation

Households are free to buy and sell these assets each period, and transactions occur prior to the realization of any shocks. For a household currently living in city i who chooses to live in city j, lifetime utility is the discounted sum of period utilities, given by $u(c_{ij}, a_j)$. The houshold faces a period-by-period budget constraint of the form $c_{ij} + (p_j - \delta_j - \kappa_j)\, h_j = y + p_i h_i$ where y is the household endowment and p_i is the equilibrium price in city i. The subscript ij denotes a household that begins in city i and chooses to live in city j, recognizing that consumption may be different for two households who both move to j but who began in different cities.

For each city, there is a fixed supply of homes. This assumption can be interpreted as each city having a fixed quantity of land that must be combined with housing materials in a fixed proportion in order to produce housing services, and that the depreciation and catastrophic shocks represent regular maintenance and disaster-rebuilding, respectively. Alternatively, the assets can be interpreted as trees that bear two kinds of fruit: a fixed a_j and a variable $y - \delta_{jt} - \kappa_{jt}$. Seen in this light, the model is similar to those of Barro (2006, 2013), where we have allowed for a variety of asset trees from which households must choose just one.

In equilibrium, households will not choose to move; they will have already sorted into the city that maximizes their utility given relative prices. By assumption, each period's location decisions are made before the shocks are observed and thus relative prices are invariant from period to period and depend only on *expected* shocks.

We now consider the following asset pricing exercise to calculate the willingness to pay for real estate in different cities. If a household residing in city i purchases a home in city j for price p_{ij}, they expect to receive utility $U_{ij} = E[u(y + (p_i - p_{ij}) - \delta_j - \kappa_j, a_j)] + \sum_{t=1}^{\infty} \beta^t E[u(y - \delta_{jt} - \kappa_{jt}, a_j)]$. By setting $U_{ij} = U_i$, where U_i is the utility the household would receive if they stay, we can solve for the maximum price p_{ij} that the household would pay to move to city j.

$$
\begin{aligned}
E[u(y + (p_i - p_{ij}) - \delta_j - \kappa_j, a_j)] + \sum_{t=1}^{\infty} \beta^t E[u(y - \delta_{jt} - \kappa_{jt}, a_j)] \\
= \sum_{t=0}^{\infty} \beta^t E[u(y - \delta_{it} - \kappa_{it}, a_i)]
\end{aligned}
\tag{1}
$$

In the initial scenario, the κ and δ processes are stationary, and the equation can thus be simplified.

$$
\begin{aligned}
(1-\beta)E[u(y + (p_i - p_{ij}) - \delta_j - \kappa_j, a_j)] + \beta E[u(y - \delta_{jt} - \kappa_{jt}, a_j)] \\
= E[u(y - \delta_{it} - \kappa_{it}, a_i)]
\end{aligned}
\tag{2}
$$

of shocks, their concern is with the average expected shock in their choice city, rather than possible correlations across cities.

We suppose that at some initial date zero, households were free to choose locations and prices adjusted to make them indifferent. Those households who initially chose high-amenity and low-risk areas would have bid more initially and those high prices would persist in the steady state.

3.2 The Model with Heterogeneous Households

A similar equation can be derived in the case of heterogeneous households. While the potential types of household heterogeneity are limitless, we focus on three key cases: variable income levels, variable self-protection abilities, and the formation of local endogeneous social networks.[5] The first takes the form of a different endowment y_h, where h indexes households; the second involves a utility parameter ρ_h that reduces the effects of the catastrophic shock κ; and the third is modeled as a fixed moving cost μ. Solving the budget constraint for c and substituting again gives an equation that can be solved for the willingness to pay of household h in city i considering a move to city j.

(3)

$$(1-\beta)E[u(y_h+(p_i-p_{ij})-\delta_j-(1-\rho_h)\kappa_j,a_j)]+ \\ \beta E[u(y_h-\delta_{jt}-(1-\rho)\kappa_{jt},a_j)]-(1-\beta)\mu = E[u(y_h-\delta_{it}-(1-\rho)\kappa_{it},a_i)]$$

We can use this equation to solve for initial distribution of households across cities. We further assume that the distributions of $E[\delta_i]$, $E[\kappa_i]$, and a_i are such that *a priori*, all residents agree on which is the"worst" city, which we denote city l. Note that in equilibrium, $p_l = 0$. Consider then Equation (3) for household h in city l considering a move to city j. To solve for the distribution of households, consider each city $j \in J$ and calculate the willingness to pay p_{lj} for each household. Ordering these bids from highest to lowest, and recalling that each city has a fixed supply of homes, call $\hat{p}_j$ the willingness to pay of the marginal household. Take the city with the highest $\hat{p}_j$, and allocate to that city those households willing to pay at least $\hat{p}_j$. After allocating these households, repeat the process for the remaining households and cities until all households are allocated. This is the initial equilibrium distribution of households. Note also that the order in which the cities are selected offers an implicit ranking of the quality of life in these cities.

We use this distribution to solve for the set of prices across all cities. Beginning with the last two cities allocated. Because the worst city l has $p_l = 0$, the price of the next-to-worst city is the price that makes the marginal household in city l just indifferent between choosing the next city. Repeat this process for each city, moving up the implicit ranking identified previously. The last city priced

[5]The third case is reminiscent of Krupka (2009), where each household invests in human capital that enhances its particular local amenities.

will be the first city that households were allocated to: that with the highest marginal willingness to pay.[6]

After allocating households and solving for each city's prices, the resultant equilibrium will initially be stable: the relative values of the various shocks are stable across cities, and no household will be willing to pay to move a better city nor interested in paying less for less amenable city. This finding will not, in general, hold true in the next section after introducing climate change.

4 Climate Change Risk as "New News"

We now introduce climate change. Climate change is a one-time unanticipated event that alters the future risks of different cities in the economy. There is no learning *per se*: agents simply wake up to a new probability distribution of future outcomes. As an example, they may discover that climate change will affect Miami in the year 2040, Chicago in 2060, and Denver in 2080. They will also uncover the magnitude of the effect in each city. In particular, households learn that the distribution of catastrophic shocks $\kappa_{i,t}$ will worsen in the future for each city, as a function of the stock of global greenhouse gases. For each city, we suppose that there is a threshold level of greenhouse gases ϕ_i that will trigger the one-time transition from relatively-low to relatively-high risk, where the relative changes may vary by city. If greenhouse gases rise predictably, then this translates to a threshold year which we call τ_i at which point city i will increase in risk. We proceed with these assumptions in place.

4.1 Real Estate Pricing Impacts of Climate Change with Homogenous Households

The economy is in steady-state equilibrium when climate change is discovered. Once all cities have transitioned from their low- to high-risk state, the economy will be in a new steady-state equilibrium and a new version of Equation (2) will hold. We now consider what will happen to these bid functions during the transition to this new equilibrium. For convenience, we suppose that utility is quasilinear in the consumption good.[7]

With homogeneous households and fixed housing supply, prices in each period will ensure that no household will choose to move in any future period. With this equilibrium condition, we can write down the bid function for a household

[6] Note that the equilibrium price p_j will in general not be equal to that calculated when allocating households across cities, $\hat{p}_j$. The former is calculated based on the marginal household's willingness to pay to move from their next-best city while the latter was calculated based on the willingness to pay to move from the worst city.

[7] This simplification departs from Barro (2013), where the strict concavity of utility is critical in generating a premium for risky assets. Were we to maintain strict concavity, the null finding of no price change would be an even more surprising result.

living in city i considering a move to city j as a one-time choice between the discounted stream of amenities and shocks in city i and those in city j. The expected depreciation shock in city i is written δ_i and the expected catastrophic shock in city i is written κ_i^L or κ_i^H for low- and high-risk periods, respectively.

$$
\begin{aligned}
p_{ij} &= p_i + \frac{1}{1-\beta}\left[(\delta_i - \delta_j) + u(a_j) - u(a_i)\right] \\
&\quad + \sum_{t=0}^{\tau_i} \beta^t \kappa_i^L + \frac{\beta^{\tau_i}}{1-\beta}\kappa_i^H - \sum_{t=0}^{\tau_j} \beta^t \kappa_j^L - \frac{\beta^{\tau_j}}{1-\beta}\kappa_j^H
\end{aligned} \tag{4}
$$

Willingness to pay to move from city i to city j is increasing with the relative amenity value in j and decreasing with the relative expected losses in j. Willingness to pay is decreasing in the transition year τ_i but increasing in the transition year τ_j. Note that cross-effects are not important in the homogeneous case as the price in any other city j' will be such that no household would be strictly better off by moving there.

It is clear from Equation (4) that any future changes in local climate will be reflected in house prices immediately. To an observer, the only difficulty in ascertaining whether the relative price has fallen in city j would be if τ_j were sufficiently distant that the discounted effects of climate change are negligible.

4.2 Climate Change's Impact on the Cross-City Spatial Equilibrium in the Essential Heterogeneity Case

We now investigate how our three types of household heterogeneity affect the equilibrium housing price dynamics in response to new information about the severity of climate change. We are especially interested in cases where a neutrality result holds, in which real estate prices of high-amenity but at-risk locales like Miami remain unchanged despite the discovery of climate changes that adversely affects such cities. As before, the three dimensions of heterogeneity are captured by household income y_h, household self-protection ability ρ_h, and the moving cost μ. The self-protection parameter takes a value between zero and one and measures the portion of a catastrophic shock that affects a particular household; a high value indicates that a household is not greatly affected.

Proposition 1 *Changes in relative climate risk across cities will alter the relative prices of those cities only if the changes in risk alter the willingness to pay of the marginal resident. If the marginal resident of an at-risk city possesses perfect self-protection capabilities, costly local endogenous networks, or a high enough income, then their willingness to pay will be unchanged and prices will not change despite an inarguable increase in climate risk.*

Income heterogeneity will produce *ex ante* sorting whereby the rich locate in (and bid up the price of) high-amenity cities. So long as the rich are rich enough they will choose to remain in high-amenity Miami after the new news of climate change—despite its increased risk of catastrophic shocks.[8] Because the choice set of cities is bounded, there exists a highest-amenity city. Suppose that utility is separable and strictly concave in consumption, and that for high-income households we have that $\frac{\partial u(c_i,a_i)}{\partial a_i} > \frac{\partial u(c_i,a_i)}{\partial c_i}$ for even high-amenity cities. In order to enjoy the best amenities in the country, the very wealthiest are willing to rebuild their houses every year.[9]

For those at the other end of the income scale, however, climate shocks will compound their already-high marginal utility of consumption. If the poorest are unable to bid their way ouf of low-amenity but high-risk locales, then they will suffer particularly large costs from climate change. Because of the limited ability to pay of the poor, and the already low amenity value of these locations, the fall in observed prices in these locales will be smaller than that observed in the case of homogeneous households—and smaller than the average household's willingness to pay to avoid climate change. Another way of saying this is that the middle class don't have to place large bids in order to outbid the poor for houses in safer cities. Income heterogeneity at both the upper and lower ends will thus serve to underestimate the average costs of climate change.

Returning to the quasi linear utility case, the possibility of heterogeneity means that the bid function for an individual of type h in city i for a home in city j must be modified:

$$p_{ij} = p_i + u(a_j) - u(a_i) - (E[\delta_j] - E[\delta_i]) - (1 - \rho_h)(E[\kappa_j] - E[\kappa_i]) - \mu \tag{5}$$

Self-protection against the risk of climate change provides a source for the neutrality result. In the extreme, a Miami resident with the ability to perfectly self-protect will exhibit no change in their willingness to pay for living in a risky city so long as its amenities are unaffected. Even in the face of seemingly extreme climate catastrophes, a Miami filled with such households will retain its initial price. A Denverite with no self-protection abilities will reduce her bid for Miami real estate one-for-one with the change in expected losses from catastrophic shocks. And indeed, they—like the econometrician—will be surprised to see that Miami residents with high self-protection show no inclination to leave nor to pay less to remain in Miami.

Finally, endogenous localized social capital provides a third source for the neutrality result. The presence of the moving cost—our stand-in for the endogenous formation city-specific social capital—induces a wedge between the willingness to pay of the marginal resident of Miami and the marginal non-resident

[8] If the rich face meaningful risk of death, they will retreat to less-risky cities and leave the poor to enjoy the amenities in riskier cities. Avoiding risky cities is a type of input in the health and safety production function, and in this case the rich will place a greater value on avoiding risk (Hall and Jones, 2007).

[9] Of course, the best amenities might be in a low-risk city. If the unconditional distribution of disaster risk across cities is the same as its distribution conditional on amenity values, then rich will choose high-amenity but low-risk areas. It is the correlation of amenities (beaches) with risks (hurricanes) that leads to an underestimation of willingness to pay to avoid climate risk.

who settles in an alternative locale. Before settling on cities, the two marginal households—one just within the margin and one just outside—have nearly identical bids for Miami property. The winning bidder values Miami at price p_m and so the household that just misses out values it at $p_m - \Delta$. Upon settling into Miami and its next best alternative, respectively, the marginal Miami resident and non-resident see their bids drift apart: due to the cost of moving, the non-resident would now bid only $p_m - \Delta - \mu$ while the resident would rather pay $p_m + \Delta$ than move to their next-best alternative.

The moving cost μ could also be interpreted as the cost of locating in any except the household's "preferred" city, where this preference is exogenously determined. For instance, some residents of Miami prefer it due to its proximity to other nearby countries, a plausible interpretation of the sizable populations of Cubans, Colombians, and Venezuelans that live in the area. A similar wedge would open in this case, and could justify the continued *increase* in population that Miami has seen despite the discovery of climate change.

Whether due to endogenous networks or exogenous preference, the moving cost produces a wedge between the bid functions of the marginal resident and and the marginal non-resident. This wedge between residents and non-residents implies that, so long as the increase in the (future, uncertain) costs of climate catastrophes are smaller than the (immediate, guaranteed) costs of moving and establishing a new social network, Miami residents may rationally choose to remain rather than to move.

5 Three Extensions

In this section, we sketch three extensions of the model that merit future research. In our basic model, a fixed supply of land meant that the only observable outcome variable was relative prices, and an endowment economy meant that the only actors were households. These extensions relax these strict assumptions and explore the consequences, while maintaining the core intuition that sorting by heterogeneous agents might limit the observed responses of real estate prices, wages, and migration to climate shocks.

First, consider the case of introducing a national government that engages in coastal maintenance, provides public goods and reimburses homeowners for some portion of catastrophic losses. To simplify our analysis, we have abstracted away from introducing governmental social insurance, such as FEMA, to protect at-risk cities using federal tax revenue.[10] At first glance such spatial subsidies create a spatial moral hazard effect as the federal government is implicitly subsidizing risk taking by those who love coastal locations.[11] In our model, there is

[10]Popular Flood Insurance Law Is Target of Both Political Parties

[11]Kousky et al. (2006) discuss the interaction between government place based investments and household locational choice. In their model, multiple equilibria emerge as the government is more likely to build seawalls if more people are expected to live there and more people will

a subset of the population who inelastically demand to continue to live in at-risk cities. This willingness to pay is due to idiosyncratic matching of households' preferences to the attributes of different locations and due to the endogenous networks built up over time, which the household knows it will lose if it moves away. In this sense, Miami solves a co-ordination problem: despite the fact that the city faces new risk its total package of attributes compensates for the risk and keeps the rational household in place. In such a setting, the benevolent government will recognize that those who remain are more "victims" than opportunists.

Within the model, the discovery of the catastrophic shock process comes as truly "new news": it's a zero-probability event against which agents cannot have insured themselves. Once discovered, agents are free to move elsewhere to avoid future climate change—if they can find a willing trading partner, a possibility that can only arise with population heterogeneity. For Miami, climate change will not induce in-migration as the city is now a worse prospect than before; at the same time infra-marginal residents may not wish to leave and, in any case, will find few willing partners in a sale. These facts suggest a role for a national government to invest in place-specific subsidies—whether defensive protections like sea walls or transfers in the event of a catastrophe—for Miami and, so long as the subsidy is not too great, there is no concern of moral hazard.

A second modification to the model would be the introduction of endogenous local housing supply. Our formal model focuses on the housing demand side and simply fixes an inelastic housing supply, which implies that any change in the marginal willingness to pay would cause an immediate change in prices. This price sensitivity gives substance to our neutrality results. However, endogeneity of housing supply also enables the possibility of net population changes in high-risk and low-risk locations—an additional source of data to the researcher.

Even with endogenous housing supply, the durability of housing capital will nevertheless yield a kinked housing supply curve as presented in Glaeser and Gyourko (2005). They argue that in a city such as Detroit the durability of housing means that there is a fixed supply of existing older homes (built when Detroit was the car capital of the world) yielding a vertical supply curve up to the point where the price of housing exceeds the marginal cost to developers of building new housing. In this endogenous-housing extension to our model, any Miami resident who prefers to leave following the discovery of the catastrophic shock process would be able to do so. As in the Detroit of the Glaeser and Gyourko (2005) model, durable housing capital will remain in place despite these evacuees: supply is downwardly inelastic as before, and thus as before prices in Miami are sensitive to any decrease in willingness to pay.

A final extension of the model would be to introduce local labor markets in which firms hire workers, rent land, and invest in city-specific capital. Firms might face different self-protection costs than households, and might expect

move to an area where sea walls are expected to be built.

different reimbursement from government programs. However, firms would also sort spatially: service-sector firms with low capital requirements (like households with effective self-protection) may face a negligible penalty from locating in Miami. This sectoral sorting would tend to keep wages high in Miami despite climate risks to Miami's capital goods. Furthermore, high-amenity but risky locales may specialize in attracting wealthy retirees who earn capital income from safer regions. This will create a small but well-compensated labor pool in high-amenity at-risk areas. In all of these cases, the inclusion of firms generates additional dimensions along which sorting acts to minimize the observed changes in at-risk locales. Conversely, capital-intensive firms may follow their workers to at-risk locales. In this case, the cost of insuring their capital will lower the wage offers in risky areas.

6 Empirical Implications for Hedonic Research Measuring Disaster Capitalization

Economists often estimate dynamic hedonic models to test if real estate prices change in response to changes in local public goods such as air quality improvements (Chay and Greenstone, 2005), Superfund site cleanups (Greenstone and Gallagher, 2008; Gamper-Rabindran and Timmins, 2011), and improvements in urban transport infrastructure (Zheng and Kahn, 2013). Our model of emerging climate risk, where the discovery of this risk is new news to households, lends itself to an event study framework. We now seek to position our paper's findings within this existing literature.

Consider the following hedonic regression, where ϕ_i is a continuous variable that indexes susceptibility to climate risk. In particular, ϕ_i is the threshold level of CO_2 that will trigger a transition from the low- to the high-risk state in city i. For example, suppose that $\phi_{Miami} = 450ppm$. When the level of atmospheric CO_2 reaches 450 *ppm*, the risk and severity of climate disaster will undergo a one-time increase from their current levels. For simplicity, suppose that all cities face identical initial climate risk, that ϕ_i triggers an identical increase in disaster risk for all cities, and that the interest rate is constant.[12] The only variation across cities comes from the timing of the transition, which is governed by ϕ_i; a "risky" city is therefore one that will experience climate change sooner than later.

Suppose the econometrician observes sales prices for a large sample of homes with the same physical structure scattered across a range of cities over many year. The econometrician observes each city's quality of life attributes and each city's susceptibility to climate disaster as indexed by ϕ_i. However, the econometrician does not observe household characteristics of those buying and

[12]Within our model, these simplifications amount to a common κ for all cities before climate change, a new (but still common) κ after, and the previous assumption of quasilinear utility.

selling houses.[13] Finally, we denote by τ the year of climate change discovery, and $\mathbf{1}_\tau(t)$ takes the value 1 only for the year τ. Under these assumptions, we can write down an event study regression model, where the change in price upon the discovery of climate change is regressed upon the index of climate risk suspectibility.

$$Price_{h,i,t} - Price_{h,i,t-1} = a \times Z_i + b \times \mathbf{1}_\tau(t) \times \phi_i + U_{h,i,t} \tag{6}$$

In this regression, b represents the compensating differential for a higher threshold for climate change. In the context of our model with homogeneous households, the average person in the economy would be willing to pay b to avoid the extra maintenance costs and the marginal increase in the death risk associated with a lower threshold of ϕ_i—that is, associated with additional time spent under the high-risk climate regime. The regression coefficient b should reflect the payment that keeps her just indifferent in expected lifetime utility.

Now consider the case in which people differ with respect to their incomes, their self-protection capabilities, and their localized social capital. Suppose that there are two types of cities, coastal (e.g., Miami) and inland (Denver) where the threshold ϕ_i is smaller in coastal cities. The price of coastal real estate is fixed by the willingness to pay of the marginal coastal resident. In the extreme case of self-protection in which the marginal coastal resident can perfectly offset climate disasters, the marginal bid for coastal real estate would not change at all upon the discovery of climate change and the researcher would thus recover an estimate of zero for b and conclude that markets are not pricing risk. This is the empirical counterpart to the neutrality result given in Proposition 1.

Conversely, if the marginal Miami resident has no self-protection abilities, then the price of Miami real estate will fall and the researcher will conclude that Miami residents are suffering large climate-triggered losses—even if the typical Miami resident is a self-protector who faces limited utility costs from climate change. In this case, the unobserved variation in the ability to self protect against catastrophic risks will create the appearance that coastal households are exposing themselves to a high degree of risk, relative to the price discount they receive for this exposure. These results have a similar logic as that of Shogren and Stamland (2002, 2005) who focused on what can be inferred from conventional value of a statistical life hedonic wage regressions in the presence of population essential heterogeneity (Heckman et al., 2006).

Populations may also differ in unobserved location-specific demand. This possibility further complicates the interpretation of the hedonic real estate regression presented above. Households that build valuable city-specific social networks may lose access to this social capital if they leave, and even the marginal coastal household may have a discontinuous willingness to pay for their current city relative to the alternatives. When climate change is discovered, the increased

[13] We are assuming that households are buying and selling homes (perhaps because of life cycle considerations) and this generates the sales data that the econometrician observes.

climatic shocks will represent an expected cost to these households and yet the marginal coastal household may choose to remain if the economic rents exceed the climatic losses.[14] In this case, the dependent variable—the price change of real estate—does not provide any insight into the underlying demand curve, nor the changing welfare of the residents of at-risk cities in light of climate change.

A similar case emerges when income heterogeneity leads the extremely wealthy to sort into Miami due to its high amenity value. After accounting for the increased costs of climate catastrophes, the very rich nevertheless have a higher marginal utility from amenities than from consumption. In the high-income limit, climate change therefore has no effect on their bid functions for Miami real estate. As in the case of endogenous social networks, the fact that prices do not change after the advent of climate change does not necessarily imply that underlying welfare is unchanged.

These examples show that inferences to be drawn from observations of risk capitalization are limited, but the regressions are not useless: the bid of the marginal resident places bounds on costs of climate change for both residents and non-residents. The marginal willingness to pay to avoid the risks of coastal cities can thus be interpreted as an upper bound for the willingness to pay for a typical resident, and a lower-bound for the typical non-resident.

Consider again the case with two city types: coastal and inland. The initial change in prices upon the discovery of climate change will produce upper and lower bounds for the willingness to pay to avoid risk for coastal and inland residents, respectively. After discovery, the prices of both cities will decline over time as the onset of climate change nears due to the dwindling number of "low-risk" periods; these price changes could tighten the bounds on willingness to pay. The rates of price change in the two city types may change again after coastal cities transition to high risk,[15] providing additional information, and the eventual relative prices after all cities have transitioned to high-risk may further illuminate the scope of these bounds.

7 Conclusion

Climate change is likely to pose different costs on different cities. Coastal cities and cities located close to rivers will face greater flood risk while other cities such as Phoenix may face extreme summer heat. Such dynamics in location specific attributes suggests that forward-looking asset markets such as real estate should reflect the present discounted value of these relative risks.

[14] Due to their status as port cities and the historical (and ongoing) roles as entry points for immigrants, many coastal cities feature large ethnic enclaves that generate valuable social capital for major population segments. This suggests that coastal cities, differentially susceptible to climate change, may also have populations with differentially strong social ties.

[15] For instance, due to high-income individuals evacuating high-amenity coastal cities only after they transition to high-risk.

In this paper, we have introduced an equilibrium system of cities model in which households hold common expectations of spatial variation in the risks that different cities face. We document that a standard event study research design will yield very different estimates of the risk premium for being exposed to extra climate change risk depending on the degree of household heterogeneity. While in standard asset pricing, asset risk contains no idiosyncratic component and the CAPM style model captures the risk premium, in the case of housing—one's home bundles both an asset's rate of return and one's access to a specific city's attributes and to the social connections one has built in that location. This idiosyncratic match (either on unobserved tastes or endogenously built up social capital) creates a wedge between how an insider values remaining in the area versus how others in the society value the asset (Miami) now that the new news about climate change is common knowledge. We document that owners of Miami real estate are now faced with abnormally high risks, but—unlike in the case of risky equity—they do not appear to receive a large compensation for bearing this risk.

The model has implications for event study style hedonic real estate research. In the presence of the three dimensions of heterogeneity that we have presented, an empirical researcher's reduced form estimate of risk capitalization will provide bounds on the willingness to pay for avoiding new risks (Bajari and Benkard, 2005), and further changes in relative prices may narrow these bounds. Our findings highlight the key role of explicitly modeling the residential sorting process (Kuminoff et al., 2013).

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A Appendix

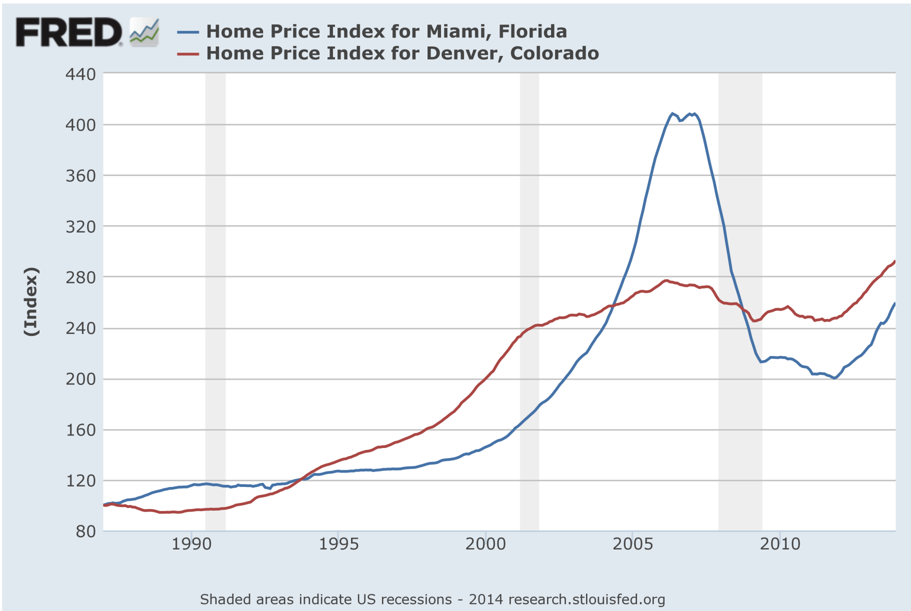

Figure 1: Home price indices for Miami and Denver.