The Distributional Consequences of Climate Change

Housing Wealth, Expectations, and Uncertainty

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January 22, 2024

Introduction

Introduction

How do climate news and uncertainty affect housing wealth?

- Most of median US household's wealth, home value depends on forward-looking prices
- Answer in dynamic spatial **heterogeneous agent** model of US with **housing markets**
- General HA modeling companion paper, plus new DL method for global solution

Purpose

Provide machinery to:

- Model climate **news** and **uncertainty**'s effects on endogenous house prices and rents
- Quantify **heterogeneous** welfare impacts by location, wealth, income, housing
- Incorporate **existing empirical estimates**: climate impacts, projections, uncertainty

Capture and quantify how:

- Climate news affects household wealth in present
- Easier migration: spatial inequality $\downarrow$ in physical impacts, $\uparrow$ in housing wealth impacts
- Ongoing uncertainty largely borne by renters through higher rents

Dynamic Spatial Climate Assessment Literature

	Climate Impacts	Adaptations
Desmet et al. (2021)	Land Area (Coastal Flooding)	Investment, Migration
Nath et al. (2023)	Sectoral Productivity	Trade, Sectoral Reallocation
Cruz & Rossi-Hansberg (2023)	Productivity, Amenities	Trade, Migration Innovation, Natality
Bilal & Rossi-Hansberg (2023)	Amenities, Productivity, Capital Depreciation	Investment, Migration **Anticipation**

- Brings high-dimensional space into modeling how climate impacts shaped by equilibrium responses/adaptations
- Computability limits: heterogeneity, frictions, **anticipation**, uncertainty
- With companion paper: State space 3k $\rightarrow$ 200m, solve in hours on PC

Broader Dynamic Spatial Literature

Introduction

"[Climate policy] analysis must be grounded in and reflect a world where there are many market imperfections, ... where risk is central, and where the distribution of income and welfare is a crucial issue."
– Nicholas Stern (LSE)

Model

Dynamic Spatial HA model With Housing Markets

- Kaplan, Mitman, Violante (2020) households + space[1] + climate change[2]
- Households: Vary by portfolio, age. Invest and migrate s.t. frictions and uncertainty
- Housing: Local households trade, lease, build: Determine local prices + rents
- Climate: Stochastic global temperature impacts local economic fundamentals
  - Productivity, amenities, energy costs, disaster damages

[1] 1713 PUMAs covering contiguous U.S.
[2] Or, Giannone et al. (2023) + rental real estate + climate change

Aggregate and Household States

Time is discrete, in decades. In period t:

Aggregate state:

$$\mathbf{\Gamma}_t = \Big(\underbrace{\mathbf{x}_t}_{\text{Household State Distribution}}, \underbrace{\{H_{it}\}_{i\in I}}_{\text{Location-Level Housing Stocks}}, \underbrace{\mathbf{D}_t}_{\text{Climate State}} \Big)$$

Location i prices:

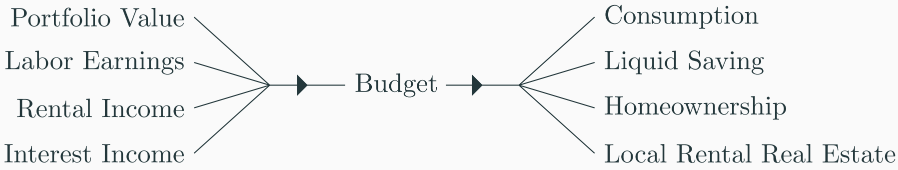
$$\underbrace{q_i(\mathbf{\Gamma}_t)}_{\text{Housing Price Level}}, \underbrace{\rho_i(\mathbf{\Gamma}_t)}_{\text{Housing Rent Level}}$$

Household j state:

$$\mathbf{x}_{jt} = \Big\{ \underbrace{b_{jt}}_{\text{Bondholdings}}, \underbrace{z_{jt}}_{\text{Income Type}}, \underbrace{h^{\text{live}}_{jt}}_{\text{Owned Home Size}}, \underbrace{h^{\text{let}}_{jt}}_{\text{Investment Real Estate Size}}, \underbrace{a_{jt}}_{\text{Age}}, \underbrace{i_{jt}}_{\text{Location}} \Big\}$$

Household Decision

Each period:



- Subject to frictions + uncertainty, household maximizes expected lifetime utility
- Household chooses location each period following location preference shocks Details
- Households live 20-80, born with heterogeneous liquid wealth, income, location

Frictions

- To adjust, sell and re-buy owned home h_{jt}^{live} or investment real estate h_{jt}^{let}
- Must pay ϕ share of sale price as realtor's fee
- All real estate locally owned
- Can borrow in liquid bonds, up to κ share of real estate holdings value, subject to:

$$\underbrace{r^m}_{\text{Borrowing Interest Rate}} > \underbrace{r^f}_{\text{Saving Interest Rate}}$$

- Moving incurs fixed monetary costs, bilateral utility costs
- Uninsurable idiosyncratic income risk, aggregate climate news risk

Algebra

Income and Expenses

$$\text{Net Income}_{jt} = \underbrace{A_{it} z_{jt}}_{\text{earnings}} + \underbrace{r^f b_{jt} \mathbb{1}[b_{jt} \geq 0]}_{\text{interest income}} + \underbrace{\rho_{it} h^{\text{let}}_{jt}}_{\text{rental income}}$$

$$- \underbrace{g_{jt}}_{\text{goods}} - \underbrace{\rho_{it} h^{\text{rent}}_{jt}}_{\text{rent}} - \underbrace{r^m b_{jt} \mathbb{1}[b_{jt} < 0]}_{\text{interest expenses}} - \underbrace{\chi^{\text{live}}_{it} h^{\text{live}}_{jt} - \chi^{\text{let}}_{it} h^{\text{let}}_{jt}}_{\text{maintenance}}$$

For $s \in \{\text{live}, \text{let}\}$, maintenance consists of

$$\chi^s_{it} = \underbrace{\chi^s}_{\text{Fixed Cost}} + \underbrace{y_{it}}_{\text{Energy Cost}} + \underbrace{\delta_{it}}_{\text{Disaster Damages}}$$

$$\chi^{\text{live}} < \chi^{\text{let}}$$

Utility

- Period utility is from goods consumption g, housing services h, local amenity α_{it}:

$$u\left(g, h, \alpha_{it}\right) = \frac{\left(\alpha_{it}\left(g^{1-\sigma} + \gamma h^{1-\sigma}\right)^{\frac{1}{1-\sigma}}\right)^{1-\eta} - 1}{1-\eta}.$$

- If the household owns a home, they occupy it. Otherwise, they rent.

$$h_{jt} = \begin{cases} h_{jt}^{\text{live}} & h_{jt}^{\text{live}} > 0 \\ h_{jt}^{\text{rent}} & \text{otherwise} \end{cases}$$

- Before terminal period, exponential discounting at rate β
- At terminal period, bequest utility given by final portfolio value Details

Recursive Form

Housing Markets

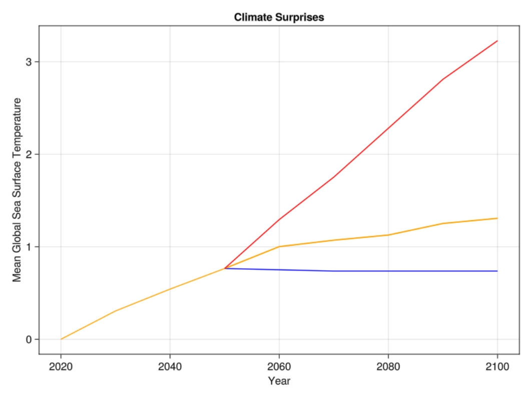
- A durable housing stock H_{it} in each location depreciates at rate δ^{dep}
- Households can access instant construction technology at marginal cost as in Saiz (2010):

$$c_{it}\left(H_{it}\right) = \Pi_i H_{it}^{\beta_i}.$$

- If housing supply expands, price equals marginal cost:

$$H_{it}^{S}\left(q\right) = \begin{cases} c_{it}^{-1}\left(q\right) & q \geq c_{it}\left(1 - \delta^{\text{dep}} H_{it}\right) \\ (1 - \delta^{\text{dep}}) H_{it} & \text{otherwise.} \end{cases}$$

Global Climate Process



Median news shock realizations at every year except 2050.

- "Onset shock" to initial steady state: SST_t begins evolving stochastically
- Each period, observe news shock
- Abstract from storm realizations, focus on news
- Eventually converges back to steady state

Full Process

Local Climate Sensitivities

Spatially-heterogeneous climate damages (log-)linear in global **temperature** SST_t:

$$\begin{aligned}
\text{Labor Productivity:} \quad & \log A_{it} = c_i^A + g_i^A \mathrm{SST}_t \\
\text{Location Amenity:} \quad & \log \alpha_{it} = c_i^\alpha + g_i^\alpha \mathrm{SST}_t \\
\text{Energy Costs:} \quad & y_{it} = c_i^y + g_i^y \mathrm{SST}_t \\
\text{Disaster Damages:} \quad & \log \delta_{it} = c_i^\delta + g_i^\delta \mathrm{SST}_t .
\end{aligned}$$

Empirically supported and generalizable across years, scenarios

Equilibrium

A recursive stochastic equilibrium is

- A set of household policy and value functions solving the Household's Problem
- An aggregate transition function over

$$\Gamma = \{\mathbf{x}, \mathbf{H}, D\}$$

- Prices $q_i(\Gamma)$, rents $\rho_i(\Gamma)$ satisfying real estate and rental housing market clearing:
  - Owner-occupied plus rental housing equals housing stock
  - Rental housing demanded equals rental real estate owned

Details

Quantification

Quantification

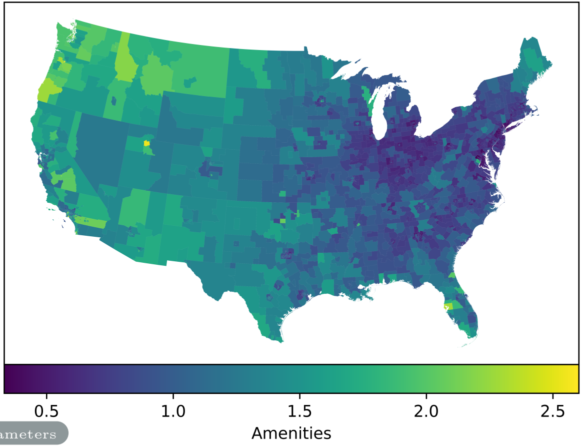
1. Baseline Parameters (Spatially-constant and location-specific): Determine steady state
2. Climate Process: Distribution of anticipated future global temperature paths
3. Climate Sensitivities: Impact of global temperature on local economic fundamentals

1. Steady State Calibration

Calibrate steady state to 1990 US Census (5% PUMS), 1992 SCF

- Non-spatial parameters: Calibration Table
- Location-specific parameters. Set local baseline:
    - Productivity A_i to match mean earnings
    - Amenity α_i to match population
    - Construction cost Π_i to match house price index
    - Rent ρ_i to clear markets

1. Steady State Calibration: Spatial Parameter “Inversion”



Spatial Parameters

2. Global Climate Process

- Calibrate median path to RCP4.5 scenario
- Match empirical uncertainty over:
  - Future emissions
  - Effect of emissions on future temperature
  - Effect of emissions on future disaster damages
- Ensemble distributions + insurance premium data informative of uncertainty
- Challenge: Combine into single climate process
- Strategy: Use model of Bayesian household observing climate process to "sum" sources of uncertainty Details

3. Climate Sensitivities

Model: Global temp affects local productivity, amenities, energy costs, disaster damages

Challenge: Find impact estimates which are

- Compatible with model
- Mutually consistent in identification
- Applicable to different locations, years, scenarios

Exploit these facts:

- Climate models translate global temperatures to local temperature measures, Heating Degree Days (HDD) and Cooling Degree Days (CDD), approximately locally-linearly
- Recent empirical impact estimates almost (log-)linear in local HDD/CDD

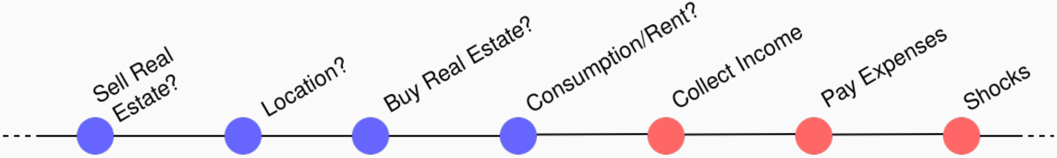
Details Disaster Damages

Computation

Computation

1. Separate HA model solution into:
   - Intra-period household's problem given continuation V, initial population distribution
   - *Generic* outer loop (Steady-state, calibration, transition, global solution, etc.)
2. Decompose intra-period household's problem into simple, sub-periods, "stages"
3. Build model easily using reusable "stages:" other models can mix and match
4. Implement general *outer-loop* deep learning global solution method

Sub-Periods: "Conventionally" Solved but *Modular*



Multiplicative performance benefits:

1. Simple, optimized, prepackaged for CPU/GPU/cluster
2. Search over one dimension at a time
3. Identify and overcome bottlenecks (interpolation, grid search) in non-vectorized Julia

Fixing Bottlenecks: Dynamic Information Sharing

Example: Consumption-saving by grid search

- If $MPC \geq 0$, then my optimal saving is between my wealth-neighbors'
- Don't need to search over entire axis!
- By "sharing" information between wealth-neighbors: $O(N^2) \rightarrow O(N \log N)$
- Incompatible with vectorization (Python, Matlab) but fast in Julia

Global Solution

Recent Work (e.g. Azinovic-Gaegauf-Schneider, 2019):

Problem: Curse of dimensionality prevents solving HA model with aggregate uncertainty

Idea: Use neural net to approximate policy, value functions

Companion Paper:

Problem: Training policy is hard and restrictive

Idea: Use neural net to predict continuation value, solve policy "live" during simulation

Problem: Policy grid search is too slow for this

Idea: Decompose computational problem, fix bottlenecks affecting all HA modeling

Results

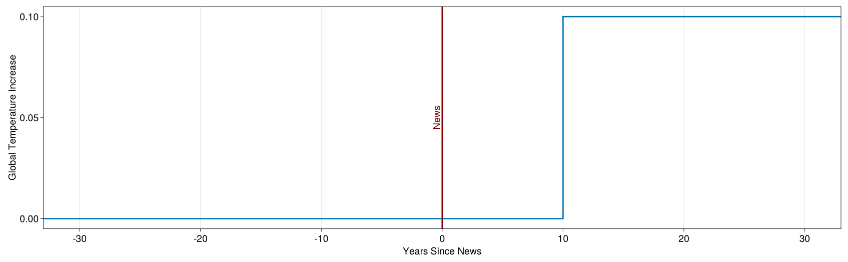
Results

How do climate **news** and **uncertainty** affect housing wealth?

- Start with MIT shock to global temperature expectations:
  - Effect of news shocks
  - Role of migration
- Move to full stochastic climate process:
  - Effects of uncertainty

MIT Shock to Expectations

In initial steady state, learn about permanent 0.1°C warming in 10 years:

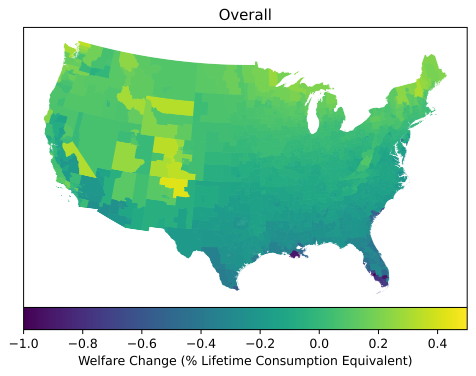


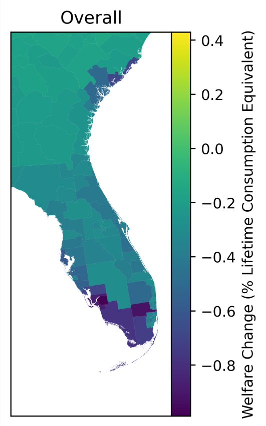
Now:

- Spatial distribution of impacts
- Equilibrium responses
- Heterogeneous welfare impacts of housing price response

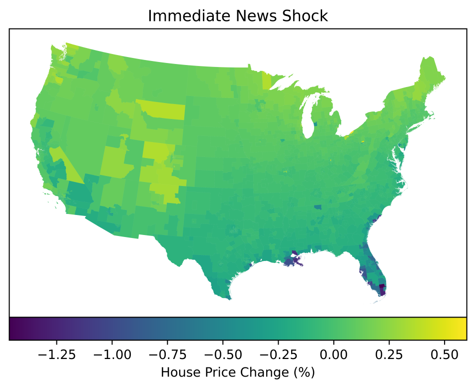
Spatial Distribution of Impacts

"Welfare:" Percentage lifetime consumption equivalent.

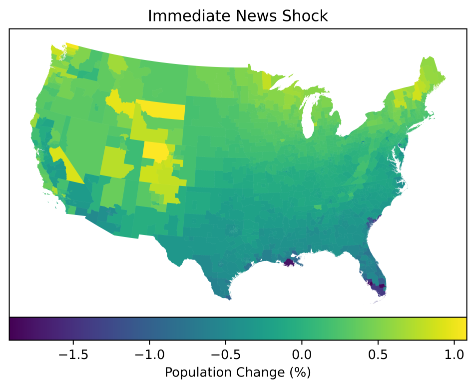




Immediate Equilibrium Response

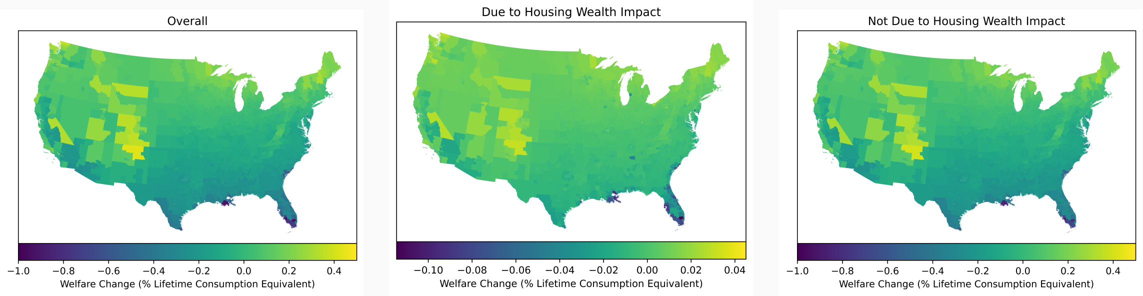


Price Response

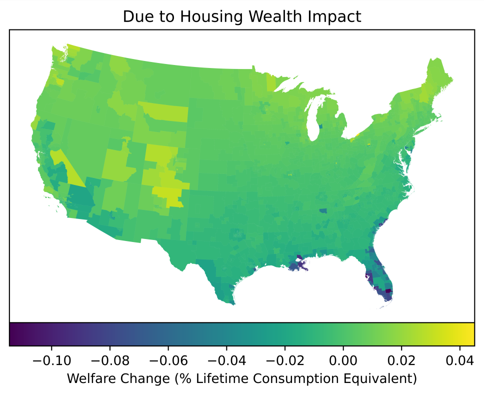


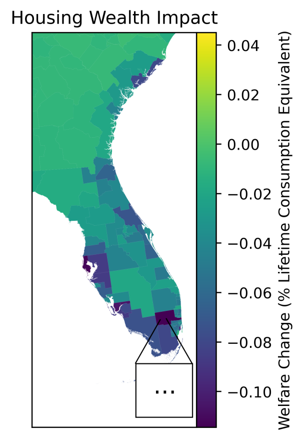
Population Response

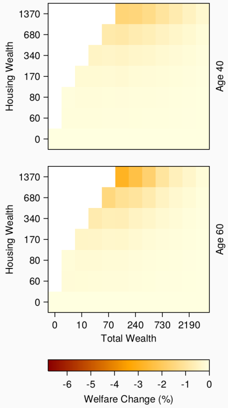
Decompose Welfare Impact: Housing Wealth vs. Other



Welfare Impact Due To Price Response







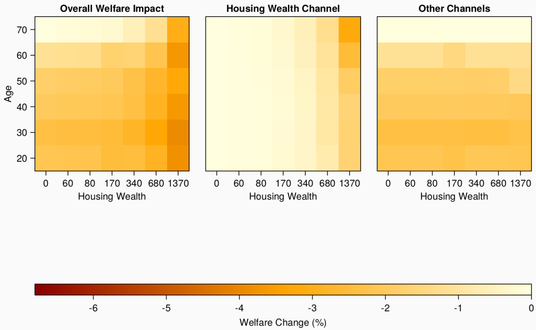
Other Margins

Slice: Everglades PUMA,
Median income, no investment real estate

Welfare Impact by Age and Housing Wealth

Slice:

- Everglades PUMA
- Median wealth
- Median income
- No investment real estate



Role of Migration

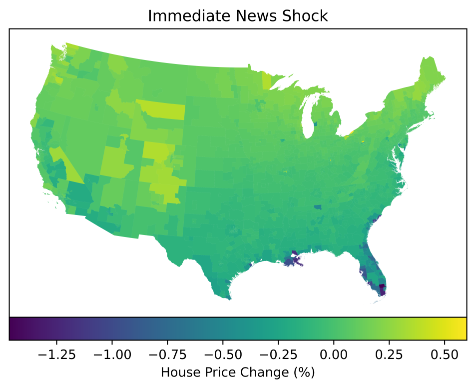
Consider version of model without migration:

- All parameters equal to baseline model
- Migration is not allowed
- Locations have baseline model steady-state populations

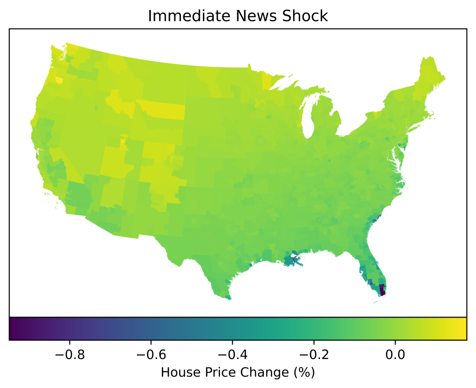
Compare:

- Price responses
- Welfare impacts

Price Responses



With Migration



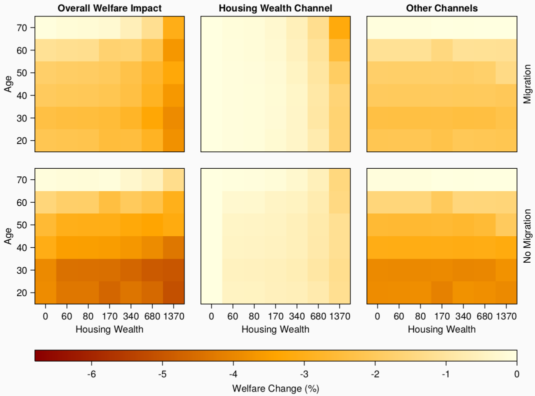
No Migration

- Price response 48% smaller on average

Welfare Impact by Age and Housing Wealth

Slice:

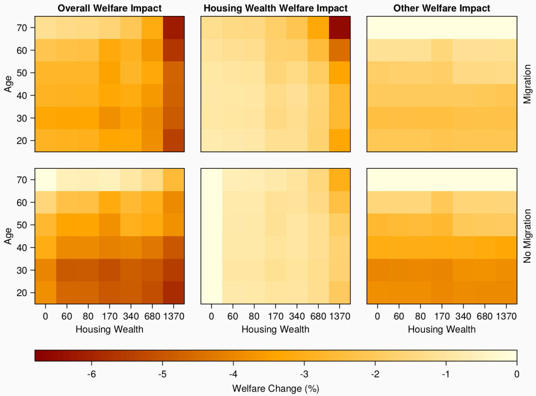
- Everglades PUMA
- Median wealth
- Median income
- No investment real estate



Welfare Impact by Age and Housing Wealth: Real Estate Investor

Slice:

- Everglades PUMA
- Median wealth
- Median income
- 8 bedrooms investment real estate



Other News Shocks

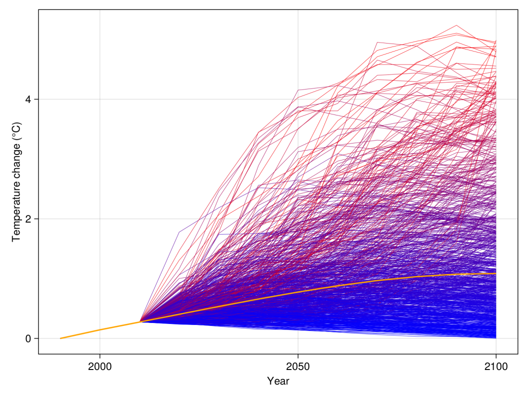
Broadly similar:

- Negative news shock in full process
- Positive news shock similar but opposite
- Onset shock

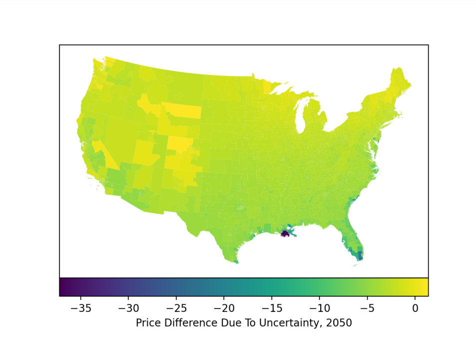
Onset shock: Immediate effective transfer of housing wealth of $41bn across space in 1990.

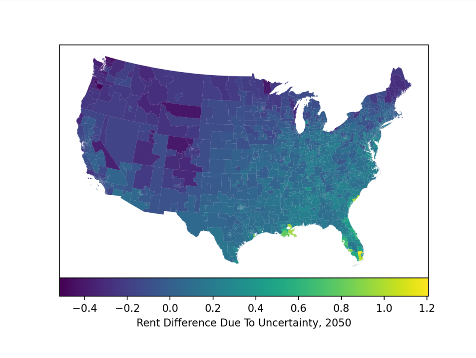
One difference: Full process has ongoing uncertainty.

Ongoing Uncertainty



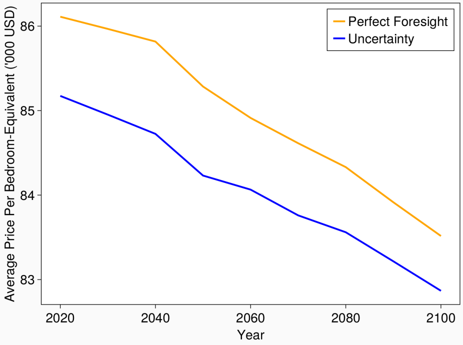
- Consider mean lifetime utility for household born in 2050 *along* median path realization
- Compare median path with uncertainty to perfect foresight



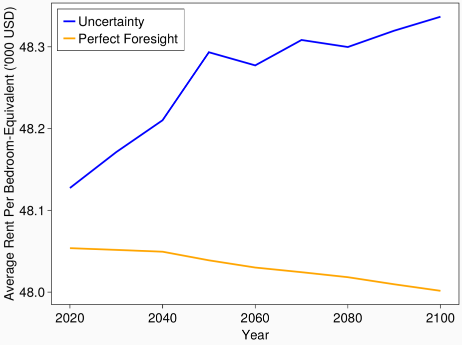


- 2050 housing prices 1.24% lower with uncertainty compared to perfect foresight
- 2050 rent 0.53% higher with uncertainty due to reduced supply of rental real estate
- Risk premium: cheaper housing and higher average returns for richer households

Welfare Impact Inequality: Risk Premium

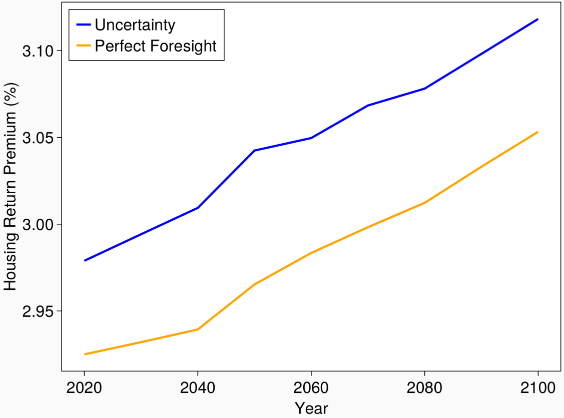


Average US House Prices



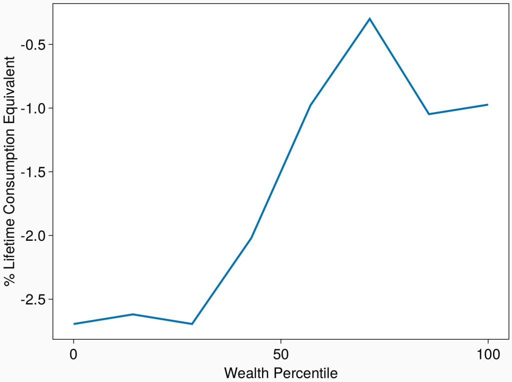
Average US Housing Rent

Risk Premium



Housing Investment Risk Premium

Welfare Impact Inequality: Role of Uncertainty



Impact of Uncertainty on Mean Realized Lifetime Utility (2050 Cohort, Median Path)

- Distributional welfare impact equivalent to $94bn wealth transfer from bottom half to top at birth in 2050 (median path)

Conclusion

Conclusion

- Model how climate news and uncertainty affect housing wealth
  - News of climate change onset: $\sim$ \$41bn housing wealth transfer across space in 1990
  - Ongoing climate uncertainty: $\sim$ \$94bn wealth transfer from poorer half to richer (at birth in 2050, median path)
- Many climate, spatial, and housing concerns require such depth in modeling
- We need equilibrium models with space + heterogeneity + frictions + uncertainty
- Computational contribution general for HA modeling

Discussion

Broader Dynamic Spatial Literature

Dynamic Spatial Models

- Desmet, Nagy, and Rossi-Hansberg (2018), Caliendo, Dvorkin, and Parro (2019)

With Saving or Human Capital Accumulation

- Bilal and Rossi-Hansberg (2021), Greaney (2021), Komissarova (2022)
- Kleinman, Liu, and Redding (2023), Giannone et al. (2023)
- Crews (2023), Lukas Mann JMP, Hugo Lhuiller JMP

With Flooding

- Hsiao (2023), Balboni (2021), Pang and Sun (2021), Desmet et al. (2021)

Household Homeownership and House Prices

- Kaplan, Mitman, and Violante (2020), Favilukis, Ludvigson, and Van Nieuwerburgh (2017)

Back

Location Decision

Household j in location i_0 draws i.i.d. preference shocks $\varepsilon_{jit} \sim \text{Gumbel}(0, \psi)$

If household chooses location $i \neq i_0$:

- Pay monetary moving cost F^m
- Sell all owned housing
- Receive utility $\varepsilon_{jit} - F^u(i_0, i)$

Conditional on moving,

$$P(i = \iota) \propto \exp\left(\psi V^{\text{postmove}}\left(\mathbf{x}_{jt}^{\text{postmove}}(i = \iota); \mathbf{\Gamma}_t\right) - F^u(i_0, \iota)\right)$$
$$\text{where} \quad \mathbf{x}_{jt}^{\text{postmove}}(i = \iota) = \left\{b_{jt}^{\text{postsale}} - F^m, z_{jt}, 0, 0, a_{jt}, \iota\right\}$$

Back

Housing, Frictions (Algebra)

- Household j may sell home h_{jt-1}^{live} or investment real estate h_{jt-1}^{let}
- To sell, they pay a percentage ϕ of the sale price as a realtor's fee

$$\begin{aligned}\tilde{b}_{jt}^{\text{postsale}} &= b_{jt} + q_{i_0 t}\left(h_{jt-1}^{\text{live}} + h_{jt-1}^{\text{let}}\right) - q_{it}\left(h_{jt}^{\text{live}} + h_{jt}^{\text{let}}\right) \\ &\quad - \underbrace{q_{i_0 t}\phi}_{\text{Fee}}\left(h_{jt-1}^{\text{live}}\mathbb{1}^{\text{sell live}} + h_{jt-1}^{\text{let}}\mathbb{1}^{\text{sell let}}\right)\end{aligned}$$

- To buy, must satisfy collateral constraint

$$b_{jt}^{\text{postbuy}} \geq -\kappa q_{it}\left(h_{jt}^{\text{live}} + h_{jt}^{\text{let}}\right).$$

- Negative bondholdings (mortgage) allowed at higher interest rate,

$$\underbrace{r^m}_{\text{Mortgage Interest Rate}} > \underbrace{r^f}_{\text{Bond Interest Rate}}$$

Back

Household's Problem: Income

$$
\begin{aligned}
b_{jt}^{\text{postincome}} &= b_{jt}^{\text{preincome}} + \underbrace{A_{it} z_{jt}}_{\text{earnings}} + \underbrace{r^f b_{jt}^{\text{preincome}} \mathbb{1}[b_{jt}^{\text{preincome}} \geq 0]}_{\text{interest income}} + \underbrace{\rho_{it} h_{jt}^{\text{let}}}_{\text{rental income}} \\
&- \underbrace{g_{jt}}_{\text{goods}} - \underbrace{\rho_{it} h_{jt}^{\text{rent}}}_{\text{rent}} - \underbrace{\chi_{it}^{\text{live}} h_{jt}^{\text{live}} - \chi_{it}^{\text{let}} h_{jt}^{\text{let}}}_{\text{maintenance}} - \underbrace{r^m b_{jt}^{\text{preincome}} \mathbb{1}[b_{jt}^{\text{preincome}} < 0]}_{\text{mortgage interest}} \\
&\geq -\kappa q_{it} \left(h_{jt}^{\text{live}} + h_{jt}^{\text{let}} \right)
\end{aligned}
$$

For $s \in \{\text{live}, \text{let}\}$, maintenance consists of

$$
\begin{aligned}
\chi_{it}^s &= \underbrace{\chi^s}_{\text{Fixed Cost}} + \underbrace{y_{it}}_{\text{Energy Cost}} + \underbrace{\delta_{it}}_{\text{Disaster Damages}} \\
\chi^{\text{live}} &< \chi^{\text{let}}
\end{aligned}
$$

Household's Problem: Lifecycle

Lifecycle stochastic income z_j evolves according to

$$\ln z_{jt+1} = \ln z_{jt} + \mu(a_{jt}) + \varepsilon_{jt}$$
$$\varepsilon_{jt} \sim N(0, \sigma_z^2)$$

If $a_{jt} < a^{\max}$, the household's continuation value is

$$\beta \mathbb{E}\left[V(b_{jt}^{\text{postexpense}}, z_{jt+1}, h_{jt}^{\text{live}}, h_{jt}^{\text{let}}, a_{jt}+1, i_{jt}; \Gamma_{t+1}) \mid \mathcal{I}_t\right]$$

If $a_{jt} = a^{\max}$, housing is liquidated and continuation value is derived from a bequest:

$$V^{\text{bequest}}\left(b_{jt}^{\text{bequest}}\right) = \beta Q \frac{\left(b_{jt}^{\text{bequest}}\right)^{1-\eta}}{1-\eta}$$
$$b_{jt}^{\text{bequest}} = b_{jt}^{\text{postexpense}} + (1-\phi)\, q_{it}\left(h_{jt}^{\text{live}} + h_{jt}^{\text{let}}\right)$$

Back

Full Household's Problem (After Location Choice)

$$
\begin{aligned}
& V\left(b, z, h_0^{\text{live, postmove}}, h_0^{\text{let, postmove}}, i, a\right) \\
& = \max_{h^{\text{live}}, h^{\text{let}}, g, h} -F^u\left(i, i_0\right) + u\left(g, h, \alpha_{it}\right) + \beta \mathbb{E} V_{t+1}\left(b', z', h^{\text{live}\prime}, h^{\text{let}\prime}, i, a+1\right)
\end{aligned}
$$

$$
\text{s.t.} \quad u\left(g, h, \alpha_{it}\right) = \alpha_i \frac{\left(g^{1-\sigma} + \gamma h^{1-\sigma}\right)^{\frac{1-\eta}{1-\sigma}} - 1}{1-\eta}
$$

$$
b' = R\left(\tilde{b}\right) + A_{it} e^z + \rho_{it} h^{\text{let}} - g - \rho_{it} h^{\text{rent}} - \chi_{it}^{\text{live}} h^{\text{live}} - \chi_{it}^{\text{let}} h^{\text{let}}
$$

$$
\tilde{b} = b - F^m D^{\text{move}} + \sum\nolimits_{s \in \{\text{live,let}\}} D^{\text{sell},s} \left[\left(1-\phi\right) q_{i_0 t} h_0^s - q_{it} h^s\right]
$$

$$
R\left(\tilde{b}\right) = \begin{cases} \left(1 + r^f\right) \tilde{b} & \tilde{b} \geq 0 \\ \left(1 + r^m\right) \tilde{b} & \tilde{b} < 0 \end{cases}
$$

$$
b' \geq -\kappa q_{it} \left(h^{\text{live}} + h^{\text{let}}\right)
$$

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Market Clearing Conditions

- Real estate demanded is owner-occupied plus rental real estate demanded:

$$H^{D}_{\ell t}(q) \equiv \int_{x\in\mathbf{X}} \left(h^{\text{live}}\left(x;q,\Gamma_t\right) + h^{\text{let}}\left(x;q,\Gamma_t\right)\right) \mathbb{1}\left[\ell\left(x;q,\Gamma_t\right)=\ell\right] d\lambda_t\left(x\right).$$

- Rental housing demanded is rental housing chosen by all non-homeowners:

$$H^{\text{rent}}_{\ell t}(\rho) = \int_{x\in\mathbf{X}} \left(h^{\text{rent}}\left(x;\rho,\Gamma_t\right)\right) \mathbb{1}\left[\ell\left(x;\rho,\Gamma_t\right)=\ell\right] d\lambda_t\left(x\right)$$

- Rental real estate supplied:

$$H^{\text{let}}_{\ell t}(\rho) = \int_{x\in\mathbf{X}} \left(h^{\text{let}}\left(x;\rho,\Gamma_t\right)\right) \mathbb{1}\left[\ell\left(x;\rho,\Gamma_t\right)=\ell\right] d\lambda_t\left(x\right).$$

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Reduced Global Climate Process

$\log w_{t+1} = \log w_t + g^w$	Global Energy Generation
$\log m_{t+1} = \log m_t - \rho_m w_t + \varepsilon_t^m$	Emissions Intensity
$e_t = w_t m_t$	Emissions
$\text{SST}_{t+1} = c_{\text{SST}} + \rho_c \text{SST}_t + \beta_{\text{SST}} e_t$	Global Temperature
$\log \delta_{t+1} = c_\delta + \rho_\delta \log \delta_t + \beta_\delta e_t$	Global Disaster Risk
$\varepsilon_t^m \sim \mathcal{N}(\mu_m, \sigma_m)$	News Shock

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Quantification

Calibration Table

Parameter	Interpretation	Value	Target or Source	Moment Value
Preferences:				
γ	Taste for housing	0.2	Median (renter) rent-to-income ratio	0.23
$1/\sigma$	Elasticity of Substitution (goods vs. housing)	0.87	Rent-to-income sens. to housing price	0.011
$1/\eta$	Elasticity of intertemporal substitution	0.5		
Q	Bequest motive	4.3	Mean wealth ratio oldest-to-overall	1.62
Housing:				
r_m	Mortgage interest rate	0.80	Mean wealth ratio homeowners-to-overall	1.52
ϕ	Transaction cost	0.07	Kaplan et al. (2020)	

Calibration Table (Cont.)

Parameter	Interpretation	Value	Target or Source	Moment Value
Housing:				
χ^{let}	Rental maintenance	21.3	Homeownership rate	0.68
κ	Maximum loan-to-value	0.8		
χ^{live}	Owner-occupied maintenance	10.0		
Migration:				
σ_ν	Location preference shock dispersion	0.2	Share of households moving across PUMAs	0.40
τ	Migration utility cost per km	0.0011	Share of households moving across states	0.22
F^m	Migration monetary fixed cost	13.3	Giannone et al. (2023)	

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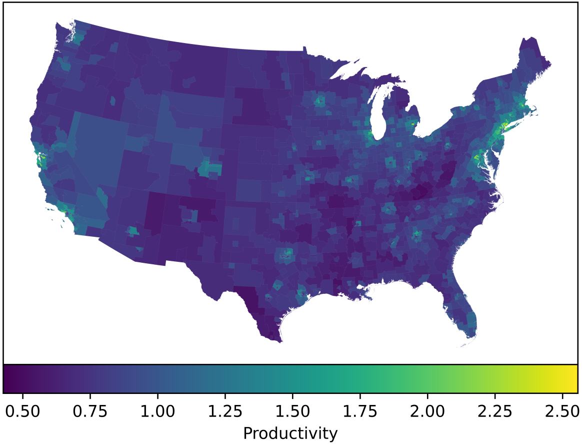
Spatial Parameters



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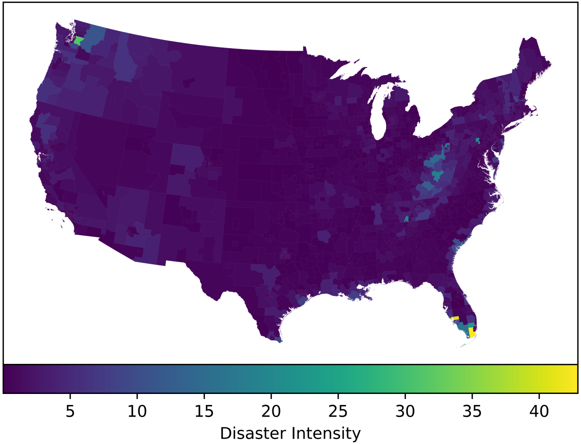
Spatial Parameters



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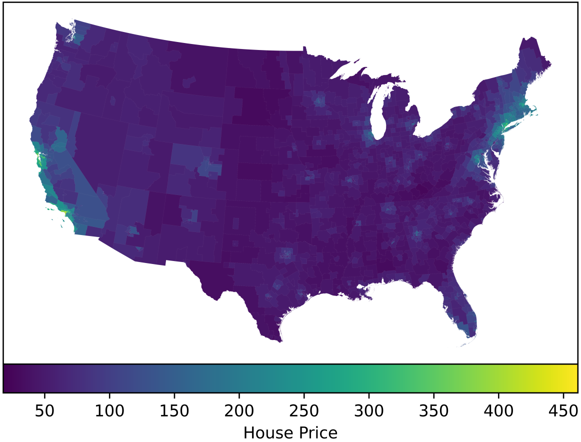

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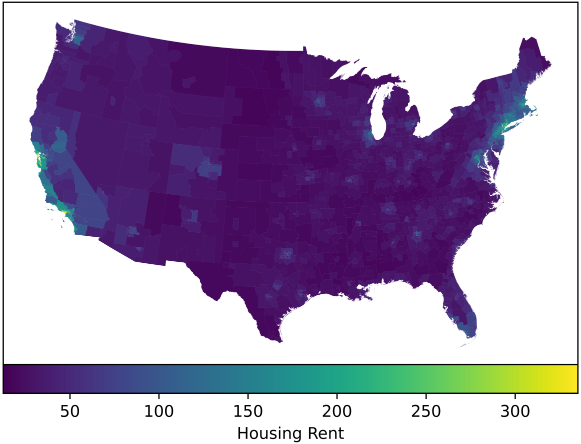

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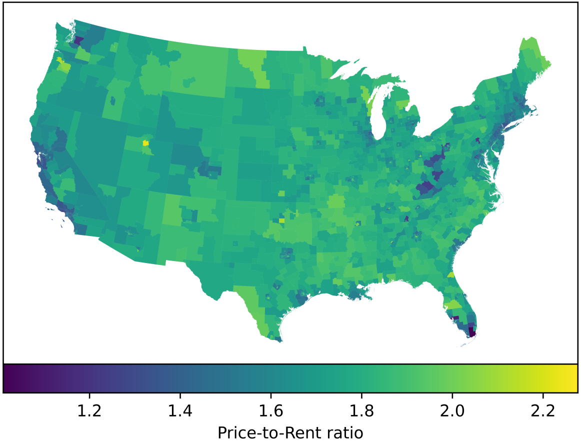

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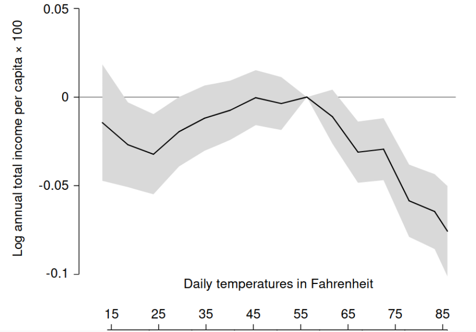
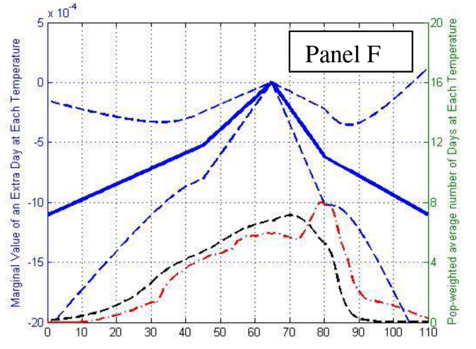
2. Climate Sensitivities Estimates: Productivity and Amenities



(a) Productivity impact of one day at a given temperature. Reprinted from Deryugina and Hsiang (2017), Figure 4, Panel 1.



(b) Utility impact of one day at a given temperature, as % of annual income. (Blue line) Reprinted from Albouy et al. (2016), Figure 9.

- Global temp → local HDD/CDD → local productivity, amenities
- Find set of compatible papers ⇒ (log-)linearize local impacts in global temperature

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Uncertainty over Climate Damages

Sources of Uncertainty

- The IPCC categorizes uncertainty over future climate damages into three categories:
  1. Internal Variability: Normal fluctuations in the climate system
  2. Model Uncertainty: Over the impact of emissions on the climate system
  3. Scenario Uncertainty: Over the future path of emissions
- I estimate market-relevant model uncertainty and internal variability using data on the responsiveness of homeowners insurance premia to disasters

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Homeowners Insurance Premia

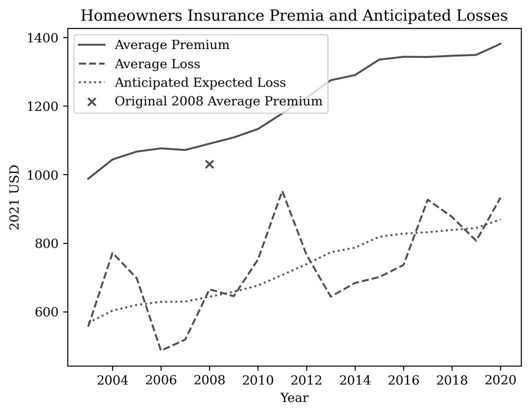

Figure 9: 1975-2020 Mean Annual Disaster Property Damage by Hazard

- Homeowners insurance companies report realized losses by hazard, loss-related expenses, and the "loss ratio."
- The "loss ratio" is the ratio of realized losses and expenses to premiums written, such that a loss ratio of 1 indicates that an insurer breaks even
- I empirically decompose loss expenses into a fixed component and a variable component depending on losses
- I invert this to obtain expected losses that insurers anticipate each year

Homeowners Insurance Premia and Uncertainty

- Intuitively, the less certain insurers are about true expected losses, the more responsive they should be to realized loss surprises
- I find that the response of average homeowners insurance premia to loss surprises is positive and statistically significant, despite the short time series
- I use a "nested Kalman filter," to estimate parameters of the insurer's learning process
- Insurers write one-year contracts. This is a static decision, allowing me to identify model uncertainty separately from scenario uncertainty

Insurer's Learning Process

- I assume that the insurer applies the following model
- Log-losses are drawn from a Normal distribution

$$d_t \sim \mathcal{N}(\mu_t, \sigma_d^2)$$

- μ_t follows an AR(1) process, affected by greenhouse gas emissions e_t

$$\mu_{t+1} = \rho\mu_t + \beta e_t + w_t$$
$$w_t \sim \mathcal{N}(0, \sigma_w^2)$$

- The insurer also observes an additional signal n_t about μ_t each period

$$n_t \sim \mathcal{N}(\mu_t, \sigma_n^2)$$

- The insurer does not observe the μ_t or β directly, but estimates them using a Kalman filter given Normal priors

Insurer's Learning Process: Kalman Filter

$$\underbrace{\begin{bmatrix} d_t \\ n_t \end{bmatrix}}_{z_t} = \underbrace{\begin{bmatrix} 1 & 0 \\ 1 & 0 \end{bmatrix}}_{H_t} \underbrace{\begin{bmatrix} \mu_t \\ \beta \end{bmatrix}}_{x_t} + v_t, \quad v_t \sim \mathcal{N}(0, \Sigma_v)$$

$$\underbrace{\begin{bmatrix} \mu_{t+1} \\ \beta \end{bmatrix}}_{x_{t+1}} = \underbrace{\begin{bmatrix} \rho & e_t \\ 0 & 1 \end{bmatrix}}_{F_t} \underbrace{\begin{bmatrix} \mu_t \\ \beta \end{bmatrix}}_{x_t} + w_t, \quad w_t \sim \mathcal{N}(0, \Sigma_w)$$

- If the insurer's prior for x_t at the end of period $t-1$ is

$$x_t \mid \mathcal{I}_t \sim \mathcal{N}(\hat{x}_t,\ \hat{P}_t),$$

  then their prior for x_{t+1} at the end of period t is

$$\begin{aligned} \hat{x}_{t+1} &= F_t(I - K_t H_t)\hat{x}_t + F_t K_t z_t \\ \hat{P}_{t+1} &= F_t(I - K_t H_t)\hat{P}_t F_t' + \Sigma_w \\ K_t &= \hat{P}_t H_t'(H_t \hat{P}_t H_t' + \Sigma_v)^{-1} \end{aligned}$$

Nested Kalman Filter

- We can rewrite the entire system including the prior as a single state space model

$$
\begin{bmatrix} x_{t+2} \\ z_{t+1} \\ \hat{x}_{t+1} \end{bmatrix} = \begin{bmatrix} F_t & 0 & 0 \\ H_t & 0 & 0 \\ 0 & F_t K_t & F_t(I - K_t H_t) \end{bmatrix} \begin{bmatrix} x_{t+1} \\ z_t \\ \hat{x}_t \end{bmatrix} + \begin{bmatrix} w_t \\ v_t \\ 0 \end{bmatrix}
$$

$$
\begin{bmatrix} w_t \\ v_t \\ 0 \end{bmatrix} \sim \mathcal{N}\left(0, \begin{bmatrix} Q_t & 0 & 0 \\ 0 & R_t & 0 \\ 0 & 0 & 0 \end{bmatrix}\right)
$$

$$
\begin{bmatrix} d_t \\ \hat{x}_t \end{bmatrix} = H_t^{\text{outer}} \begin{bmatrix} x_{t+2} \\ z_{t+1} \\ \hat{x}_{t+1} \end{bmatrix}
$$

- I then solve this for maximum likelihood like any other state space model

Disaster Damages

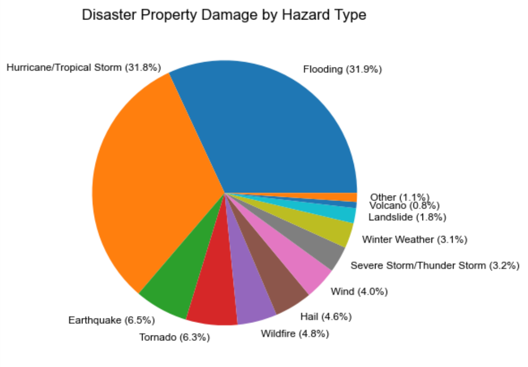

Figure 10: 1975-2020 Mean Annual Disaster Property Damage by Hazard

- I focus on flooding
- Bates et al. (2020) model county-level flood risk for 2020 and 2050 under RCP4.5
- They model coastal, fluvial, and pluvial flooding
- Due to lack of data, I linearize by global temperature between two points per location

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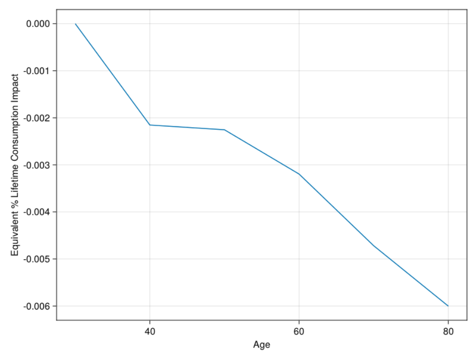
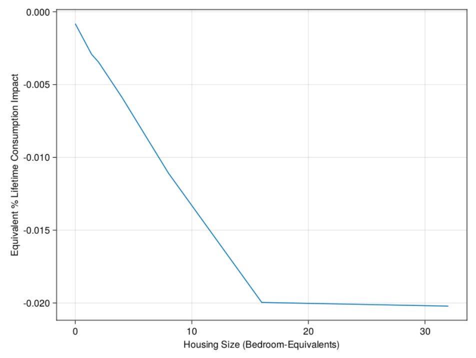
Results

Other Margins



Age



Owned Home Size

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Discussion

- No growth
- No agglomeration effects
- No institutional landlords
  - Model is closer to reality than absentee landlord
  - Model suggests *why* institutional landlords might arise/grow
  - Difficulty: How does institutional landlord not pin down prices?
- No hope of predicting *overall* house price movements due to all factors. Only effect of news shocks and uncertainty

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