# Anticipating Climate Change Across the United States

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# Introduction

- The planet is **warming**
  - Possibly severe economic impacts
  - Highly uneven across locations
- Many assessment frameworks do not account for
  - **Extreme events with local incidence**: heat waves, storms, floods...
  - **Anticipation** through forward-looking decisions: **investment** and **migration**

**Question**

- How do **anticipation** & **adaptation** shape climate change-induced **heat wave** & **storm** costs?

# This paper

- Provide a **dynamic spatial GE model** for 3143 US counties with
  - **Local extreme events** and **damages to capital**
  - **Anticipation** through forward-looking **investment** and **migration**
  - Tractability using **'Master Equation'** approach in Bilal (2023)
- Estimate **damages** from extreme events using 120 years of county-level weather data
  - **Event study estimates** of impact of extreme events on population, income and investment
  - Match in model to estimate **structural damage functions**
  - Storm $=$ 17% capital depreciation, heat wave $=$ 5% productivity $+$ 7% amenity shock
- Social costs of climate change are **much larger** than previously thought
  - **5% present welfare loss** ($3,005/pc/year) in business-as-usual scenario
  - **Damages to capital** account for half
  - **Anticipation** increases mobility and **migration** reduces inequality

# Literature

- **Frameworks**
  - **Spatial:** , Desmet Rossi-Hansberg (2014) , Donaldson et al. (2016), Caliendo et al. (2019), Cruz Rossi-Hansberg (2021, 2022), Desmet et al. (2021), Nath (2021), Kleinman et al. (2021)
  - **Representative agent:** Cai Longtzek (2019), Nordhaus Yang (1996)
  - ★ Integrate capital acc., fwd-looking migration, investment, climate damages
  - ★ Highly disaggregated environment with aggregate shocks
- **Measurement**
  - **Capital depreciation:** Tran Wilson (2022), Wilson (2017), Grenier et al. (2021), Geiger et al. (2016), Hsiang Jina (2014), Hsiang (2010), Elsner et al. (2008)
  - **Mortality:** Carleton et al. (2021), Deschenes Greenstone (2011)
  - **Productivity & others:** Carleton Greenstone (2021), Deryungina Hsiang (2017), Burke et al. (2015), Donaldson et al. (2016)
  - ★ Integrate new measurement into quantitative GE model

# Framework

# Workers

- Two types of agents: workers and capitalists
- Counties $i$, continuous time $t \geq 0$
- Worker preferences

$$\rho V_{it} = \overbrace{\max_{c,h} u\left(\left(\frac{c}{1-\beta}\right)^{1-\beta}\left(\frac{h}{\beta}\right)^{\beta}\right) + \boldsymbol{A_{it}}}^{\text{flow utility: consumption + amenities}} + \overbrace{\mathbb{E}_t\left[\frac{d\boldsymbol{V_{it}}}{dt}\right]}^{\substack{\textbf{continuation value}\\ \textbf{from aggregate changes}}}$$

$$+ \underbrace{\mu\left\{\mathbb{E}_t\left[\max_j \boldsymbol{V_{jt}} - \tau_{ij} + \varepsilon_{jt}\right] - V_{it}\right\}}_{\substack{\textbf{continuation value}\\ \textbf{from migration}}}$$

$$\text{s.t.} \quad c + \boldsymbol{r_{it}} h = \boldsymbol{w_{it}}$$

  - No savings

# Capitalists

- Immobile, risk-neutral, solve

$$\rho \mathcal{P}_{it}(K,b) = \max_{I,C} \overbrace{C}^{\text{flow utility}} + \overbrace{(I - \delta_{it} K)\frac{\partial \mathcal{P}_{it}}{\partial K}}^{\substack{\text{continuation value}\\ \text{from net investment}}} + \overbrace{\mathbb{E}_t\left[\frac{d\mathcal{P}_{it}}{dt}\right]}^{\substack{\text{continuation value}\\ \text{from aggregate changes}}}$$
$$+ \underbrace{\left[R_t b + R_{K,it} K - c_i(I/K)K + \mathcal{T}_{it} - C\right]\frac{\partial \mathcal{P}_{it}}{\partial b}}_{\text{continuation value from net savings}}$$

  - Access to national bond market to fund local investment
  - State-dependent depreciation rate $\delta_{it}$
  - Proceeds $\mathcal{T}_{it}$ from claims to national mutual fund that owns land

# Production

- Capital stock in location $i$:

$$\text{Capital } K_{it} \longrightarrow \text{Buildings } B_{it} \longrightarrow \begin{cases} \text{Housing } H_{it} \\ \text{Commercial structures } S_{it} \end{cases}$$

- Labor $N_{it}$ in location $i$:

$$\text{Labor } N_{it} \longrightarrow \begin{cases} \text{Production labor } N_{it}^{P} \\ \text{Building construction labor } N_{it}^{B} \end{cases}$$

- Buildings

$$B_{it} = L_i^{\omega} (N_{it}^{B})^{\varpi} K_{it}^{1-\omega-\varpi}$$

- Final goods

$$Y_{it} = \boldsymbol{Z_{it}} S_{it}^{\alpha} (N_{it}^{P})^{1-\alpha}$$

# Climate damages

- Global mean temperature: $T_t = T^P + \boldsymbol{T_t^D}$
  - Add natural climate variability in paper (aggregate, stochastic shocks)
  - Take **global** temperature path as exogenous since focus on US damages
- Fundamentals depend on **global temperature**, with the form

$$\delta_{it} \quad = \quad \delta_i^P + \boldsymbol{\delta_{i1}}\, \boldsymbol{T_t^D}$$

  - Similar expression for $Z_{it}, A_{it}$
  - Without loss given our perturbation approach
  - Equivalent to nonlinear damages in **local temperature**
- **Damage functions** = slopes $\delta_{i1}$ for capital
  - Similar for productivity and amenities

# Solution method

# Solution method

- GE environment with
  - Aggregate shocks $T_t^D$
  - Distribution $\left\{N_{it}, K_{it}\right\}_i$ is a state variable: **6284 indiv. states** + **6284 prices** (wages, rental rates)
- Traditional solution methods hard to use in this context
- Use the 'Master Equation' approach developed in Bilal (2023)
  - State-space **analytic perturbation** around steady-state
  - Builds on mean-field game literature
  - Solve for transitional dynamics in **seconds**
- **1$^{\text{st}}$ order** in this paper
  - Cost of climate risk (2$^{\text{nd}}$ order perturbation) coming soon in future work

# Estimation

# Data

- Economic data: 1960-2019
  - Investment: 5-year Census of manufactures
  - Wages and population from Census and BEA
- Historical climate data: Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) 1900-2019
  - Near-surface temperature, wind-speed and precipitation
  - Daily averages and within-day extremes
  - Convert from 0.5 degree x 0.5 degree cell to annual county-level

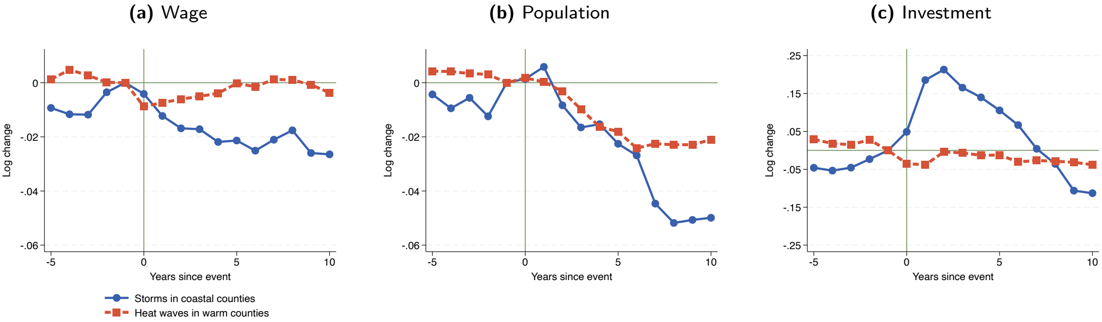
# Distributed lag specification

$$y_{it} = \alpha_i + \beta_t + \delta_{S(i),t} + \sum_{h=-5}^{10} \gamma_h D_{i,t-h} + \gamma_{6-} \bar{D}_{i,t,6-} + \gamma_{10+} \bar{D}_{i,t,10+} + \varepsilon_{it}$$

- $i$ = counties and $t$ = years
- $y_{it}$ = log wage, population, investment
- $\delta_{S(i),t}$ = state, weather decile, population and income deciles all interacted with year
- $D_{i,t-h}$ = event indicator $h$ years ago
  - Storms = windspeed or precipitation above **local threshold**
  - Heat waves = prolonged heat above **local threshold**
- $\gamma_h$ = impact of an event $h$ periods ago on outcomes today

▸ Details

# Storms and heat waves damage the economy




- **Storms = capital depreciation shock** in coastal counties only (no effect in inland counties)
- **Heat waves = productivity + amenity shock** in warm counties only (no effect in cold counties)

# Damage functions: Strategy

1. Estimate steady-state parameters by inverting model
2. **Match event study results** in model to estimate
   - Migration and investment elasticities
   - Magnitude of shocks in model associated with a **single event**
3. Estimate effect of **global temperature** on **local frequency** of events

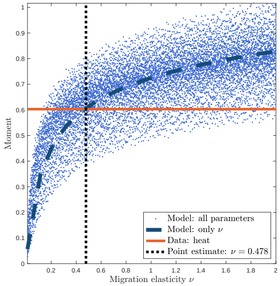
$\Rightarrow$ Combine **single event** damages with **frequency changes** to construct **damage functions**

# Damage functions 1/3: Inversion of steady-state fundamentals

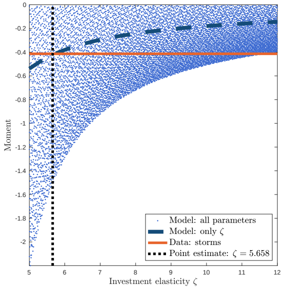
- **Inversion:** $\exists!$ vector $\{Z_i, A_i, L_i, c_i\}_i$ and symmetric matrix $\{\tau_{ij}\}_{ij}$...
- ...given elasticities and data $\{I_i, w_i, N_i, L_i\}_i$, $\{m_{ij}\}_{ij}$
- Standard inversion procedure in quantitative spatial frameworks

# Damage functions 2/3: Migration and investment elasticities

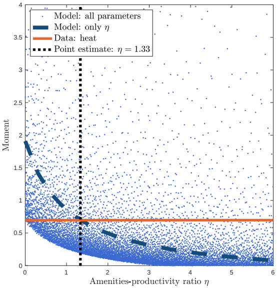
**(a)** Heat: population/investment




**(b)** Storms: population/investment



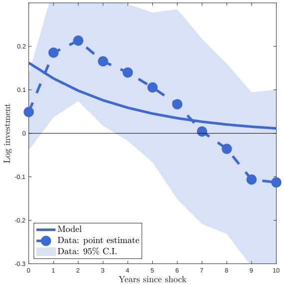

**(c)** Heat: income p.c./population



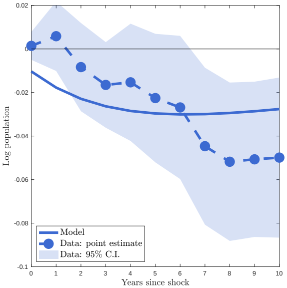

- Relative IRFs independent from shock size in model: use relative CIRs 10 years out
- Simulate IRFs for 10,000 parameter vectors $(\nu, \zeta, \eta) \in [0, 2] \times [5, 12] \times [0, 6]$
  - For amenity-productivity and capital depreciation shock
  - Invert model, solve for steady-state, solve for FAME and IRFs
  - $\eta = \frac{a_{i1}}{\chi_{i1}}$ = relative amenity/productivity impact of heat

# Damage functions 2'/3: Magnitude of storm shocks

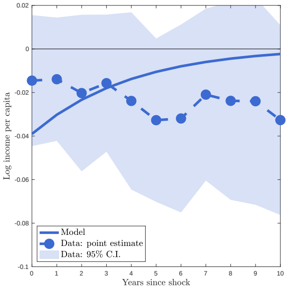
**(a)** Storms: investment




**(b)** Storms: population




**(c)** Storms: income per capita

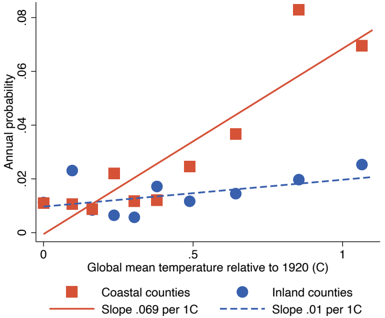



- 1-in-50-years storm in coastal counties = **17% capital depreciation** shock
- 1-in-20-years heat wave in warm counties = **5% productivity & 7% amenity** shock

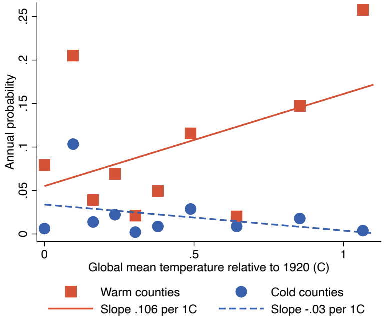
▸ Heat waves

# Damage functions 3/3: Warming makes extreme events more frequent

**(a)** 1-in-50 years storm (precipitation and wind)




**(b)** 1-in-20 years heat wave (temperature)

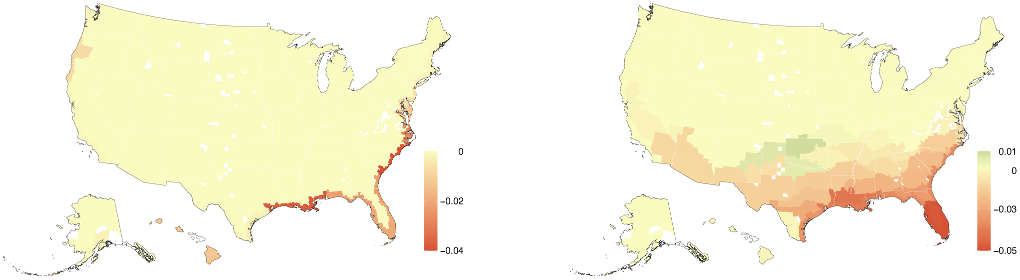



- Leverage 120 years of weather data
- Damage functions interact change in frequency with damages from event, e.g.:

$$\delta_{it} = \delta_i^P + \delta_{i1} T_t^D \quad , \quad \delta_{i1} = \underbrace{p_{i1}^{\text{storm}}}_{\substack{\text{Freq. change with } T_t \\ \text{for every location } i}} \cdot \underbrace{17\% \cdot \mathbf{1}\{i \text{ coastal}\}}_{\substack{\text{Damage from} \\ \text{single event}}}$$

▸ NOAA storm counts

# Damage functions

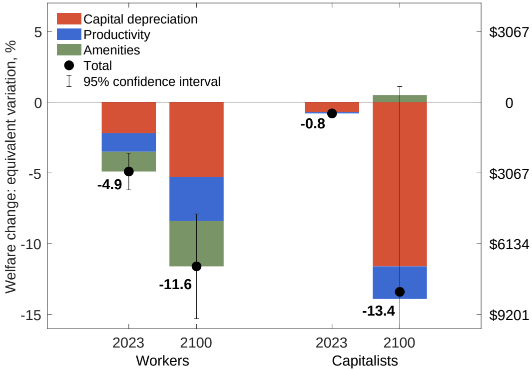



**(a)** Change in annual capital depreciation $\delta_{i1}$ (+1°C) **(b)** Change in log productivity $z_{i1}$ (+1°C)

- 26% of capital and 27% of population in counties where depreciation rises

# Results

# Climate damages are twice as large as previously thought

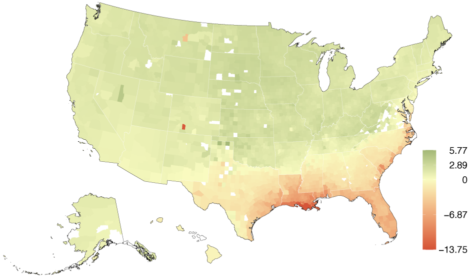



- Gradual 3°C warming from 2023 to 2100 as in BAU
- 45-88% of damages due to capital depreciation
- Damages are linear in global temperature: rescale results for any scenario

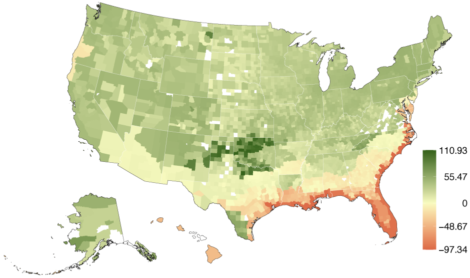
▸ Details

▸ Neoclassical growth model calculation

# Welfare losses are most severe in Southeastern US



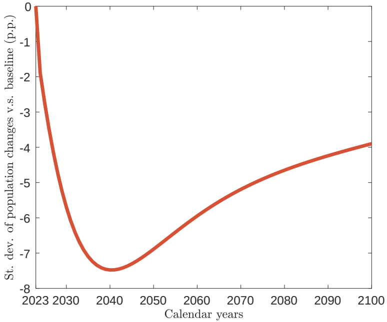

**(a)** 2023 worker welfare relative to aggregate (-4.9%)



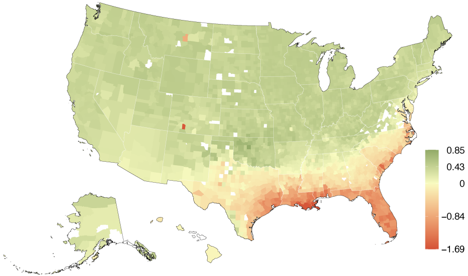

**(b)** Population change by 2100 (%)

- Workers in Louisiana, Texas, Florida, South Carolina lose over 10% ($6,133/year)
- Florida loses half of its population by 2100

# Mobility falls and inequality rises without anticipation




**(a)** Dispersion in population change relative to baseline

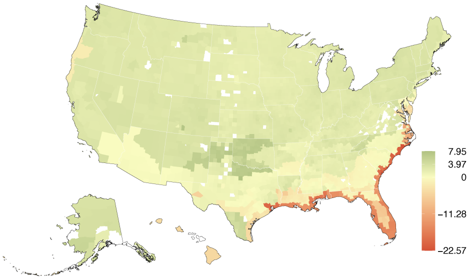



**(b)** Worker welfare in 2050 relative to baseline (p.p.)

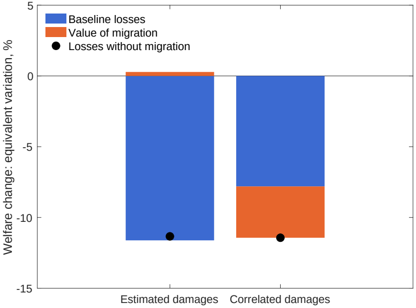
- Agents now believe that future temperatures remain equal to time-$t$ value
- Lack of mobility **exacerbates climate damages** for workers in exposed counties
- **Capitalists benefit** from lack of mobility through higher returns in exposed counties

▸ Workers: details ▸ Capital

# Migration provides insurance in the cross-section only




**(a)** 2023 worker welfare without migration relative to baseline




**(b)** 2100 aggregate welfare losses

- Welfare costs exceed 25% ($15,333/year) on Atlantic coast without migration
- **Aggregate benefits negligible in the US**: climate damages $\perp$ local valuations
  - Substantial aggregate benefits with **artificial** climate damages **correlated** to local valuations


Capitalists
Full decomposition

# Conclusion

# Conclusion

- Quantitative dynamic spatial assessment model of the U.S. economy with 3,000+ counties
  - Forward-looking migration and capital investment decisions
- Estimate reduced-form and structural effect of storms and heat waves
  - Solve for counterfactuals in seconds
- Costly effects of climate change, largely due to capital
- Framework opens the door to
  - Cost of climate change risk: $2^{\text{nd}}$ order perturbation (SAME, Bilal 2023)
  - Climate justice & inequality across worker groups
  - Integration with climate block & scale up to world economy

**Thank you!**

# Appendix

# State variables

- To understand method, simplify problem to simplify notation for now
  - Fixed capital in each location (no capitalist decision problem)
- State variables:
  - Time $t$ because deterministic rise in global mean temperature $T_t^D$
  - Distribution of workers across locations $N_{it}$
- Population distribution evolves according to

$$\frac{dN_{it}}{dt} = \mu \left( \sum_k \pi_{ji}(V_t) N_{jt} - N_{it} \right)$$

where

  - $\pi_{ji}(V_t)$ are migration shares from $j$ to $i$
  - Depend on equilibrium values $V_t = (V_{1t}, ..., V_{It})$

Back to main presentation

# Master Equation: Step 1/3

- Write flow utility of workers as function of state variables
- Use static equilibrium conditions
- Obtain

$$\max_{c,h \text{ s.t. } c+r_{it}h=w_{it}} A_{it} + u\left(\left(\frac{c}{1-\beta}\right)^{1-\beta}\left(\frac{h}{\beta}\right)^{\beta}\right) \equiv \mathcal{U}_i(T_t^D, N_{it})$$

Back to main presentation

# Master Equation: Step 2/3

- Express continuation value from aggregate changes in state space
- Use change of variables

$$V_{it} = V_{it}(N_t) \qquad (\star)$$

where

  - $t$ subscript on $V$ **only** captures dependence on deterministic temperature
  - $N_t = (N_{1t}, ..., N_{It})$ is population distribution

- Obtain

$$\mathbb{E}_{it}\left[\frac{dV_{it}}{dt}\right] = \underbrace{\frac{\partial V_{it}}{\partial t}}_{\text{change in } T_t^D} + \underbrace{\sum_j \frac{\partial V_{it}}{\partial N_j}\frac{\partial N_{jt}}{\partial t}}_{\substack{\text{change in } N_t\text{:} \\ \text{chain rule on } (\star)}}$$

Back to main presentation

# Master Equation: Step 3/3

- Use law of motion for population to relate change in $N_t$ to equilibrium

$$\sum_j \frac{\partial V_{it}}{\partial N_j} \frac{\boldsymbol{\partial N_{jt}}}{\boldsymbol{\partial t}} = \sum_j \frac{\partial V_{it}}{\partial N_j} \boldsymbol{\mu} \left( \sum_k \boldsymbol{\pi_{ji}(V_t) N_{jt} - N_{it}} \right)$$

- Putting it all together, obtain **Master Equation**

$$\begin{aligned} \rho V_{it} \quad = \quad & \underbrace{\mathcal{U}_i(T_t^D, N)}_{\text{flow payoff in } i} + \underbrace{\frac{\mu}{\nu} \log \left( \sum_j e^{\nu(V_{jt} - \phi_{ij})} \right) - \mu V_{it}}_{\text{continuation value from migration}} \\ + \quad & \underbrace{\underbrace{\frac{\partial V_{it}}{\partial t}}_{\text{change in } T_t^D} + \underbrace{\sum_j \frac{\partial V_{it}}{\partial N_j} \mu \left( \sum_k \pi_{ji}(V_t) N_{jt} - N_{it} \right)}_{\text{change in } N_t}}_{\text{change in aggregates}} \end{aligned}$$

Back to main presentation

# The Master Equation

$$
\begin{aligned}
\rho V_{it}(N) \quad = \quad & \underbrace{\mathcal{U}_i(T_t^D, N)}_{\text{flow payoff in } i} + \underbrace{\frac{\mu}{\nu} \log \left( \sum_j e^{\nu(V_{jt} - \phi_{ij})} \right) - \mu V_{it} \Big\}}_{\text{continuation value from migration}} \\
+ \quad & \underbrace{\underbrace{\frac{\partial V_{it}}{\partial t}}_{\text{change in } T_t^D} + \underbrace{\sum_j \frac{\partial V_i}{\partial N_j} \mu \left( \sum_k \pi_{ji}(V_t) N_j - N_i \right)}_{\text{change in } N_t}}_{\text{change in aggregates}}
\end{aligned}
$$

- State-space/recursive representation of equilibrium
- Single equation to be solved
- Introduced in Mean Field Games literature by Cardaliaguet et al. (2019)
- Bellman equation on space of population distributions $N = (N_1, ..., N_I)$: still hard to solve

▸ Back to main presentation

# Perturbations of the Master Equation

- To make progress, use **analytic** perturbation of the Master Equation
  - Suppose we have found a steady-state without aggregate shocks
  - When scale parameter $\epsilon$ is not too large, write to **first order**

$$V_{it}(z_1, N) = V_i^{SS} + \epsilon \left\{ \sum_j v_{ij} n_j + \Omega_{it} \right\}$$

  where
    - $n_j = \frac{N_j - N_j^{SS}}{\epsilon}$ is deviation in population from steady-state
    - $v_{ij} = \frac{\partial V_i}{\partial N_j}(0, N^{SS})$ is derivative around steady-state
- Obtain **First-order Approximation to the Master Equation**
  - Substitute first-order perturbation into nonlinear Master Equation
  - Identify coefficients to get restrictions on $v_{ij}, \Omega_{it}$
  - Just like linearizing the RBC model, just larger state space!
- Similar logic to **second order**, just more components

Back to main presentation

# Deterministic FAME

FAME for $\boldsymbol{v_{ij}} \in \mathbb{R}^{I \times I}$ in matrix form

$$\rho \boldsymbol{v} = D + M\boldsymbol{v} + \boldsymbol{v}M^* + \boldsymbol{v}G\boldsymbol{v}$$

where

- $D$ captures direct price impact of population changes

$$\text{D is diagonal, } D_{ii} = \frac{\partial \mathcal{U}_i}{\partial N_i}\Big|^{SS} = \xi(1-\varpi)u'(C_i^{SS})C_i^{SS}/N_i^{SS}$$

- $M\mathbf{v}$ captures **own migration response**

$$M = \mu(m^{SS} - \mathrm{Id})$$

  where $m^{SS}$ is the matrix of steady-state migration shares

- $\mathbf{v}M^*$ captures **others' migration at steady-state decisions** (GE direct)

$$M^* \text{ is the transpose of } M$$

- $\boldsymbol{v}G\boldsymbol{v}$ captures **others' migration responses** (GE interaction)

$$G = \nu\mu\left[\mathrm{diag}\left((m^{SS})^* N^{SS}\right) - (m^{SS})^* \mathrm{diag}\left(N^{SS}\right) m^{SS}\right]$$

Back to main presentation

# Properties of the FAME

FAME for $\boldsymbol{v_{ij}} \in \mathbb{R}^{I \times I}$ in matrix form

$$\rho \boldsymbol{v} = D + M\boldsymbol{v} + \boldsymbol{v}M^* + \boldsymbol{v}G\boldsymbol{v}$$

- Standard Bellman equation
- Block-recursive
  - $v$ independent from $\Omega$
  - No additional fixed point on distribution b/c embedded in Master Equation
- From infinite to finite dimension
  - Only need perturbation in $N_j$ holding $N_k = N_k^{SS}, k \neq j$ fixed
- Explicit steady-state dependence of $D, M, G$

# Trend FAME

- Obtain similar FAMEs for temperature shocks

$$\rho \mathbf{v}_t^T = \Psi T_t^D + \mathrm{M}\mathbf{v}_t^T + \mathbf{v}^d \mathrm{P}^d \mathbf{v}_t^T + \frac{\partial \mathbf{v}_t^T}{\partial t}$$

- Even simpler because interaction takes determistic FAME $\mathbf{v}^d$ as given
- Simply iterate backward over time $t$

# Computation of the FAME

FAME for $\boldsymbol{v_{ij}} \in \mathbb{R}^{I \times I}$ in matrix form

$$0 = D + (M - \rho \mathrm{Id})\boldsymbol{v} + \boldsymbol{v}(M^* + G\boldsymbol{v})$$

- Nonlinear **Sylvester equation**
- Standard Sylvester equation if $G = 0$, use standard routines
- Simple **iterative algorithm**: given $\boldsymbol{v}^{(n)}$, solve for $\boldsymbol{v}^{(n+1)}$

$$0 = D + (M - \rho \mathrm{Id})\boldsymbol{v}^{(n+1)} + \boldsymbol{v}^{(n+1)}\left(M^* + G\boldsymbol{v}^{(n)}\right)$$

  - Given $\boldsymbol{v}^{(n)}$, becomes standard Sylvester equation in $\boldsymbol{v}^{(n+1)}$
  - Important to use last iteration $\boldsymbol{v}^{(n)}$ as given in right part of interaction
  - Because household $\boldsymbol{v}^{(n+1)}$ takes **as given** others' valuations $\boldsymbol{v}^{(n)}$

Back

# Law of motion

- No fixed point on prices/distributions because embedded law of motion into HJB
- Given solution to FAME, obtain impulse responses directly

$$\frac{d\boldsymbol{n_t}}{dt} = (M^* + G\mathbf{v}^{\boldsymbol{d}})\boldsymbol{n_t} + G\mathbf{v}_{\boldsymbol{t}}^{\boldsymbol{T}}$$

- Can also compute invariant distribution in **stochastic steady-state**
  - How far does economy wander from determinstic steady-state on average
- All derivations generalize to **second order**: it is the **SAME**
  - Working on it, for today only FAME

# Treatment definition

- Use meteorological variables $X_{it}$ in
  - (Storm) Maximum daily windspeed in the year
  - (Flood) Maximum daily precipitation in the year
  - (Heat) Fraction of days with temp. $>$ p95 of national distrib. in 1900-1920
- Residualize to capture adaptation:

$$X_{it} = \alpha_i + \beta_t + Z_{it}$$

- Construct indicator of extreme value for $Z_{it}$

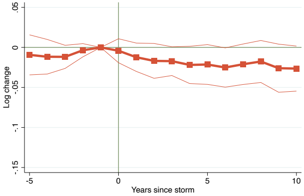
$$D_{it} = \mathbf{1}[Z_{it} \geq \mathrm{p}(Z)]$$

where $\mathrm{p}(Z)$ denotes some percentile of $Z_{it}$ across all $i$ for $t \in [1900, 1920]$
  - $99^{\text{th}}$ percentile for storms and floods
  - $95^{\text{th}}$ percentile for heat

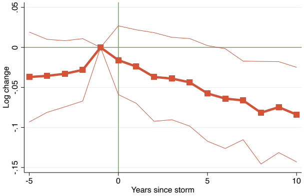
Back to main presentation

# Impact of 1-in-50-years storm in coastal counties

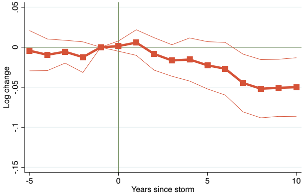
**(a)** Wage



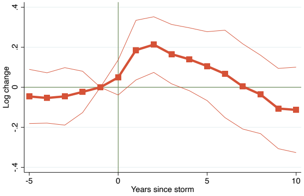

**(b)** Employment




**(c)** Population



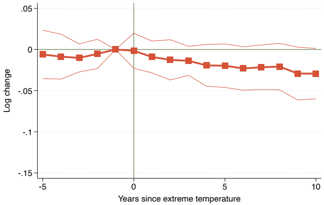

**(d)** Investment



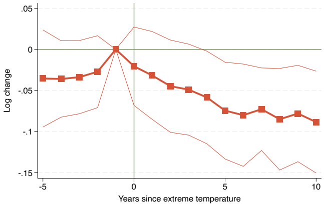

▸ Back to main presentation

# Impact of 1-in-50-years storm in coastal counties, w/o Louisiana

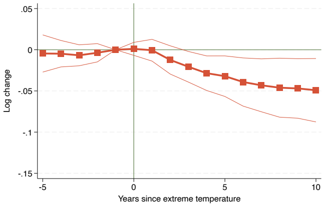
**(a)** Wage



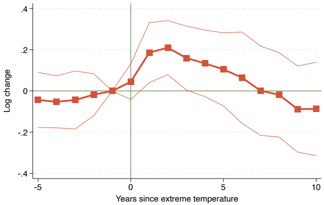

**(b)** Employment




**(c)** Population



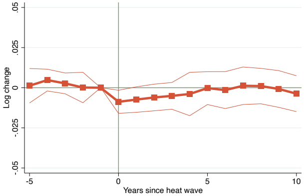

**(d)** Investment



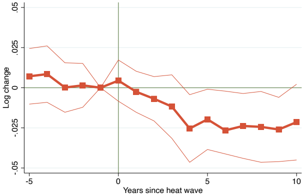

▸ Back to main presentation

# Impact of 1-in-20-years heat wave in warm counties

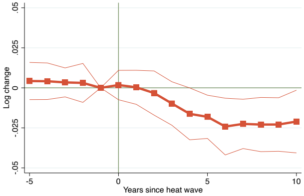
**(a)** Wage



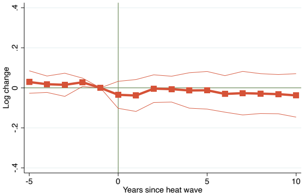

**(b)** Employment




**(c)** Population



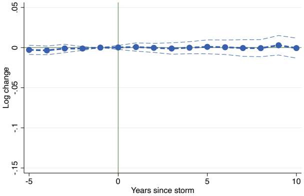

**(d)** Investment



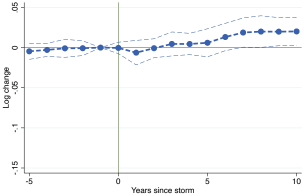

▸ Back to main presentation

# Impact of 1-in-50 years storm in inland counties

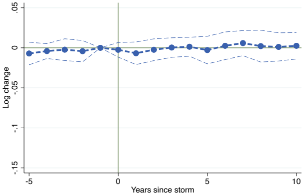
**(a)** Wage



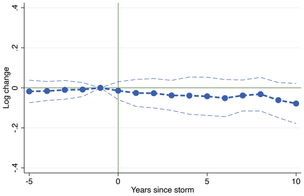

**(b)** Employment




**(c)** Population



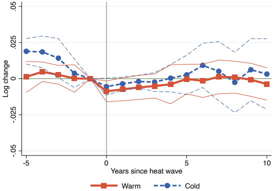

**(d)** Investment



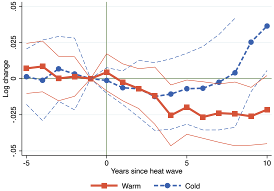

Back to main presentation

# Impact of 1-in-20 years heat wave in warm and cold counties

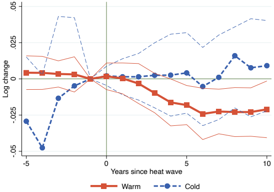
**(a)** Wage



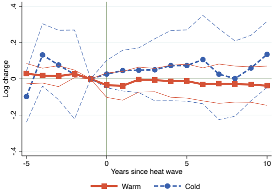

**(b)** Employment




**(c)** Population



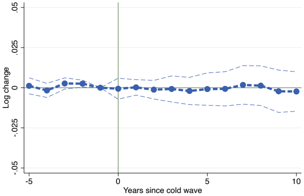

**(d)** Investment



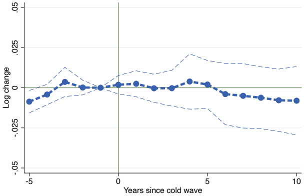

Back to main presentation

# Impact of 1-in-20 years cold wave in cold counties

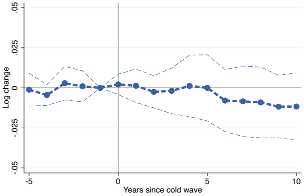
**(a)** Wage



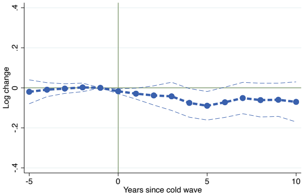

**(b)** Employment




**(c)** Population



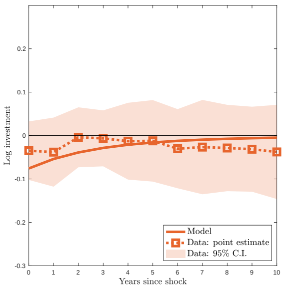

**(d)** Investment



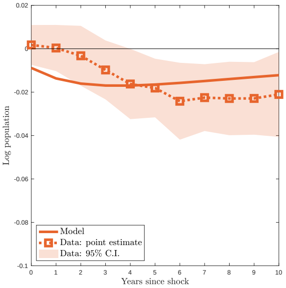

Back to main presentation

# Size of shocks: Heat waves

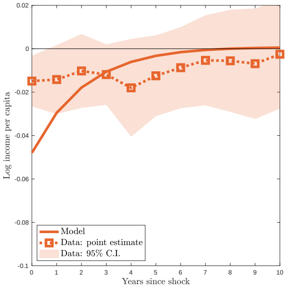
**(a)** Heat: investment




**(b)** Heat: population




**(c)** Heat: wage




- 1-in-20-years heat wave in **warm** counties:
  - 5.1% negative productivity shock $\equiv \chi^{\text{heat,warm}}$
  - 6.8% negative amenity shock in **warm** locations $\equiv a^{\text{heat,warm}}$

Back to storms

# Mechanisms

| | Welfare | | | | Allocations | |
|---|---|---|---|---|---|---|
| | Workers | | Capitalists | | Population | Capital |
| | 2023 | 2100 | 2023 | 2100 | 2100 | 2100 |
| Baseline | | | | | | |
| Aggregate (%) | -4.9 | -11.6 | -0.8 | -13.4 | | -31.8 |
| St.dev. (p.p.) | 2.4 | 4.2 | 5.6 | 46.4 | 40.8 | 45.9 |
| Discount rate: Aggregate (%) | | | | | | |
| 5% | -3.4 | -12.0 | -0.5 | -12.8 | | -32.0 |
| 2% | -6.2 | -12.0 | -0.6 | -12.2 | | -33.8 |
| 1% | -8.5 | -12.4 | -0.6 | -11.9 | | -34.7 |
| By type of damages: Aggregate (%) | | | | | | |
| Capital depreciation | -2.2 | -5.3 | -0.7 | -11.6 | | -23.9 |
| Temperature | -2.7 | -6.3 | -0.1 | -1.8 | | -7.9 |
| Productivity | -1.3 | -3.1 | -0.1 | -2.3 | | -5.8 |
| Amenities | -1.4 | -3.2 | 0.0 | 0.5 | | -2.2 |

Back to main presentation

# NOAA storm counts

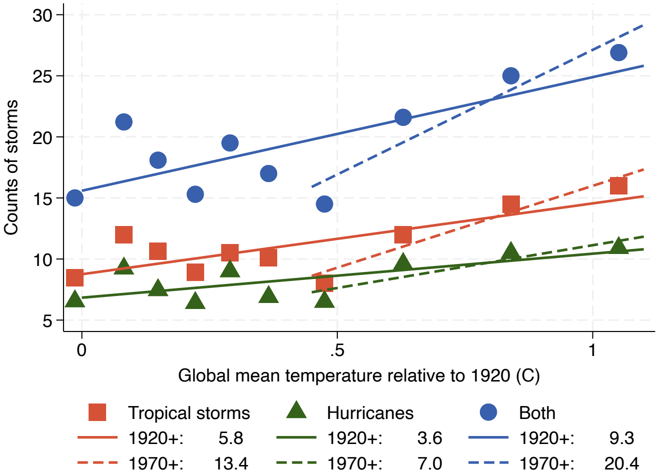



**Figure:** NOAA storm counts by global mean temperature

Back to main presentation

# Neoclassical growth model calculation

- Consider the steady-state of the RBC model:

$$\begin{aligned} C + \delta K &= K^{\alpha} \\ \alpha K^{\alpha-1} &= \delta + \beta^{-1} \end{aligned}$$

- Obtain

$$\frac{C_{\delta}}{C} = \frac{1}{\delta + \frac{\alpha\beta^{-1}}{1-\alpha}} + \frac{1}{\delta + \beta^{-1}}$$

- Using estimated damage functions, obtain 1 p.p. increase in $\delta$ in aggregate for $+3^{\circ}$C
  - 26% of capital exposed, 27% of population

- Using neoclassical growth formula with $\delta = 0.08, \alpha = 0.3, \beta = 0.95$, obtain

$$\frac{dC}{C} = 0.03,$$

similar to 0.05 in quantitative exercise by 2100.

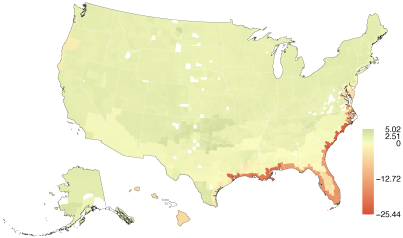
▸ Back to main presentation

# Mechanisms

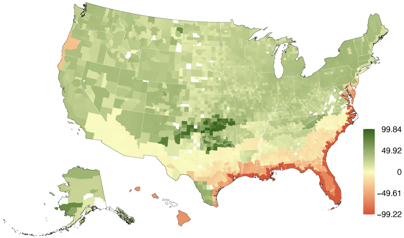
| | Welfare | | | | Allocations | |
|---|---|---|---|---|---|---|
| | Workers | | Capitalists | | Population | Capital |
| | 2023 | 2100 | 2023 | 2100 | 2100 | 2100 |
| Baseline | | | | | | |
| Aggregate (%) | -4.9 | -11.6 | -0.8 | -13.4 | | -31.8 |
| St.dev. (p.p.) | 2.4 | 4.2 | 5.6 | 46.4 | 40.8 | 45.9 |
| Discount rate: Aggregate (%) | | | | | | |
| 5% | -3.4 | -12.0 | -0.5 | -12.8 | | -32.0 |
| 2% | -6.2 | -12.0 | -0.6 | -12.2 | | -33.8 |
| 1% | -8.5 | -12.4 | -0.6 | -11.9 | | -34.7 |
| By type of damages: Aggregate (%) | | | | | | |
| Capital depreciation | -2.2 | -5.3 | -0.7 | -11.6 | | -23.9 |
| Temperature | -2.7 | -6.3 | -0.1 | -1.8 | | -7.9 |
| Productivity | -1.3 | -3.1 | -0.1 | -2.3 | | -5.8 |
| Amenities | -1.4 | -3.2 | 0.0 | 0.5 | | -2.2 |

▸ Back to main presentation

# Capitalists lose on the Southeastern coast




**(a)** 2023 capitalist welfare rel. to ag. (-0.8%)



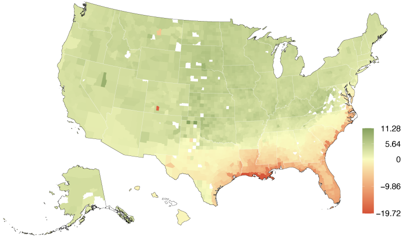

**(b)** Capital stock change by 2100 (%)

- Workers in Louisiana, Texas, Florida, Sth Carolina lose $\geq$ 10% (\$6,133/year)
- Capitalists on the South-Eastern Atlantic coast lose $\geq$ 20% (\$12,267/year)

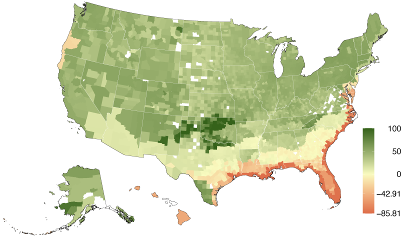
▸ Welfare in 2100 ▸ Back to main presentation

# 2100 welfare cost of 3°C additional warming by 2100

**(a)** Worker welfare in 2100 rel. to ag. (-11.6%)




**(b)** Capitalist welfare in 2100 rel. to ag. (-13.4%)




- Losses magnified in South-East
  - Workers in New Orleans: $\geq 30\%$, \$18,400/year
  - Capitalists in New Orleans: $\geq 60\%$, \$36,800/year
- Large gains for capitalists in North
  - Workers in-migrate $\Rightarrow$ capital return & investment $\uparrow$

▸ Back to main presentation

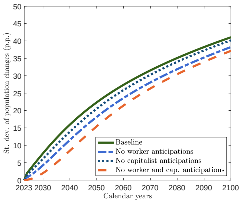
# Mineral and Petroleum counties

- Mineral county, Colorado, and Petroleum county, Montana differ from their neighbors
  - Large negative effects from climate relative to aggregate
  - Neighbors benefit relatively
  - Why?
- Consequence of bilateral migration flows in data
- **Only** migration destination from Mineral county, CO is Terrebone county, Louisiana
  - Just south of New Orleans
  - Only possible migration destination after inverting model
  - Implies that losses in coastal Louisiana spill over to Mineral county, CO
- Similarly, **only** migration destination from Petroleum county, MT is Baldwin county, Alabama
  - On Alabama coast, high damage area

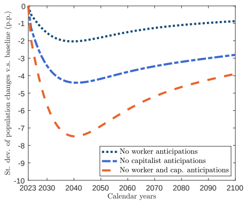
▸ Back to main presentation

# Shutting down anticipations: workers

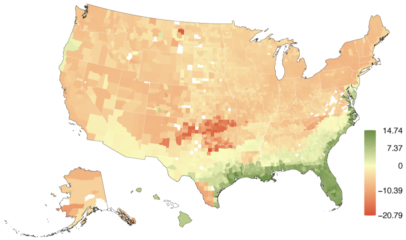
**(a)** Population change dispersion in baseline scenario.



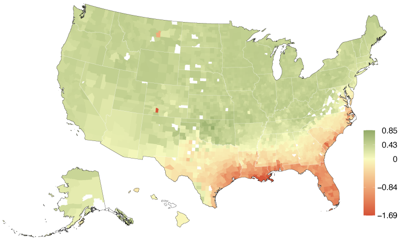

**(b)** Population change dispersion relative to baseline.




**(c)** Relative population change in 2050 (p.p.).



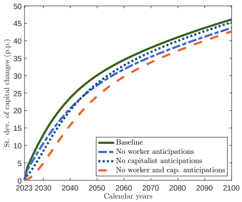

**(d)** Relative worker welfare change in 2050 (p.p.).



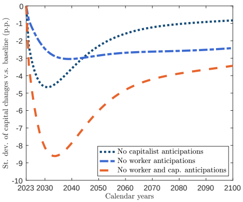

▸ Back to main presentation ▸ Capital

# Shutting down anticipations: capital

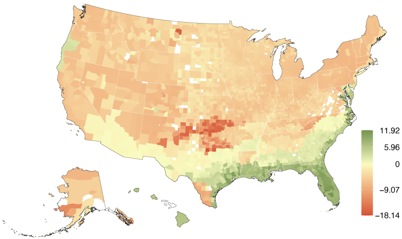
**(a)** Capital change dispersion in baseline scenario.



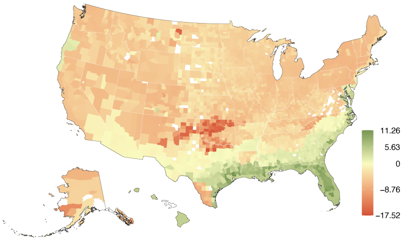

**(b)** Capital change dispersion relative to baseline.




**(c)** Relative capital change in 2050 (p.p.).



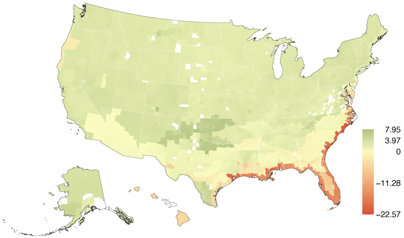

**(d)** Relative capitalist welfare change in 2050 (p.p.).



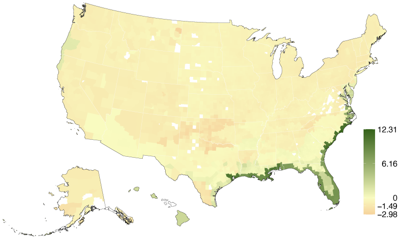

▸ Back to main presentation

# Migration provides insurance in the cross-section only

**(a)** 2023 worker welfare without migration vs. baseline




**(b)** 2023 capitalist welfare without migration vs. baseline




- Shutting down migration hurts workers in South-Eastern coastal counties
    - Welfare costs can exceed 25% ($15,333/year)
- But helps capitalists who benefit from higher population & capital demand
    - Welfare benefits can exceed 10% ($6,133/year)

▸ Back to main presentation

# Welfare

- Changes in aggregate welfare $\overline{V}_t = \sum_i N_i V_{it}$:

$$
\begin{aligned}
d\overline{V} \quad &= \quad \underbrace{\mathbb{E}_N[v_t^T]}_{\text{direct impact}} + \underbrace{\mathbb{C}\text{ov}_N\left[\frac{dN_i}{N_i}, V_i^{SS}\right]}_{\text{value reallocation}} \\
&+ \quad \underbrace{\mathbb{C}\text{ov}_N\left[\mathbb{E}_N[v_{\bullet j}^N], \frac{dN_j}{N_j}\right] + \mathbb{C}\text{ov}_K\left[\mathbb{E}_N[v_{\bullet j}^K], \frac{dK_j}{K_j}\right] + \mathbb{E}_K\left[\mathbb{E}_N[v_{\bullet j}^K]\right] d\overline{K}}_{\text{GE effects}}
\end{aligned}
$$

- Identical if use $\mathcal{W}_{it} = \frac{1}{\nu} \log\left(\sum_i e^{\nu(V_{it} - \tau_{ij})}\right)$ to account for taste shocks