Spatial Environmental Economics: Climate Change in Space and Time

Adrien Bilal

Stanford University

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Introduction

- Our economy is deeply connected to the **environment**, e.g.
  - Lower air quality due to car **pollution** causes respiratory illnesses (not today)
  - A **warming world** affects the entire fabric of the economy: **today's focus**
- **Climate change** is one of the most pressing issues of our century
- Rising global temperature is associated with climatic events affecting billions of people worldwide
  - Heat waves, wildfires, droughts
  - Floods, coastal storms, sea level rise and warming
  - Possibly more
- Also associated with the energy transition (not today)
- **3 defining features of climate change impacts**
  - A myriad of highly **localized** impacts
  - Intensifying over a **protracted** time horizon
  - To which societies can partly **adapt**, privately or through policies

What is Spatial Environmental (Climate Change) Economics?

- A fast growing field that incorporates some or all of these 3 features
  (recent reviews: Desmet Rossi-Hansberg 2024, Balboni Shapiro 2025)

- Takes the **spatial heterogeneity** of climate impacts seriously

⇒ Measure **exposure** accurately
  - Start from plausibly identified diff-in-diff (Dell et al. 2012, Burke et al. 2015, Carleton et al. 2022)
  - Infer damages and aggregate in structural framework (Moore Diaz 2015, Cruz Rossi-Hansberg 2024)

⇒ Allow for **adaptation** through **spatial reallocation** and **trade**
  - Households, workers; firms, capital
  - Almost always requires a structural framework, carefully constrained by data

- Adaptation is **slow and costly**: the **transition** to a warmer world matters for welfare
  - Goods face trade costs (Donaldson et al. 2016, Conte et al. 2022)
  - Workers face **migration costs** (Desmet et al. 2021, Balboni 2025)
  - Assets can become **stranded**: housing and structures cannot move (today's paper)

Where does Spatial Environmental (Climate Change) Economics stand?

- Huge progress in past 10 years
  - High-resolution data (Deschênes and Greenstone 2011, Tran and Wilson, 2023)
  - New generation of quantitative spatial models (Ahlfeldt et al. 2015, Redding and Rossi-Hansberg 2017)
  - Gradually incorporating dynamics (Desmet et al. 2018, Rudik et al. 2022, Krusell and Smith 2022)
- Many important and exciting **open questions** ahead
  - Does **capital** exposure matter for climate impacts? (today's paper)
  - Does **uncertainty about future warming** reshape spatial reallocation and adaptation?
  - Does **localized exposure** change the political economy of climate policies?
  - Is **local policy intervention** required in addition to private adaptation?

Anticipating Climate Change Across the United States

Bilal and Rossi-Hansberg, 2023, *R&R Econometrica*

- Many assessment frameworks abstract from key mechanisms for **damages** and **adaptation**

- **Damage functions** often estimated using annual average temperature only
  - May understate climate impacts
  - **Extreme heat** affects workers, **coastal storms** destroy capital

- **Adaptation** often myopic and/or only on worker side
  - May understate ability of economy to adapt
  - Forward-looking **investment** and **migration** decisions

- **Question:** How do **anticipation/adaptation** shape climate impacts due to **heat waves/storms**?

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 **twice 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, 2024), Desmet et al. (2021), Nath (2021), Kleinman et al. (2023), Balboni (2025)
  - **Representative agent/few locations:** Cai Longtzek (2019), Nordhaus Yang (1996), Fried (2022)
  - ⋆ Integrate capital accumulation, 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), Dell et al. (2012), Burke et al. (2015), Donaldson et al. (2016)
  - ⋆ Integrate new causal estimates into quantitative GE model

Framework

Workers

- Two types of agents: workers and capitalists
- Counties i, continuous time $t \geq 0$
- Workers solve the Bellman equation (Caliendo et al. 2019)

$$
\begin{aligned}
\rho V_{it} \quad &= \quad \overbrace{\max_{c,h} u\left(\left(\frac{c}{1-\beta}\right)^{1-\beta}\left(\frac{h}{\beta}\right)^{\beta}\right) + \boldsymbol{A_{it}}}^{\text{flow utility: consumption + amenities}} \quad + \quad \overbrace{\mathbb{E}_t\left[\frac{d\,\boldsymbol{V_{it}}}{dt}\right]}^{\text{continuation value from aggregate changes}} \\
&+ \quad \underbrace{\mu\left\{\mathbb{E}_t\left[\max_j \boldsymbol{V_{jt}} - \tau_{ij} + \varepsilon_{jt}\right] - V_{it}\right\}}_{\text{continuation value from migration}} \\
\text{s.t.} \quad & c + \boldsymbol{r_{it}} h = \boldsymbol{w_{it}}
\end{aligned}
$$

- ε_{jt} distributed EV-I $\Rightarrow$ logistic migration shares based on **forward-looking value V_{jt}**

▸ Details

- No savings

Capitalists

- Immobile, risk-neutral, solve

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

  - Capital evolves according to $\frac{dK_{it}}{dt} = I_{it} - \delta_{it} K_{it}$ and investment satisfies $c_i'(I_{it}/K_{it}) = \frac{\partial \mathcal{P}_{it}}{\partial K}$
  - Access to national bond market to fund local investment
  - State-dependent depreciation rate δ_{it}
  - Proceeds θ_{it} from claims to national mutual fund that owns land
  - Split between workers and capitalists (Kleinman et al. 2023)

Production

- Capital stock in location i:

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

- 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

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

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 δ_{i1} for capital
  - Similar for productivity and amenities

Solution method

Overview of solution method

- GE environment with
  - Aggregate shocks T_t^D
  - Distribution $\{N_{it}, K_{it}\}_i$ is a state variable: **6284 indiv. states** + **6284 prices** (wages, rental rates)
- Traditional solution methods can be hard to use in this context
- Use 'Master Equation' (Bilal, 2023): state-space **perturbation** around steady-state
- Features
  - Fast (fraction of second to minute), replicable recipe, formula for counterfactual standard errors
  - In paper use only 1st order, but can also use to 2nd order to study uncertainty (in progress)
  - Perturbation (surprisingly!) accurate
- Alternatives
  - Traditional global methods: infeasible
  - Exact hat algebra (Caliendo et al. 2019): can be hard to scale, confined to perfect foresight transitions
  - Sequence space (Auclert et al. 2021): hard with so many prices (difficult to even store Jacobian)
  - Neural networks (Gu et al. 2025, Sun 2025): may get global solution but slower/need customization

Details

Estimation

Estimation strategy

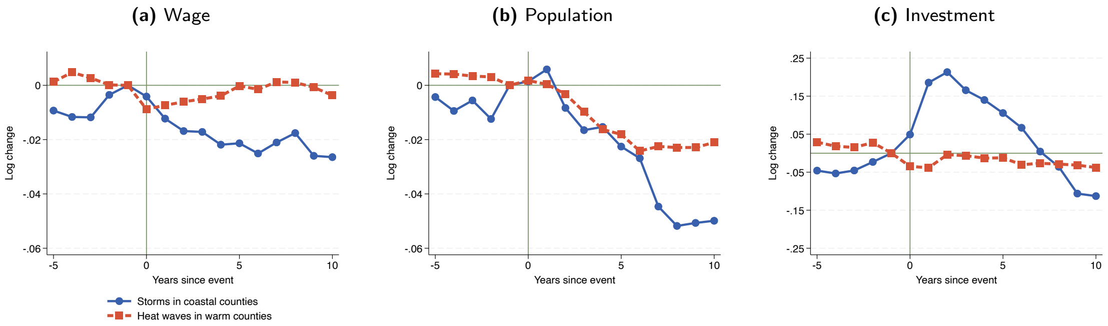
1. Assemble new dataset on extreme events and economic activity in US over past century ▸ Details

2. Estimate DiD impact of extreme events on economic outcomes ▸ DL specification

3. Match DiD in model by indirect inference
    - Estimate size of shock associated with each event
        - ⋆ Common approach (Moore Diaz 2015, Kahn et al. 2021, Rudik et al. 2022, Cruz Rossi-Hansberg 2024)
        - ⋆ But for extreme events instead of local mean temperature
    - Estimate migration and investment elasticities ▸ Model inversion ▸ Elasticities
        - ⋆ Requires solving and inverting model thousands of times
        - ⋆ Uses relevant variation for elasticities, akin to IV strategy
        - ⋆ Less common in literature

4. Combine with relationship between global temperature on local frequency of events
    - Similar to using forecasts of local mean temperature

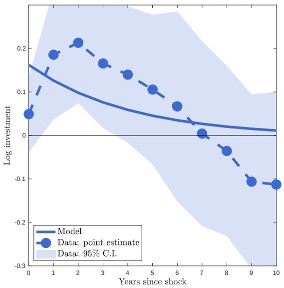
Storms and heat waves damage the economy



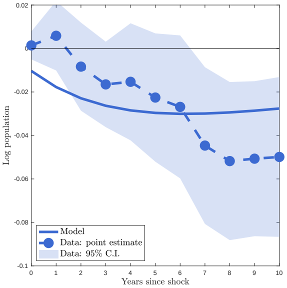
- **Storms**
  - In climate data: windspeed or precipitation above threshold
  - Economic impact: **capital depreciation shock** in coastal counties (no effect inland)
- **Heat waves**
  - In climate data: prolonged heat above threshold
  - Economic impact: **productivity + amenity shock** in warm counties (no effect in cold)

The magnitude of storm shocks

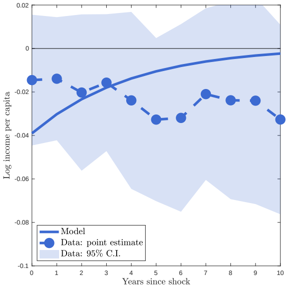
(a) Storms: investment



(b) Storms: population



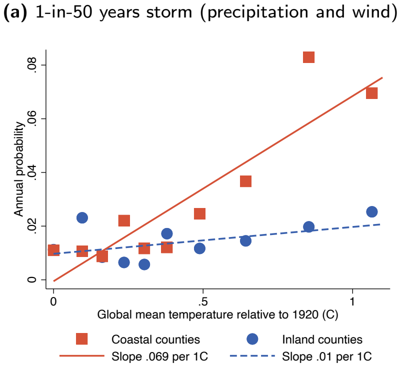
(c) Storms: income per capita

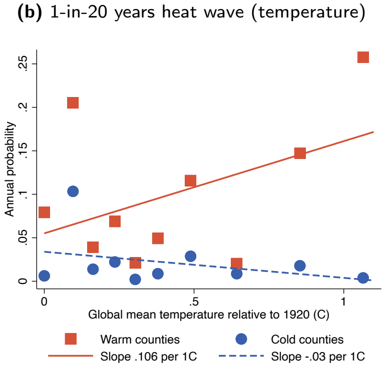


- 1-in-50-years storm in coastal counties = **17% capital depreciation** shock
- 1-in-20-years heat wave in warm counties = **5% productivity & 7% amenity** shock

Heat waves

Warming makes extreme events more frequent



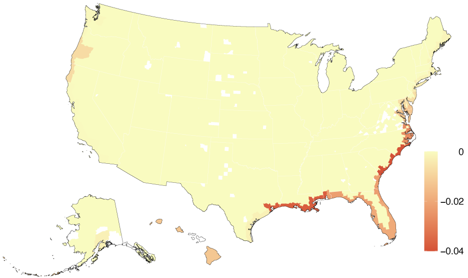


- Leverage 120 years of weather data, consistent with raw NOAA storm counts
- Damage functions interact change in frequency with damages from event, e.g.:

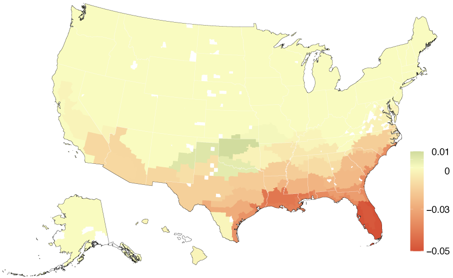
$$\delta_{it} = \delta_i^P + \delta_{i1} T_t^D \quad , \quad \delta_{i1} = \underbrace{p_{i1}^{\text{storm}}}_{\substack{\text{Freq. change with } T_t \\ \text{for every location } i}} \cdot \underbrace{17\% \cdot \mathbf{1}\{i \text{ coastal}\}}_{\substack{\text{Damage from} \\ \text{single event}}}$$

NOAA storm counts

Damage functions



(a) Change in annual capital depreciation δ_{i1} (+1°C)

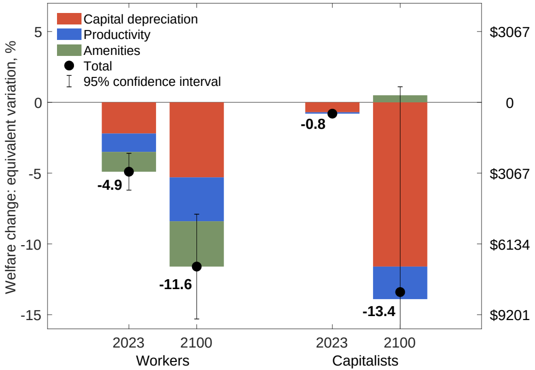


(b) Change in log productivity z_{i1} (+1°C)

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

Results

Climate damages are twice as large as previously thought

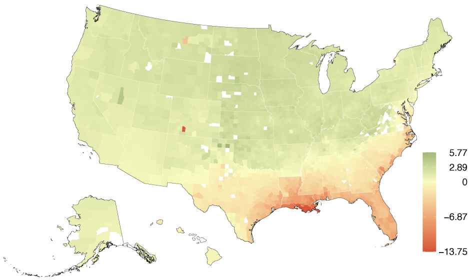


- Business as usual gradual 3°C warming from 2023 to 2100
- 45-88% of damages due to capital depreciation

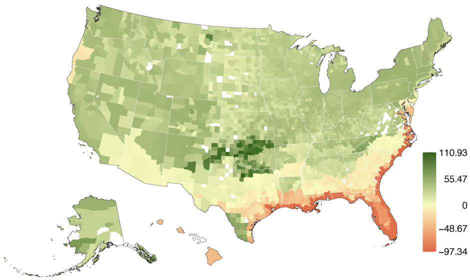
▸ Details

▸ Neoclassical growth model calculation

Welfare losses are most severe in Southeastern US



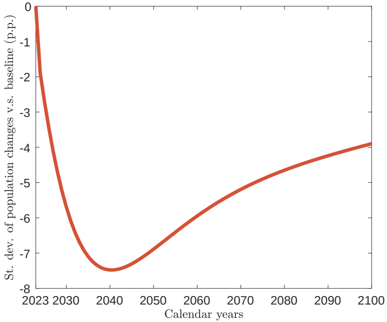
(a) 2023 worker welfare relative to aggregate (-4.9%)



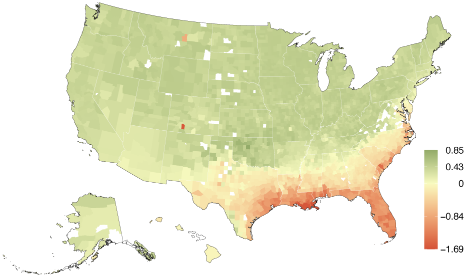
(b) Population change by 2100 (%)

- 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 ▸ No migration
- **Capitalists benefit** from lack of mobility through higher returns in exposed counties

▸ Workers: details ▸ Capital

Conclusion

Conclusion

- This paper: one step toward incorporating key forces shaping climate impacts in GE
  - High resolution framework to study climate change with capital and anticipation
  - Closely connected to data
- A lot of important and exciting **open questions** remain
  - Does **uncertainty about future warming** reshape spatial reallocation and adaptation?
  - Does **localized exposure** change the political economy of climate policies?
  - Is **local policy intervention** required in addition to private adaptation?

Thank You!

Appendix

Migration decisions

- Migration decisions depend on expected values

$$m_{ijt} = \frac{e^{\nu(V_{jt} - \tau_{ij})}}{\sum_k e^{\nu(V_{kt} - \tau_{ik})}}$$

  - Workers care about the forward-looking value of locating in j when deciding to move

- Get a **law of motion for the distribution** of workers across locations N_{it}

$$\frac{dN_{it}}{dt} = \mu \left(\sum_k m_{kit} N_{kt} - N_{it} \right)$$

  - Just counting how many workers move in and out of each location
  - In continuous time everything expressed in changes instead of levels
  - Otherwise exactly as in discrete time

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Investment decisions

- In paper show that $\mathcal{P}_{it}(K, b) = Q_{it} K + b + \mathcal{T}_{it}$, where $\mathcal{T}_{it}$ is the PDV of $\{\theta_{is}\}_{s \geq t}$
  - Linearity not crucial at all for approach
  - Allows for dual interpretation of a national mutual fund investing locally

- Investment and capital follow

$$c_i'(I_{it}^*/K_{it}) = Q_{it} \qquad I_{it}^* = c_{i0} Q_{it}^{\zeta} K_{it} \qquad \frac{dK_{it}}{dt} = \left(c_{i0} Q_{it}^{\zeta} - \delta_{it}\right) K_{it}$$

  - where $c_i(I/K) = \frac{c_{i0}^{-1/\zeta}}{1+1/\zeta} (I/K)^{1+1/\zeta}$
  - Law of motion of capital only depends on local variables $\neq$ population

- "Tobin's Q" satisfies

$$\rho Q_{it} = R_{K,it} + \underbrace{\frac{c_{i0} Q_{it}^{1+\zeta}}{1+\zeta}}_{\text{investment-costs}} - \delta_{it} Q_{it} + \mathbb{E}_t \left[\frac{dQ_{it}}{dt} \right]$$

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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

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

where

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

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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

- Use chain rule to obtain

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

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Master Equation: Step 3/3

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

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

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

$$\begin{aligned} \rho V_{it} &= \underbrace{\mathcal{U}_i(T_t^D, N)}_{\text{flow payoff in } i} + \underbrace{\mu \left\{ \frac{1}{\nu} \log \left(\sum_j e^{\nu(V_{jt} - \tau_{ij})} \right) - V_{it} \right\}}_{\text{continuation value from migration}} \\ &+ \underbrace{\underbrace{\frac{\partial V_{it}}{\partial t}}_{\text{change in } T_t^D} + \underbrace{\sum_j \frac{\partial V_{it}}{\partial N_j} \mu \left(\sum_k m_{kj}(V_t) N_{kt} - N_{jt} \right)}_{\text{change in } N_t}}_{\text{change in aggregates}} \end{aligned}$$

Back to main presentation

The Master Equation

$$\rho V_{it} = \underbrace{\mathcal{U}_i(T_t^D, N)}_{\text{flow payoff in } i} + \underbrace{\mu \left\{ \frac{1}{\nu} \log \left(\sum_j e^{\nu(V_{jt} - \tau_{ij})} \right) - V_{it} \right\}}_{\text{continuation value from migration}}$$

$$+ \underbrace{\underbrace{\frac{\partial V_{it}}{\partial t}}_{\text{change in } T_t^D} + \underbrace{\sum_j \frac{\partial V_{it}}{\partial N_j} \mu \left(\sum_k m_{kj}(V_t) N_{kt} - N_{jt} \right)}_{\text{change in } N_t}}_{\text{change in aggregates}}$$

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

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Perturbations of the Master Equation

- To make progress, use **analytic** perturbation of the Master Equation
  - Suppose we have found a steady-state when temperature is constant $T_t \equiv T^P$
  - When warming T_t^D is not too large, write to **first order**

$$V_{it}(N) - V_i^{SS} = \sum_j \boldsymbol{v_{ij}} n_j + \boldsymbol{v_{it}^T}$$

    - ⋆ $n_j = N_j - N_j^{SS}$ is deviation in population from steady-state
    - $\boldsymbol{v_{ij} = \frac{\partial V_i}{\partial N_j}(0, N^{SS})}$ captures transition back to steady-state absent aggregate shocks
    - $\boldsymbol{v_{it}^T}$ captures pure effect of aggregate shocks
- Obtain **First-order Approximation to the Master Equation**
  - Substitute first-order perturbation into nonlinear Master Equation
  - Identify coefficients to get restrictions on v_{ij}, v_{it}^T
  - Just like linearizing the RBC model, just larger state space!
- Similar logic to **second order**, just more components

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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

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

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

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

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

- $\boldsymbol{v}M^*$ 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)

$$G = \nu\mu\Big[\text{diag}((m^{SS})^* N^{SS}) - (m^{SS})^* \text{diag}(N^{SS}) m^{SS}\Big]$$

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Properties of the deterministic FAME

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

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

- Standard Bellman equation
- Block-recursive
  - v independent from v^T
  - 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

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Solving the deterministic 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 $\boldsymbol{v}^{(n)}$

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Trend FAME

- Obtain similar FAME for effect of temperature

$$\rho \mathbf{v}_t^T = \Psi T_t^D + (M + \mathbf{v}G)\mathbf{v}_t^T + \frac{\partial \mathbf{v}_t^T}{\partial t}$$

  - where Ψ captures direct price impact of temperature changes

$$\Psi_i = \frac{\partial \mathcal{U}_i}{\partial T_i}\Big|^{SS} = a_{i1} + u'(C_i^{SS})C_i^{SS}(1-\beta)\chi_{i1}$$

- Even simpler because interaction takes determistic FAME $\mathbf{v}$ as given
  - Now linear Bellman equation

- Simply iterate backward over time t given terminal condition v_∞^T satisfying

$$\rho \mathbf{v}_\infty^T = \Psi T_\infty^D + (M + G\mathbf{v})\mathbf{v}_\infty^T + 0$$

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Law of motion

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

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

- 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**
  - Includes aggregate risk in spatial model
  - See Bilal (2023) for aggregate risk with dynamic migration only
  - See Bilal et al. (202?) for aggregate risk also with capital

Back

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

Back

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**
- γ_h = impact of an event h periods ago on outcomes today

▸ Details

▸ Back

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
  - See Proposition 6 and Appendix E in paper
  - Get capital from steady-state investment
  - Get buildings, housing and structures from capital production function
  - Get productivity from wages
  - Get investment cost from investment decisions & Tobin's Q
  - Get migration costs from migration shares
  - Get amenities from steady-state population shares

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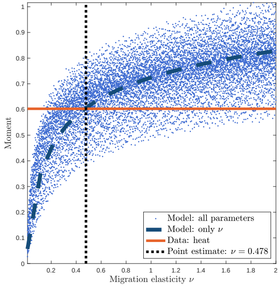
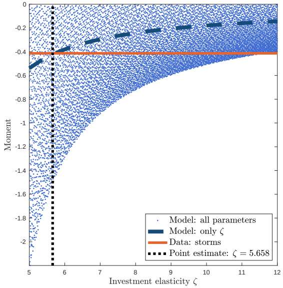
Damage functions 2/3: Migration and investment elasticities [appendix]

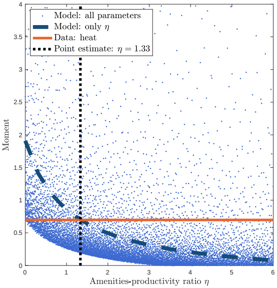
(a) Heat: population/investment



(b) Storms: population/investment



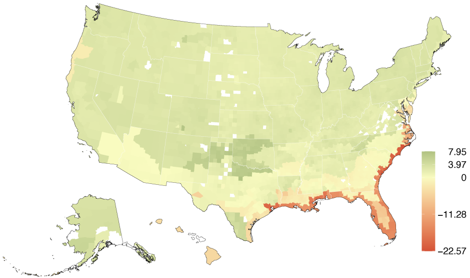
(c) Heat: income p.c./population



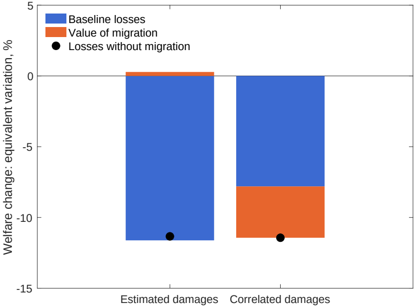
- Relative IRFs independent from shock size in model: use relative CIRs 10 years out
- Simulate IRFs for 10,000 parameter vectors $(\nu, \zeta, \eta) \in [0, 2] \times [5, 12] \times [0, 6]$
  - For amenity-productivity and capital depreciation shock
  - Invert model, solve for steady-state, solve for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

▸ Back

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

Back to main presentation   Capitalists   Full decomposition

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^{th} percentile for storms and floods
  - 95^{th} percentile for heat

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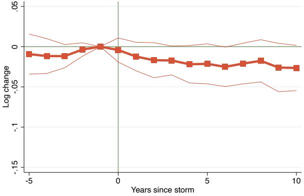
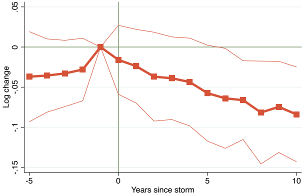
Impact of 1-in-50-years storm in coastal counties

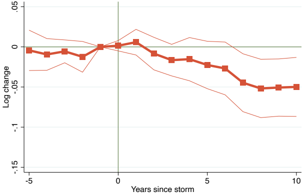
(a) Wage



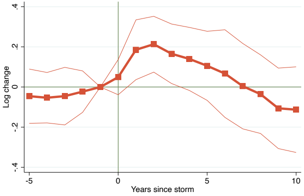
(b) Employment



(c) Population



(d) Investment



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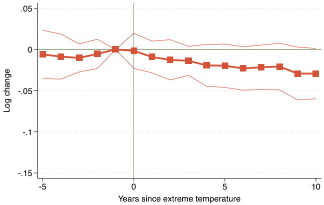
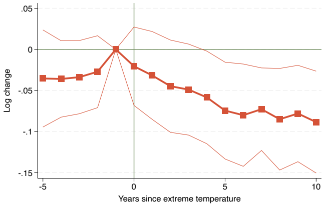
Impact of 1-in-50-years storm in coastal counties, w/o Louisiana

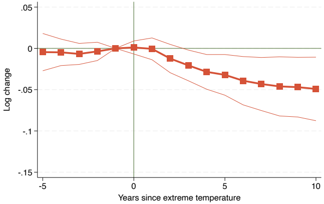
(a) Wage



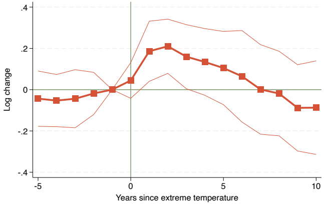
(b) Employment



(c) Population



(d) Investment



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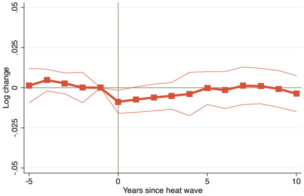
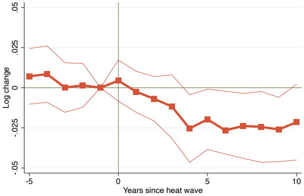
Impact of 1-in-20-years heat wave in warm counties

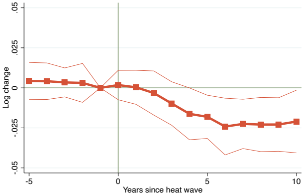
(a) Wage



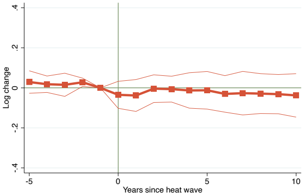
(b) Employment



(c) Population



(d) Investment



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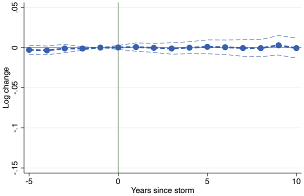
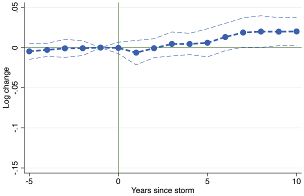
Impact of 1-in-50 years storm in inland counties

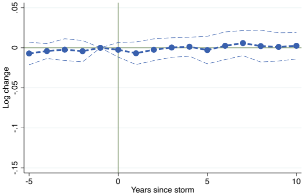
(a) Wage



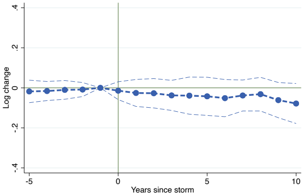
(b) Employment



(c) Population



(d) Investment



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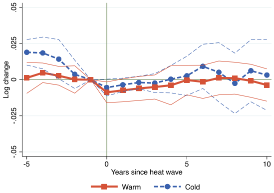
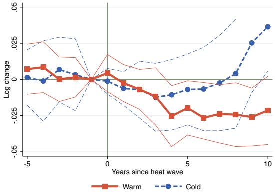
Impact of 1-in-20 years heat wave in warm and cold counties

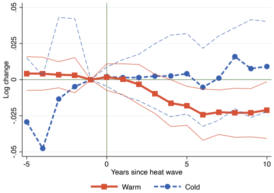
(a) Wage



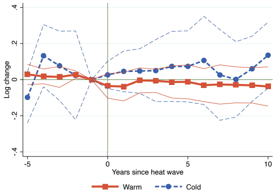
(b) Employment



(c) Population



(d) Investment



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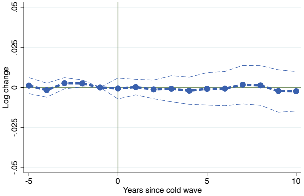
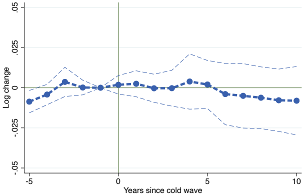
Impact of 1-in-20 years cold wave in cold counties

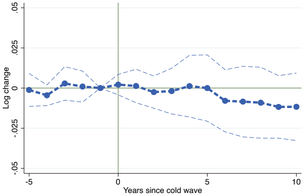
(a) Wage



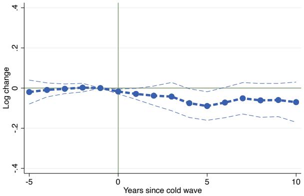
(b) Employment



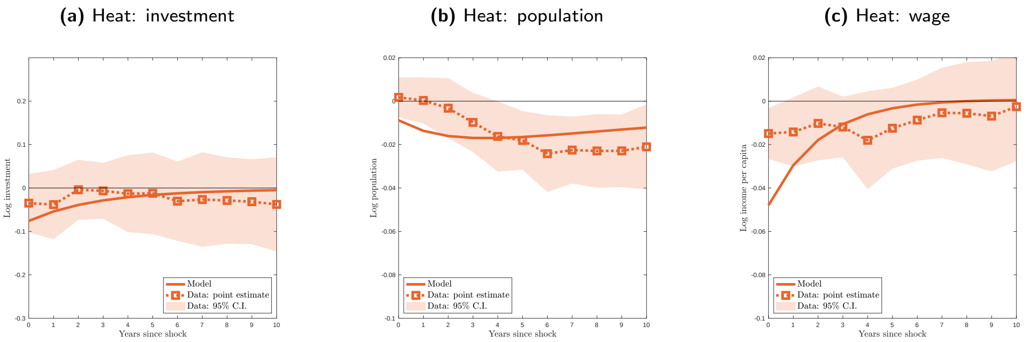
(c) Population



(d) Investment



Size of shocks: Heat waves



- 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

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NOAA storm counts

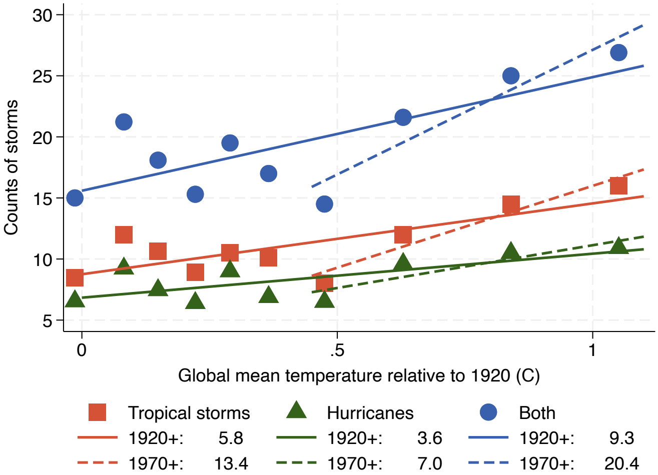

Figure: NOAA storm counts by global mean temperature

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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 δ 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.

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Mechanisms

	Welfare				Allocations	
	Workers		Capitalists		Population	Capital
	2023	2100	2023	2100	2100	2100
Baseline						
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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

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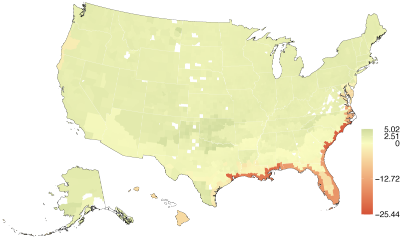
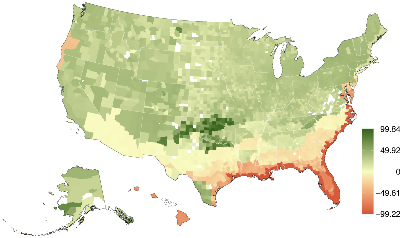
Capitalists lose on the Southeastern coast



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



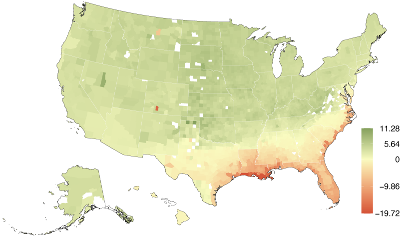
(b) Capital stock change by 2100 (%)

- 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)

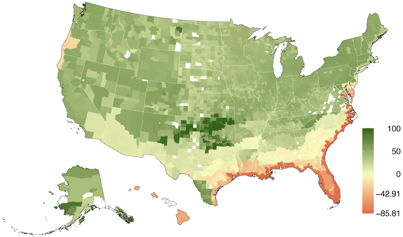
▸ Welfare in 2100 ▸ Back to main presentation

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

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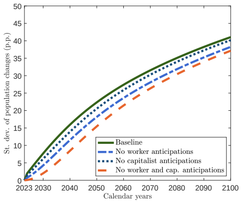
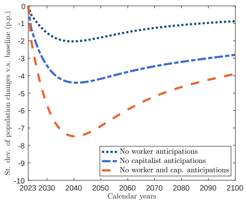
Shutting down anticipations: workers

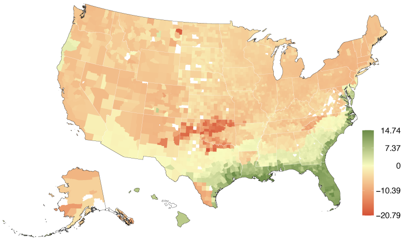
(a) Population change dispersion in baseline scenario.



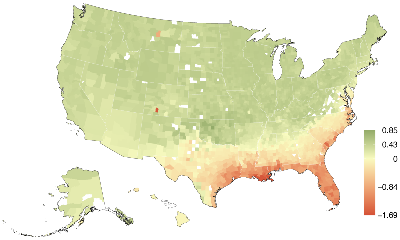
(b) Population change dispersion relative to baseline.



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



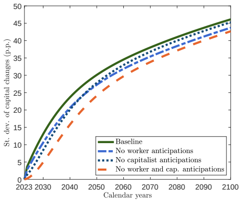
(d) Relative worker welfare change in 2050 (p.p.).



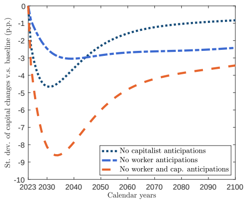
Back to main presentation   Capital

Shutting down anticipations: capital

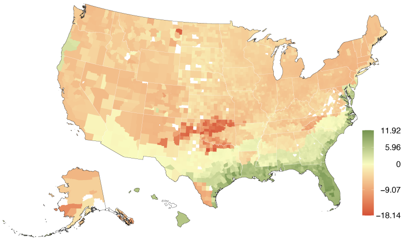
(a) Capital change dispersion in baseline scenario.



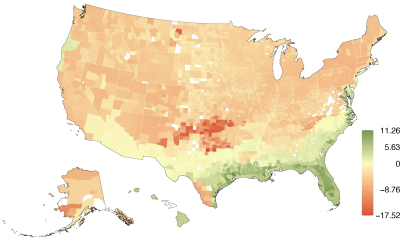
(b) Capital change dispersion relative to baseline.



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



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



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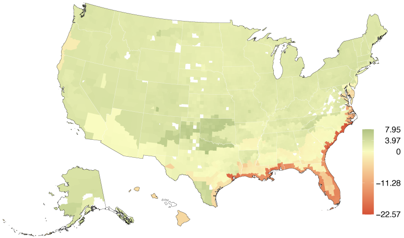
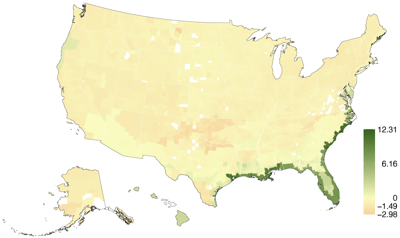
Migration provides insurance in the cross-section only

(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)

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Welfare

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

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

- 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

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