The (Mis)Allocation Channel of Climate Change

Evidence from Global Firm-level Microdata

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STEG Annual Conference 2025, Oxford

The Misallocation Channel of Climate Change

- Estimated macroeconomic consequences of climate change are significant:
  - → Burke et al. (2015): ≈ 23% of global GDP by 2100
  - → Bilal et al. (2024): ≈ 50% of global GDP by 2100
  - → Usually modeled/identified as aggregate TFP losses since Nordhaus (1992).

Question: What are the micro-level channels behind these aggregate estimates?

- In an efficient economy, marginal products are equalized across firms.

$$\text{Aggregate TFP} = \underbrace{\text{“Technology”}}_{\text{Aggregation of physical productivity}}$$

Previous literature: climate change affects technology (≈ physical productivity)

- Heat drags down labor productivity, disrupts transportation...
- Temperature ↑ → production possibility frontier contracts → Lower TFP

The Misallocation Channel of Climate Change

What are the micro-level channels behind these aggregates?

- In a distorted economy, there is dispersion in marginal products across firms:.

$$\text{Aggregate TFP} = \underbrace{\text{Technology}}_{\text{Efficient Frontier}} - \underbrace{\text{Misallocation Losses}}_{\text{Inefficiencies}}$$

This paper: climate change affects across-firm capital misallocation.

- Heat leads to inefficiencies: less productive firms ends up with too much capital
- Temperature ↑ → dispersion of "investment mistakes" ↑→ Lower TFP
- Climate change moves the economy further away from the efficient frontier

An illustrative example:

- **Technology:** machines are, on average, only 80% productive during heat shocks
- **Misallocation:** malfunctioned machines could have been more productive in plants with ACs!

Literature

- **Empirical climate econometrics**: we propose measurable channel decomposition of how climate damages aggregate TFP;
  - → This enables us to measure a new channel: *the misallocation channel*.

  (Dell, Jones, and Olken 2012; Hsiang 2016; Deryugina and Hsiang 2017; Mérel and Gammans 2021; Carleton et al. 2022; Lemoine 2018)
- **Macroeconomic modeling of climate change**: we emphasize how firm heterogeneity shapes the cost of climate change.

  (Nath 2023; Caggesse et al. 2024; Nath, Ramey, and Klenow 2023; Cruz and Rossi-Hansberg 2023; Bakkensen and Barrage 2021; Casey, Fried, and Gibson 2022; Rudik et al. 2021)
- **Climate and Long-run Development**: we find the misallocation channel to be a key driver of cross-country TFP differences.

  (Montesquieu 1748; Sachs and Warner 1997; Gallup, Sachs, and Mellinger 1999; Nordhaus 2006; Dell, Jones, and Olken 2012)
- **Misallocation**: we exploit temperature shocks as quasi-natural experiments to identify the environmental driver of misallocation.

  (Hsieh and Klenow 2009; Sraer and Thesmar 2023; Bau and Matray 2023)
- **Value of weather forecasts**: we estimate the aggregate consequences of temperature forecast errors.

  (Schlenker and Taylor 2021; Shrader 2023; Shrader, Bakkensen, and Lemoine 2023)

This paper...

Main Idea:

- Climate-induced misallocation is an important (if not major) driver of aggregate climate damage

The Plan:

1. Causal evidence and reduced-form measurement of climate-induced misallocation
2. Projection of global welfare losses under future climate change scenarios
3. Explain and identify the mechanisms in a simple firm dynamics model
4. Quantitatively re-examine the impact of climate on comparative development, growth and income convergence

Measurement: Climate-TFP Accounting

- A lower bound approach:
  → focus only on across-firm misallocation within each region-sector $n = (s, r)$.
- HK09 + all micro fundamentals can be affected by $\tilde{\mathbf{T}}_{rt}$ in an arbitrary but smooth way
- Total output is a CES aggregation of differentiated products,

$$Y_{nt} = \left(\int B_{ni}(\tilde{\mathbf{T}}_{rt}, \cdot)^{\frac{1}{\sigma_n}} Y_{nit}^{\frac{\sigma_n - 1}{\sigma_n}} di \right)^{\frac{\sigma_n}{\sigma_n - 1}},$$

- Subject to demand, firms face capital distortions in production:

$$\max_{P_{nit}, K_{nit}, L_{nit}} P_{nit} \underbrace{A_{ni}(\tilde{\mathbf{T}}_{rt}, \cdot) K_{nit}^{\alpha_{Kn}} L_{nit}^{\alpha_{Ln}}}_{Y_{nit}} - \left(1 + \tau_{ni}^{K}(\tilde{\mathbf{T}}_{rt}, \cdot)\right) R_{nt} K_{nit} - W_{nt} L_{nit}$$

$$\text{MRPK}_{nit} := R_{nt}(1 + \tau_{ni}^{K}(\tilde{\mathbf{T}}_{rt}, \cdot))$$

- Any mechanisms causing ex-post capital return differences will show up as $\tau_{ni}^{K}(\tilde{\mathbf{T}}_{rt}, \cdot)$.

Measurement: Climate-TFP Accounting

- Under the standard assumption of joint log-normality between A_{nit}, B_{nit} and $(1+\tau^K_{nit})$ in any cross-section, **aggregate TFP** of a region-sector $n=(s,r)$ can be decomposed as:

$$\log \mathrm{TFP}_n(\tilde{\mathbf{T}}_{rt},\cdot) = \underbrace{\frac{1}{\sigma_n-1}\log\left[\mathbb{E}_i \mathrm{TFP}_{ni}(\tilde{\mathbf{T}}_{rt},\cdot)^{\sigma_n-1}\right]}_{\text{Technology}} - \underbrace{\frac{\alpha_{Kn}+\alpha_{Kn}^2(\sigma_n-1)}{2}\,\mathrm{var}_{mrpk_{ni}}(\tilde{\mathbf{T}}_{rt},\cdot)}_{\text{MRPK Dispersion Across Firms}}$$

- Dispersion in MRPK lowers aggregate TFP.

- All aggregate sufficient statistics are all smooth functions of $\tilde{\mathbf{T}}_{rt}$, which yields:

$$\frac{d\log \mathrm{TFP}_n(\tilde{\mathbf{T}}_{rt},\cdot)}{d\tilde{\mathbf{T}}_{rt}} = \frac{d\ \mathrm{Technology}_n(\tilde{\mathbf{T}}_{rt},\cdot)}{d\tilde{\mathbf{T}}_{rt}} - \underbrace{\frac{\alpha_{Kn}+\alpha_{Kn}^2(\sigma_n-1)}{2}\,\frac{d\,\mathrm{var}_{mrpk_{ni}}(\tilde{\mathbf{T}}_{rt},\cdot)}{d\tilde{\mathbf{T}}_{rt}}}_{\text{The Misallocation Channel}}$$

- We can measure the **total** effect of climate on $\mathrm{var}_{1+\tau^K_{ni}}(\tilde{\mathbf{T}}_{rt},\cdot)$ without taking a stance on the exact sources of the heterogeneity in $\tau^K_{ni}(\tilde{\mathbf{T}}_{rt},\cdot)$.

Measurement and Data

$$\frac{d\log \text{TFP}_n(\tilde{\mathbf{T}}_{rt},\cdot)}{d\tilde{\mathbf{T}}_{rt}} = \frac{d\ \text{Technology}_n(\tilde{\mathbf{T}}_{rt},\cdot)}{d\tilde{\mathbf{T}}_{rt}} - \underbrace{\frac{\alpha_{Kn}+\alpha_{Kn}^2(\sigma_n-1)}{2}\frac{d\,\text{var}_{mrpk_{ni}}(\tilde{\mathbf{T}}_{rt},\cdot)}{d\tilde{\mathbf{T}}_{rt}}}_{\text{The Misallocation Channel}}$$

To identify the misallocation channel, we use:

- Standard parameters drawn from the literature: $\alpha_{Kn} = 0.35$, $\sigma_n = 4$
- Firm-level microdata from 32 countries: $\approx$ 80 m. firm-year obs.
  - → Orbis Historic: 1995-2018 for 30 European countries
    - ▶ Good coverage of total sales in many countries
  - → China NBS + India ASI
    - ▶ Census for "above-scale" manufacturing firms
  - → Under Cobb-Douglas, we measure misallocation using

$$\text{var}_{mrpk_{nit}} = \text{var}\left[\log\left(\frac{\text{Revenue}_{nit}}{\text{Capital Stock}_{nit}}\right)\right]$$

for each region-sector-year. (e.g. all firms within UKJ14, Manufacturing, 2024)

- Weather and Climate Data: Daily Temperature from ERA5 (0.1°× 0.1°)
- Medium-Range Weather Forecast Data (ECMWF)

Average Effect of Temperature on MRPK Dispersion

We regress region-sector-level MRPK dispersion on the distribution of daily temperatures.

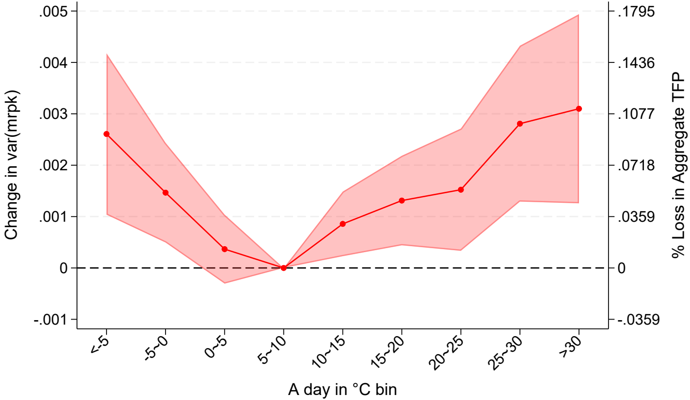
$$\text{var}_{mrpk_{(s,r),t}} = \sum_{b \in B/(5 \sim 10^\circ C)} \lambda^b_{\sigma^2_{mrpk}} \times \text{Tbin}^b_{r,t} + \delta_{\sigma^2_{mrpk}} \mathbf{X}_{s,r,t} + \theta_{c(r),s,t} + \eta_{s,r} + \varepsilon_{r,s,t}.$$

- r: region ("NUTS3"-level); s: sector (SIC industry group)
- $\mathbf{T}_{r,t} = \{\text{Tbin}^{<-5^\circ C}_{r,t}, ..., \text{Tbin}^{>30^\circ C}_{r,t}\}$ as days in temperature bins.
- $\mathbf{X}_{s,r,t}$ is a vector of controls: number of firms, average sales and average MRPK
- $\eta_{s,r}$: region-sector FE
- $\theta_{c(r),s,t}$: country-sector-year FE
- SE clustered at the region level

Within each region-sector, weather patterns are **exogenous** to capital distortions conditional on FEs.

Average Effect of Temperature on MRPK Dispersion

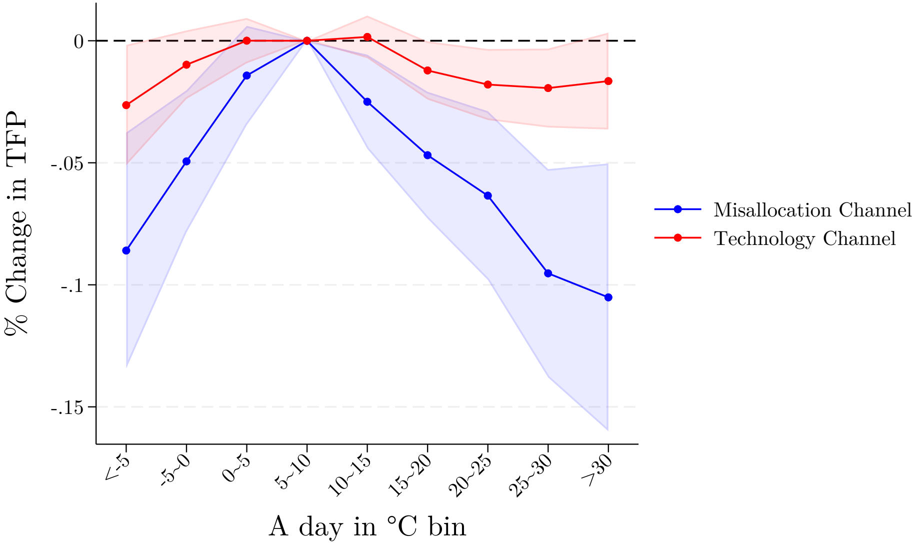
$$\text{var}_{mrpk_{(s,r),t}} = \sum_{b \in B/(5\sim 10^\circ C)} \lambda^b_{\sigma^2_{mrpk}} \times \text{Tbin}^b_{r,t} + \delta_{\sigma^2_{mrpk}} \mathbf{X}_{s,r,t} + \theta_{c(r),s,t} + \eta_{s,r} + \varepsilon_{r,s,t}.$$



If we replace a 5-10°C (41°F to 50°F) day with a hotter-than-30°C (86°F) day in a year:

- The measured MRPK dispersion will increase by about 0.31 log points;
- The measured yearly TFP will decrease by about 0.11% through capital misallocation.
  - → ≈ 40% of daily GDP

Technology vs. Misallocation



- Technology only plays a minor role in aggregate climate damage! (only $\approx \frac{1}{5}$ for heat shocks)

▸ Details

Heterogeneous Effect across Regional Income and Long-run Climate

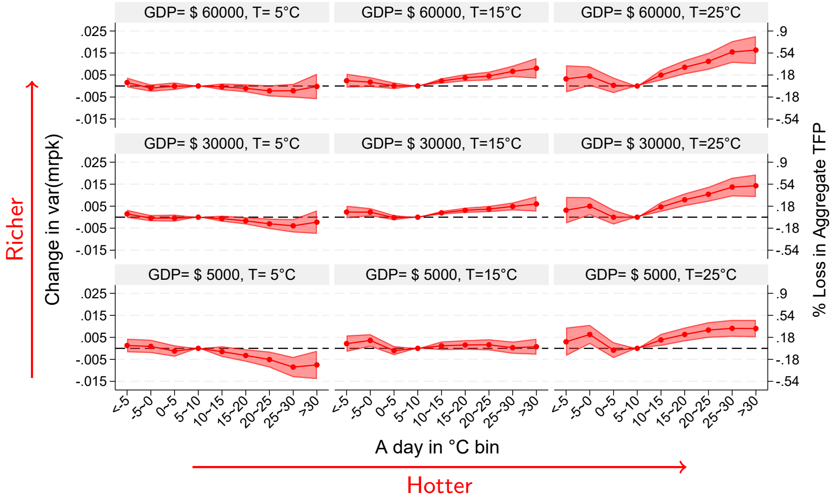
- Following Carleton et al. (2022), we interact the long-term annual average temperature of region r and average region-level GDP per capita with each temperature bin:

$$\begin{aligned} \sigma^2_{mrpk_{s,r,t}} = & \sum_{b \in B_{/(5\sim10^\circ C)}} \lambda^b_{\sigma^2_{mrpk}} \times \text{Tbin}^b_{r,t} + \sum_{b \in B_{/(5\sim10^\circ C)}} \lambda^{b,\bar{T}}_{\sigma^2_{mrpk}} \times \text{Tbin}^b_{r,t} \times \overline{T}_r \\ & + \sum_{b \in B_{/(5\sim10^\circ C)}} \lambda^b_{\text{GDP}_{pc}} \times \text{Tbin}^b_{r,t} \times \ln \overline{\text{GDP}_{pc,r}} + \delta_{\sigma^2_{mrpk}} \times \tilde{\mathbf{X}}_{s,r,t} + \alpha_{c,t} + \eta_{s,r} + \varepsilon_{s,r,t}, \end{aligned} \tag{1}$$

- The estimated first-order effect takes adaptation into account:

$$\frac{d\,\text{var}_{mrpk_{s,r}}(\tilde{\mathbf{T}}_{rt}, \cdot)}{d\text{Tbin}^b_{r,t}} \approx \lambda_{\sigma^2_{mrpk}} + \overline{T}_r \cdot \lambda^{\bar{T}}_{\sigma^2_{mrpk}} + \ln \overline{\text{GDP}_{pc,r}} \cdot \lambda^b_{\text{GDP}_{pc}}$$

Heterogeneous Effect across Regional Income and Long-run Climate

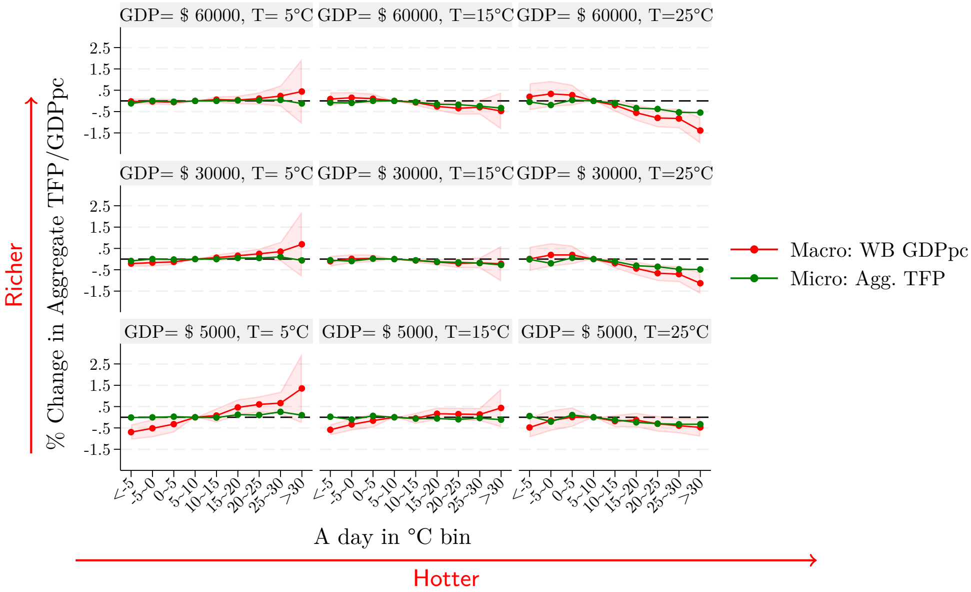


In terms of the misallocation channel:

- Hotter and more developed regions suffer more damage by heat shocks.
- Cooler regions could even benefit from heat shocks.

With Technology

Micro Estimates vs. Macro Estimates



- Micro-level estimates using only firm-level data *quantitatively* match macro estimates (GDP per capita) quite well

End-of-the-century Projections under SSP3-4.5 Warming Scenario

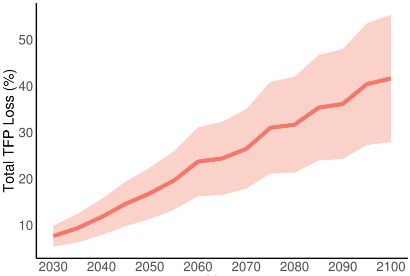
Under the assumption that $\frac{d\,\text{var}_{mrpk_{ni}}(\tilde{\mathbf{T}}_{rt},\cdot)}{d\tilde{\mathbf{T}}_{rt}} = f(\text{Long-run Climate, Income})$, we project the effect of climate-induced misallocation on aggregate TFP loss by the end of the 21st century (2081-2100) for 4,881 regions in 172 countries worldwide.

$$\underbrace{\Delta^{\text{Mis, Loss}}\ln TFP}_{\substack{\text{Misallocation Channel}\\=36.73\%}} = \sum_r \omega_{rt}\frac{\alpha_{Kr}+\alpha_{Kr}^2(\sigma_r-1)}{2}\left[\sigma^2_{mrpk}\left(\tilde{\mathbf{T}}_{r,EOC},\frac{d\sigma^2_{mrpk,r,EOC}}{d\tilde{\mathbf{T}}_{r,EOC}}\right)-\sigma^2_{mrpk}\left(\tilde{\mathbf{T}}_{r,2019},\frac{d\sigma^2_{mrpk,r,2019}}{d\tilde{\mathbf{T}}_{r,2019}}\right)\right]$$

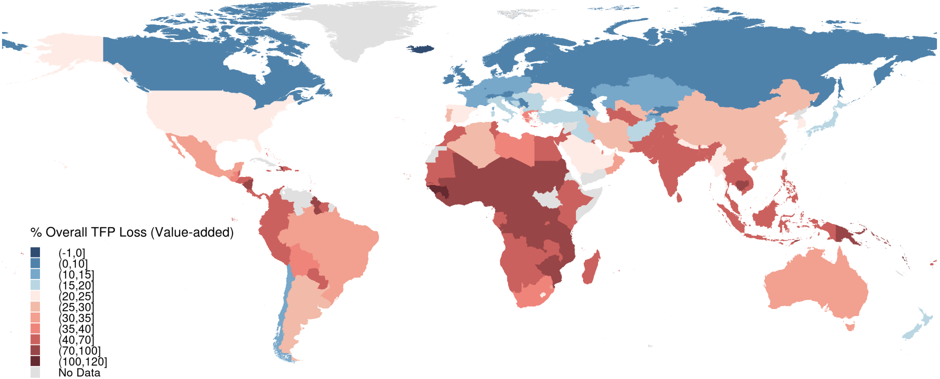
$$= \underbrace{\text{Shock Effect}}_{2.13\%} + \underbrace{\text{Level Effect}}_{11.34\%} + \underbrace{\text{Income Effect}}_{19.46\%} + \underbrace{\text{Resid.}}_{3.8\%},$$

▸ Equation ▸ Data

Figure: TFP Loss from Climate-Induced Misallocation



Future TFP Loss under SSP3-4.5 Warming Scenario



→ Large spatial heterogeneity in projected damages from the misallocation channel:

- Above 40 %: Tanzania, Malaysia, Honduras, and India.
- 20-30 %: US, Argentina, and Spain.
- Below 15 %: France, UK, Russia, and Canada.

A Simple Model of Firm Dynamics

- We want to explain why both the levels and shocks of temperature give rise to misallocation.
- A simple model with minimal ingredients: focusing on activities within (r, s).
- Firms: iso-elastic demand + Cobb-Douglas production
  - $\rightarrow$ Revenue Function: $P_{it} Y_{it} = \hat{A}_{it} K_{it}^{\hat{\alpha}_K} L_{it}^{\hat{\alpha}_L}$

A Firm's productivity is heterogeneously impacted by temperature:

$$\hat{A}_{it} = \exp\big(\underbrace{\hat{\beta}_{it}}_{\text{sensitivity}}\underbrace{(T_t - T^*)}_{\text{deviation from optimal } T^*}\big)\hat{Z}_{it}, \qquad \hat{\beta}_{it} = \underbrace{\hat{\beta}_i}_{\substack{\text{Persistent}\\ \text{sensitivity}}} + \underbrace{\hat{\xi}_{it}}_{\substack{\text{Idiosyncratic}\\ \text{sensitivity}}}$$

- Two sources of heterogeneity in $\hat{\beta}_{it}$:
  - $\rightarrow$ $\hat{\beta}_i \sim \mathcal{N}\left(\overline{\hat{\beta}_i}, \sigma^2_{\hat{\beta}}\right)$ is known by the firm: product characteristics and adaptability.
  - $\rightarrow$ $\hat{\xi}_{it} \sim \mathcal{N}\left(0, \sigma^2_{\hat{\xi}}\right)$ is i.i.d.: the likelihood of extreme events scales with $(T_t - T^*)$.

MRPK and Temperature

- "Time-to-build" Capital → investment depends on expected productivity:

$$k_{it+1} \propto \quad \mathbb{E}_t[a_{it+1}] \propto \hat{\beta}_i \mathbb{E}_t[(T_{t+1} - T^*)]$$

- After all shocks are realized, relative MRPK is higher in the firms with higher unexpected changes in productivity:

$$\begin{aligned} mrpk_{it} - \overline{mrpk_{it}} &= \frac{1}{1-\alpha_N}(\hat{a}_{nit} - \mathbb{E}_{t-1}[\hat{a}_{nit}]) \\ &= \frac{1}{1-\alpha_N}\left\{(\hat{\beta}_i - \overline{\hat{\beta}_i})\underbrace{(T_{t+1} - \mathbb{E}_t[T_{t+1}])}_{\text{T Forecast Error}} + \hat{\xi}_{it}\underbrace{(T_t - T^*)}_{\text{T Level}} + \hat{\varepsilon}_{it}\right\} \end{aligned}$$

- Who gets lower *mrpk* with a heat shock in a warm place? $(T_{t+1} - \mathbb{E}_t[T_{t+1}] > 0, T_t - T^* > 0)$
  - → Heat-averse firms with $\hat{\beta}_i < \overline{\hat{\beta}_i}$: failed to expect the low productivity caused by the temperature shock, $T_{t+1} - \mathbb{E}_t[T_{t+1}]$.
  - → Unlucky firms with $\hat{\xi}_{it} > 0$: failed to expect the low productivity caused by the damage sensitivity shock $\hat{\xi}_{it}$.
- What kind of firms have higher $\hat{\beta}_i$ in the data? Larger in size/AC-equipped.

▸ Firm-Level Evidence 1

MRPK Dispersion

Proposition: MRPK Dispersion The variance of $mrpk_{it}$ across firms in a given period is:

$$
\begin{aligned}
\sigma^2_{mrpk,(r,s),t} &= \left(\frac{1}{1-\alpha_N}\right)^2 \mathrm{Var}(\hat{a}_{nit} - \mathbb{E}_{t-1}[\hat{a}_{nit}]) \\
&= \left(\frac{1}{1-\alpha_N}\right)^2 \left[\underbrace{(T_{r,t} - T^*)^2}_{\text{Level Effect}} \sigma^2_{\hat{\xi},(r,s)} + \underbrace{(\mathbb{FE}_t[T_{t+1}])^2}_{\text{Forecast Error Effect}} \sigma^2_{\hat{\beta},(r,s)} + \sigma^2_{\varepsilon,(r,s)} \right]
\end{aligned}
$$

- MRPK dispersion $\propto$ TFP volatility $\longleftarrow$ endogenously generated by climate conditions.

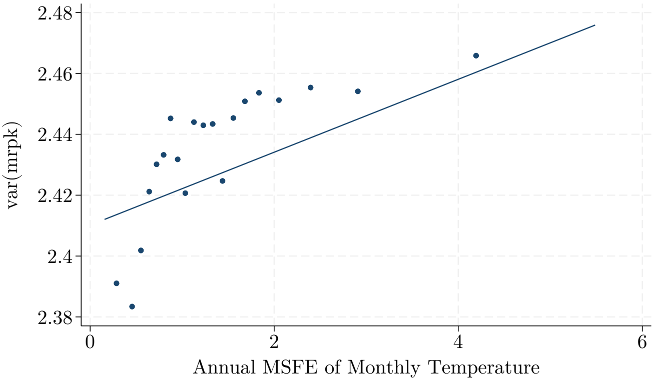
How would climate change lead to larger misallocation?

- Given everything else unchanged, a higher $\sigma^2_{\hat{\xi},(r,s)}$ and $\sigma^2_{\hat{\beta},(r,s)}$ lead to more capital misallocation
- Larger deviation from optimal temperature: $(T_{r,t} - T^*)^2$
- Larger unexpected temperature shocks: $(\mathbb{FE}_t[T_{t+1}])^2$

Forecast Error Effect

$$\sigma^2_{mrpk,(r,s)t} \propto \text{Var}(\hat{a}_{nit} - \mathbb{E}_{t-1}[\hat{a}_{nit}]) \propto \left[\underbrace{(\mathbb{FE}_t[T_{t+1}])^2\sigma^2_\beta}_{\text{Forecast Error Effect}} + \underbrace{(T_{r,t} - T^*)^2\sigma^2_\xi}_{\text{Level Effect}}\right]$$

- Mid-range temperature forecast data (1-month ahead forecast) from ECMWF.
- Misallocation is worse if the temperature forecast is inaccurate (TWFE residualized):



- a 1°C error in temperature forecast for all months → 0.5 % of annual aggregate TFP loss

Level Effect: Temperature as volatility shocks

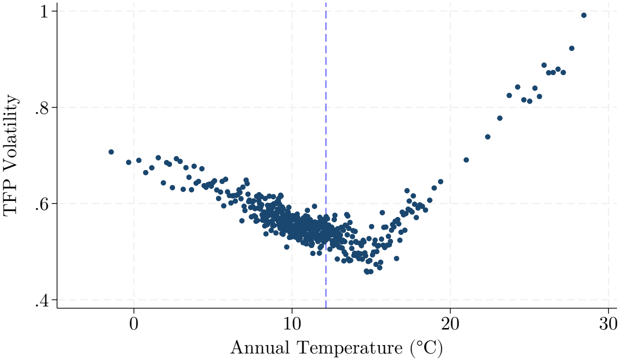
$$\sigma^2_{mrpk,(r,s)t} \propto \mathrm{Var}(\hat{a}_{nit} - \mathbb{E}_{t-1}[\hat{a}_{nit}]) \propto \Bigg[\underbrace{(\mathbb{FE}_t[T_{t+1}])^2 \sigma^2_\beta}_{\text{Forecast Error Effect}} + \underbrace{\color{red}{(T_{r,t} - T^*)^2 \sigma^2_\xi}}_{\color{red}{\text{Level Effect}}} \Bigg]$$

We test whether firm-level TFP volatility varies non-linearly with the level of temperature in the region-sector panel:

$$\mathrm{Var}_{(s,r),t}(\hat{a}_{it} - \hat{a}_{it-1}) = \alpha + \beta f(T_{r,t}) + \eta_{s,r} + \delta_{c(r),t} + \varepsilon_{s,r,t},$$

by using the "first-differenced" TFPR shocks.

- Firms' TFP volatility goes up in regions that are too hot or too cold.
- Optimal level of temperature is around 12 °C (TWFE residualized). ▸ Burke, Hsiang and Miguel 2015



Quantitative Results: Calibration

We run the following model-induced regression to calibrate the sensitivity dispersion parameters:

$$\sigma^2_{mrpk,(s,r),t} = \sigma^2_{\xi} \cdot (T_{r,t} - \hat{T}^*)^2 + \sigma^2_{\beta} \cdot \text{MSFE}_{r,t} + \iota_{s,r} + \iota_{c(r),s} + \varepsilon_{s,r,t}, \quad (2)$$

	(1)	(2)
$(T_{r,t} - \hat{T}^*)^2$	0.0045^{***}	0.0042^{***}
	(0.0008)	(0.0007)
$\text{MSFE}_{r,t}$	0.0120^{**}	0.0124^{**}
	(0.0055)	(0.0052)
Region-Sector FE	Yes	Yes
Country-Year FE	Yes	No
Country-Sector-Year FE	No	Yes
Observations	121,561	121,004
R^2	0.876	0.909

- Using the model, we will revisit the classic question through the misallocation channel:

  How much does temperature affect productivity and income inequalities in development?

  → We pair our micro estimates with gridded climate data (ERA5) and weather forecast data (ECMWF) for all regions worldwide since 1981.

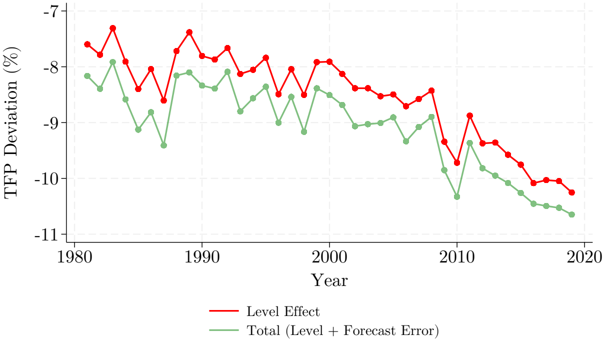
Quantitative Results: Cost of Climate-Induced Misallocation

- With Cobb-Douglas aggregators, the Global TFP can be written as:

$$\log \text{TFP}_t^{\text{Global}} = \sum_r \omega_{rt} \log \text{TFP}_{rt}.$$

- Using 1981-2019 averages, the global cost of climate-induced misallocation is around 9.1%.

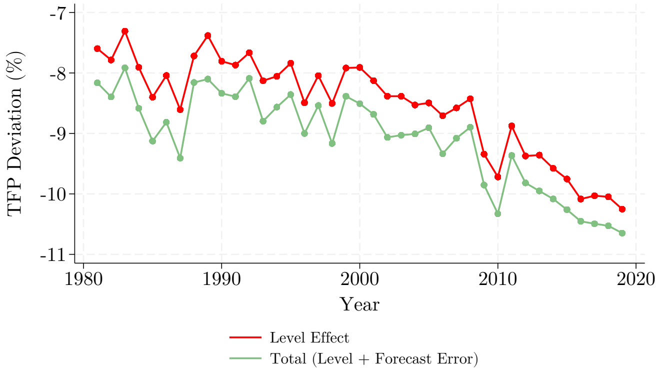
$$\underbrace{\overline{\Delta \log \text{TFP}_t^{\text{Global}}}}_{-9.1\%} = -\frac{\tilde{\alpha}_K + \tilde{\alpha}_K^2(\sigma - 1)}{2}\left[\underbrace{\sigma_\xi^2\left(\overline{\sum_r \omega_{rt}\left(T_{r,t} - T^*\right)^2}\right)}_{\substack{\text{Level Effect}\\ \approx -8.54\%}} + \underbrace{\sigma_\beta^2\left(\overline{\sum_r \omega_{rt}(\text{FE}_{t-1}[T_{r,t}])^2}\right)}_{\substack{\text{Forecast Error Effect}\\ \approx -0.54\%}}\right]$$



The Changing Cost: Climate Change and Forecast Improvements

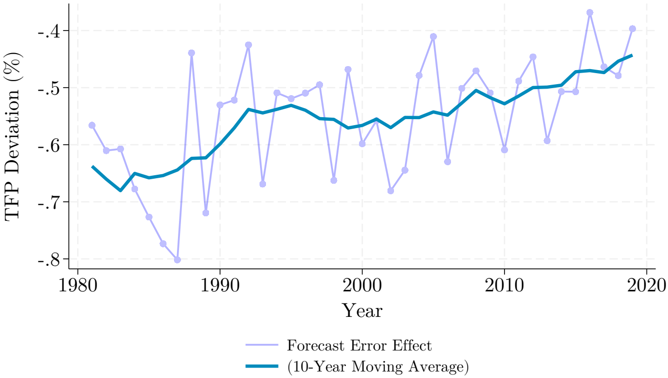
- From $t_0 = 1981$ to $t_1 = 2019$: hotter climate but better forecasts.
- Combining both leads to a 2.49% net increase in the cost of climate-induced misallocation.

$$\underbrace{\Delta^{T,\text{Mis}}_{t,t_0} \log \text{TFP}^{\text{Global}}_t}_{-2.49\%} = -\frac{\tilde{\alpha}_K + \tilde{\alpha}_K^2(\sigma-1)}{2}\left[\underbrace{\sigma_\xi^2 \Delta_{t,t_0}\left(\sum_r \omega_{rt}\left(T_{r,t} - T^*\right)^2\right)}_{\substack{\Delta\text{Level Effect}\\ \approx -2.66\%}} + \underbrace{\sigma_\beta^2 \Delta_{t,t_0}\left(\sum_r \omega_{rt}(\text{FE}_{t-1}[T_{r,t}])^2\right)}_{\substack{\Delta\text{ Forecast Error Effect}\\ \approx +0.17\%}}\right]$$



The Changing Cost: Climate Change and Forecast Improvements

- A 0.2% of TFP increase from small but steady increase in mid-range weather forecast accuracy

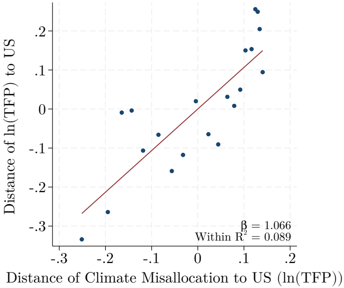


- According to Georgeson et al. (2017), the investment cost of weather information services is about 0.08% of global GDP.
- Potential benefits are at least 0.2%, implying a benefit–cost ratio greater than 2.

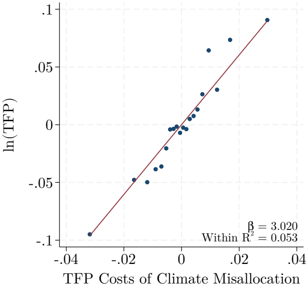
Temperature and Cross-/Within-Country Productivity Differences

- We match our model-generated country-year estimates with TFP data from the Penn World Table (PWT) 10.01.

(a) Across-country: Macro Data vs. Model



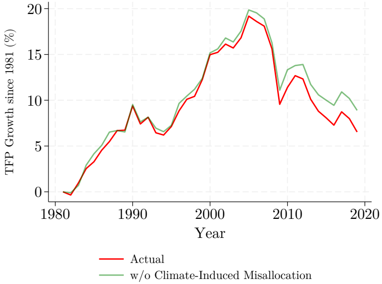
(b) Within-country: Macro Data vs. Model

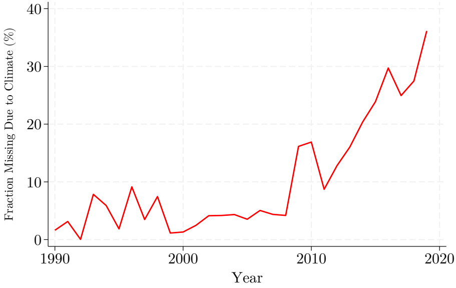


- On average, the model estimates $\Delta^{T,\text{Mis}} \log \text{TFP}_{c,t} - \Delta^{T,\text{Mis}} \log \text{TFP}_{\text{US},t}$ predicts the macro data $\ln \text{TFP}_{c,t} - \ln \text{TFP}_{\text{US},t}$ very well in the cross-section. $\longrightarrow \beta \approx 1$!
- The misallocation channel accounts for 9% of the TFP dispersion across countries and 5% of the TFP variation within a country.

Climate Change Slows Down Aggregate TFP Growth

- Global TFP would have been 2.36 p.p. higher if $\Delta^{T,\text{Mis}}_{\text{Global}} \log \text{TFP}_t$ stays at the 1981 level.
- This is equivalent to a 36% increase of cumulative growth since 1981.


(a) Actual vs. Counterfactual TFP


(b) Contribution to Cumulative Growth since 1981

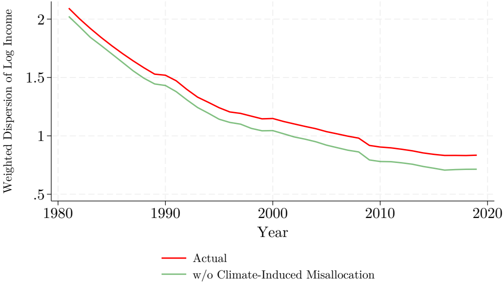
Increasing Misallocation Hinders Income Convergence

- To measure income inequality, we follow Gaubert et al. (2021) and adopt a population-weighted, between-country variance of income per capita:

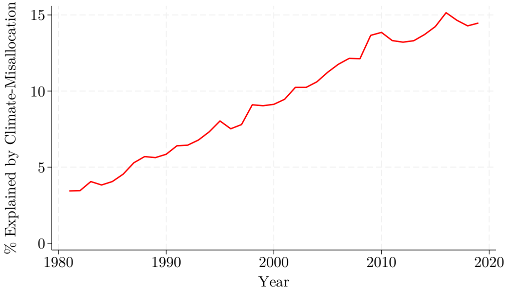
$$V_{\text{Global},t} = \sum_r \omega_{rt} \left(\ln \text{GDPpc}_{rt} - \sum_r \omega_{rt} \ln \text{GDPpc}_{rt} \right)^2 \tag{3}$$

- Actual income convergence: $V_{\text{Global},t}$ declines from 2.09 to 0.83.
- Without climate-misallocation: $\widetilde{V}_{\text{Global},t}$ declines from 2.02 to 0.71.
- The misallocation channel accounts for an increasing share of the surviving income inequalities
  - → from about 3% in 1981 to 14% in 2019

(a) Actual vs. Counterfactual Income Dispersion



(b) Contribution of Climate-Induced Misallocation



Conclusions and Policy Implications

- Established the first causal estimates and projections of **the misallocation channel of climate change**
  - → A major channel for aggregate climate damage
  - → 36.7% TFP Losses by EOC under SSP 3-4.5
- Quantitatively studied how **climate-induced volatility and weather forecast errors can result in capital misallocation** in a firm dynamics model
  - → The varying cost of climate-induced misallocation match well with macro data at the country-level.
  - → Climate-induced misallocation **accounts for an important part of comparative development**, growth and income inequality across countries.
- Policies to manage climate-induced misallocation:
  - → Mitigating global warming: $\approx$ 22% TFP loss can be avoided under RCP 2.6 compared to RCP 7
  - → Improving mid-range temperature forecast accuracy
  - → Reducing damage heterogeneity across units:
    - More “equity” across firms → higher aggregate efficiency

The (Mis)Allocation Channel of Climate Change

Evidence from Global Firm-level Microdata

Draft: **https://www.zebangxu.com/climate_allocation.pdf**

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Identification of the Causal Elasticities

$$\mathrm{var}_{mrpk_{(s,r),t}} = \sum_{b \in B/(5\sim10^{\circ}C)} \lambda^{b}_{\sigma^2_{mrpk}} \times \mathrm{Tbin}^{b}_{r,t} + \delta_{\sigma^2_{mrpk}} \mathbf{X}_{s,r,t} + \theta_{c(r),s,t} + \eta_{s,r} + \varepsilon_{r,s,t}.$$

- r: region ("NUTS3"-level); s: sector (SIC divisions).
- $\mathbf{T}_{r,t} = \{\mathrm{Tbin}^{<-5^{\circ}C}_{r,t}, ..., \mathrm{Tbin}^{>30^{\circ}C}_{r,t}\}$ as days in each temperature bins.
- $\mathbf{X}_{s,r,t}$ is a vector of control: number of observed firms, average firm-level sales and average MRPK across firms.
- $\eta_{s,r}$: region-sector FE; $\theta_{c(r),s,t}$: country-sector-Year FE; SE clustered at region level..

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The Technology Channel

We next turn to estimate how temperature affect the **aggregate "physical productivity"**:

$$\text{Technology Channel} = \frac{1}{\sigma_n - 1}\,\frac{d\log\left[\mathbb{E}_i \mathrm{TFP}_{ni}(\tilde{\mathbf{T}}_{rt},\cdot)^{\sigma_n-1}\right]}{d\tilde{\mathbf{T}}_{rt}}$$

- This is an "elasticity of the average", not the "average elasticity" à la OLS:

$$\underbrace{\frac{d\log \mathbb{E}_i\left[\mathrm{TFP}_{ni}(\tilde{\mathbf{T}}_{r,t},\cdot)^{\sigma_n-1}\right]}{d\tilde{\mathbf{T}}_{r,t}}}_{\text{Elasticity of the Average}} = \mathbb{E}_i\left[\underbrace{\frac{\mathrm{TFP}^{\sigma_n-1}_{nit}}{\mathbb{E}_i[\mathrm{TFP}^{\sigma_n-1}_{nit}]}}_{\text{Share}^E_{it}}\cdot\underbrace{\frac{d\log \mathrm{TFP}_{ni}(\tilde{\mathbf{T}}_{r,t},\cdot)^{\sigma_n-1}}{d\mathbf{T}_{r,t}}}_{\text{Elasticity}_{it}}\right] \neq \underbrace{\mathbb{E}_i\left[\frac{d\log \mathrm{TFP}_{ni}(\tilde{\mathbf{T}}_{r,t},\cdot)^{\sigma_n-1}}{d\mathbf{T}_{r,t}}\right]}_{\substack{\text{Average Elasticity}\\ \text{``OLS''}}}.$$

- OLS could bias the estimate of the average downward for heat shocks
  - → Larger firms are likely more resilient to heat, $\mathrm{cov}\left(\text{Share}^E_{it}, \text{Elasticity}_{it}\right) > 0$.
  - → We draw caution to the practice of using (unweighted) micro-level OLS estimates to make an interpretation of the aggregate impact.
- Instead, the CES index can be consistently identified via PPML with the following moment condition:

$$\mathrm{E}_i\left[\tfrac{1}{\sigma_n-1}\widetilde{\mathrm{TFP}}^{\sigma_n-1}_{nit} \mid \tilde{\mathbf{T}}_{rt}, \eta_i, \log(P_{nt}Y_{nt}), \kappa_{c(r)st}\right] = \exp\left[\beta\tilde{\mathbf{T}}_{rt} + \eta_i + \delta\log(P_{nt}Y_{nt}) + \kappa_{c(r)st}\right],$$

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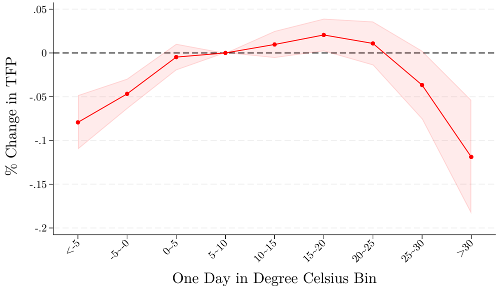
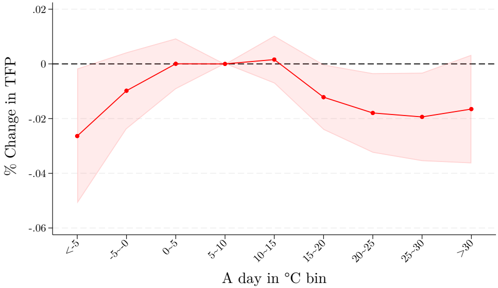
The Technology Channel: OLS vs PPML



(a) OLS: Average Elas., biased towards small firms



(b) PPML: Elast. of Average, welfare relevant

$$\beta_{\text{OLS}}^{>30^\circ C} \approx -0.1 \quad << \quad \beta_{\text{PPML}}^{>30^\circ C} \approx -0.02$$

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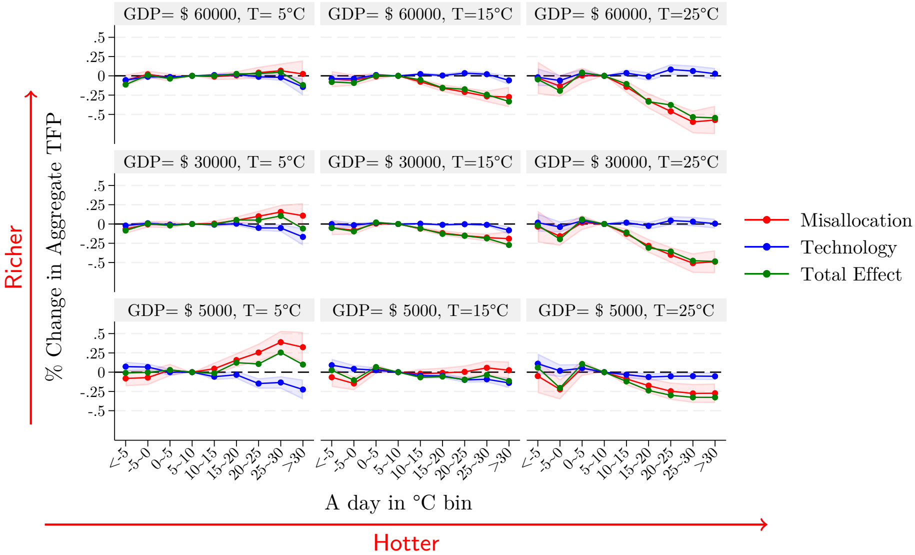
Heterogeneous Effect: Misallocation + Technology



- The misallocation channel almost always plays the dominating role in the total aggregate imapct!

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Data Source for Projections

- Projection Data Source:
  - → Changes in daily temperature distributions and long-run temperature:
    - ▶ Near-surface air temperature projection in SSP3-7.0 from CMIP-6 (ensemble average of 26 models).
  - → Changes in Income:
    - ▶ OECD Env-Growth model (Dellink et al. 2017)
    - ▶ Aggregation Weight: grid-level projected SSP-3 GDP (Wang and Sun 2022)

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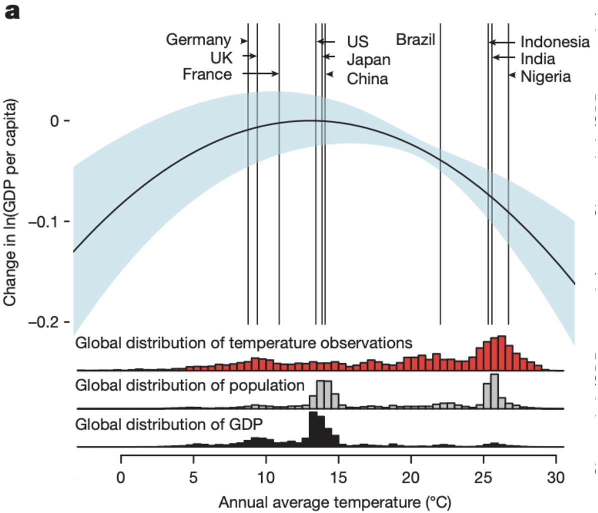
Burke, Hsiang and Miguel 2015

Their finding: Country-level economic production is smooth, non-linear, and concave in temperature with a maximum at 13°C.



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Firm-level Evidence: Heterogeneity of β_i and MRPK Responses

$$mrpk_{it} - \overline{mrpk_{it}} = \frac{1}{1-\alpha_N}\left\{ \underbrace{(\hat{\beta}_i - \overline{\hat{\beta}_i})\eta_t^T}_{\text{Temp Shock}} + \underbrace{\hat{\xi}_{it}(T_t - T^*)}_{\text{Damage Sensitivity Shock}} + \hat{\varepsilon}_{it} \right\}$$

We run the empirical counterpart:

$$\begin{aligned} \log(MRPK_{r,s,i,t}) = & \sum_{b \in B/\{5-10^\circ C\}} \lambda_b \times \text{Tbin}_{r,t}^b \\ & + \sum_{b \in B/\{5-10^\circ C\}} \lambda_{b,\hat{\beta}\text{-proxy}} \times \text{Tbin}_{r,t} \times \hat{\beta}\text{-proxy}_{it}^{r,s} + \delta \mathbf{X}_{i,t} \\ & + \delta_i + \alpha_{s,c(r),t} + \varepsilon_{s,c(r),i,t}, \qquad \hat{\beta}\text{-proxy} \in \{\text{Relative Size, AC}\}. \end{aligned} \tag{4}$$

- Given it's hard to observe $\hat{\beta}_i$, we use two proxies:
  - → Relative $\text{Size}_{it}^{r,s} := \log K_{it}^{s,r} - \overline{\log K_{it}}^{s,r}$ (Larger firms are more heat tolerant)
  - → $\text{AC}_{it}^{r,s} = 1$ if ever reported an AC installation (a proxy for adaptability, only in India ASI)
- $\lambda_{b,\hat{\beta}\text{-proxy}}$, are identified by comparing firms within the same country-sector exposed to identical temperature shocks but show differential response in (log) MRPK.
  - → A $\lambda_{b,\hat{\beta}\text{-proxy}} > 0$: relatively higher MRPK responses to shocks for heat-tolerant firms

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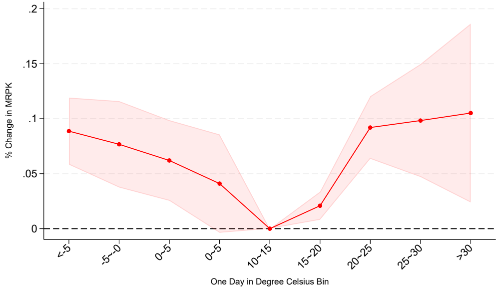
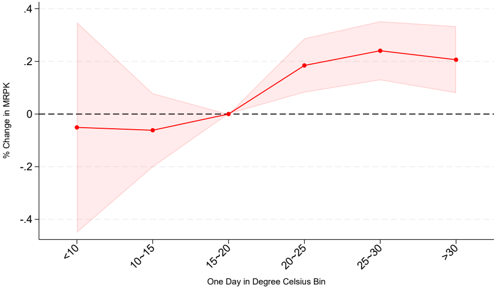
Firm-level Evidence: Heterogeneity of β_i and MRPK Responses


(a) Heterogeneous Effect from Firm Size


(b) Heterogeneous Effect from Firm Adaptability (AC)

- An additional 30°C day relative to baseline:
  - → makes a 1-SD larger firm having 0.1% higher MRPK compared to the average firm.
  - → makes an AC-equipped firm having 0.2% higher MRPK compared to those without ACs.
- $\lambda_{b,\hat{\beta}\text{-proxy}} > 0$ for heat shocks

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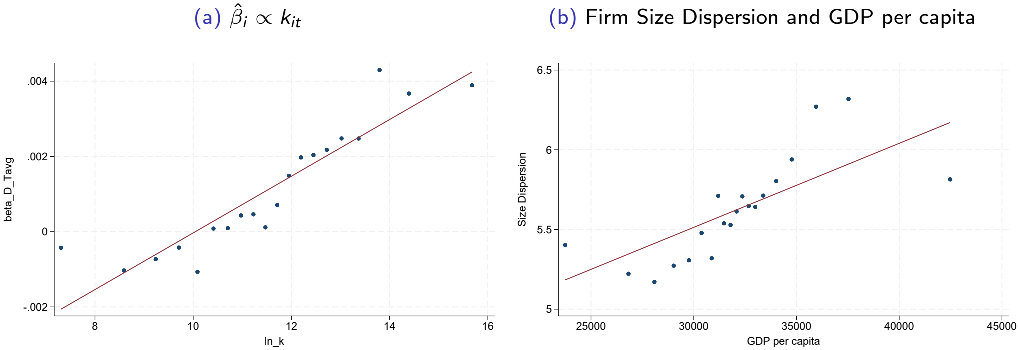
Firm-level Evidence: Heterogeneity of β_i and MRPK Responses

- This explains why richer regions suffer larger climate-induced misallocation → larger heterogeneity in firm-level sensitivity!
- Across Firms within a region-sector: $\sigma^2_{\hat{\beta}} \propto \sigma^2_k \propto \text{GDP}_{pc}$


(a) $\hat{\beta}_i \propto k_{it}$

(b) Firm Size Dispersion and GDP per capita

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