The (Mis)Allocation Channel of Climate Change

Evidence from Global Firm-level Microdata

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The Misallocation Channel of Climate Change

- Estimated macroeconomic consequences of climate change are significant:
  - $\rightarrow$ Burke et al. (2015): $\approx$ 23% of global GDP by 2100
  - $\rightarrow$ Bilal et al. (2024): $>$ 50% of global GDP by 2100
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Previous literature: climate change affects technology ($\approx$ physical productivity)

- Heat drags down labor productivity, disrupts transportation...
- Temperature $\uparrow \rightarrow$ production possibility frontier contracts $\rightarrow$ Lower TFP
  - → E.g. Machines are, on average, only 80% productive during heat shocks

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This paper: climate change affects across-firm misallocation.

- Heat leads to inefficiencies: less productive firms ends up with too much capital
  - → During heat shocks, the same machine will be more productive in a plant with ACs
- Temperature ↑ → "investment mistakes" ↑→ Lower TFP
- Climate change moves the economy further away from the efficient frontier

This paper...

Main Idea:

- Climate-induced misallocation is an important driver of aggregate climate damage

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- Climate-induced misallocation is an important 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. Quantitatively understand the mechanisms in a firm dynamics model

Measurement: Climate-TFP Accounting

- A lower bound approach:
  - $\rightarrow$ focusing on across-firm misallocation within each region-sector $n = (s, r)$.
- Similar to Hsieh and Klenow (2009), but all micro fundamentals can be affected by $\tilde{\mathbf{T}}_{rt}$.
- 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:

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

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

- Heterogeneity in $\tau_{ni}^{K}(\tilde{\mathbf{T}}_{rt}, \cdot)$ $\rightarrow$ Dispersion in MRPK across firms $\rightarrow$ Misallocation

Measurement: Climate-TFP Accounting

- Under the standrd 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:

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

- Dispersion in MRPK lowers aggregate TFP.

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- Dispersion in MRPK lowers aggregate TFP.
- Why do climate shocks matter here? To fix ideas, consider the following:

Weather Forecast: Mild

Realization: Mild

Year 1	Capital	MRPK
Ice Cream Parlor	5	2
Ski Resort	5	2

No Misallocation!

Weather Forecast: Mild

Realization: Heat wave

Year 2	Capital	MRPK
Ice Cream Parlor	5	3
Ski Resort	5	1

Large Misallocation!

Measurement and Data

The misallocation channel: how temperature affects misallocation

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

- Parameters can be directly calibrated: $\alpha_{Kn} = 0.35$, $\sigma_n = 4$.

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- Parameters can be directly calibrated: $\alpha_{Kn} = 0.35$, $\sigma_n = 4$.
- Firm-level microdata from 32 countries
  - → Orbis Historic: 1995-2018 for 30 European countries
    - ▶ Good coverage of total sales in most 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.
- Weather and Climate Data: Daily Temperature from ERA5 $0.1^\circ \times 0.1^\circ$
- Medium-Range Weather Forecast Data (ECMWF)

Average Effect of Temperature on MRPK Dispersion

We regress MRPK dispersion on the distribution of daily temperatures.

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

- 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 to remove "spurious" long-run relationship between $\mathbf{T}_{r,t}$ and development.
- $\theta_{c(r),s,t}$: country-sector-year FE to remove business cycles.
- SE clustered at the region level.

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

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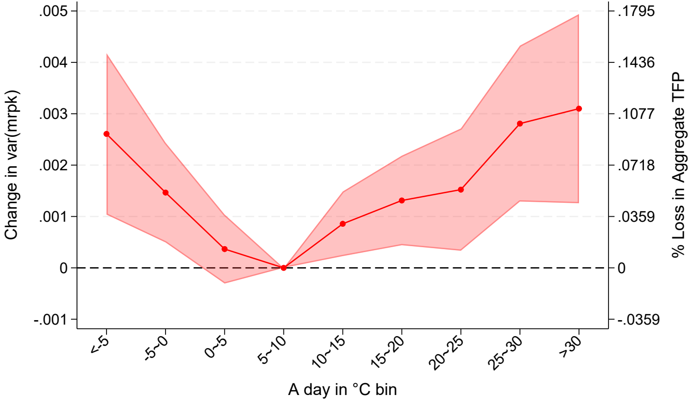

If we replace a 5-10°C (41°F to 50°F) day with a hotter-than-30°C (86°F) day in a year:

- The measured MRPK dispersion will increase by about 0.003;
- The measured yearly TFP will decrease by about 0.11% through capital misallocation.

  $\rightarrow \approx \frac{1}{3}$ of daily GDP

Regression Details

Heterogeneous Effect across Regional Income and Long-run Climate

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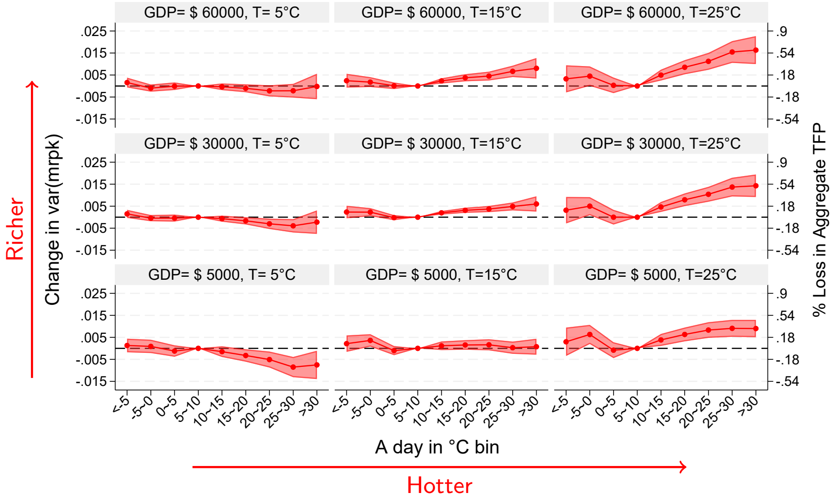
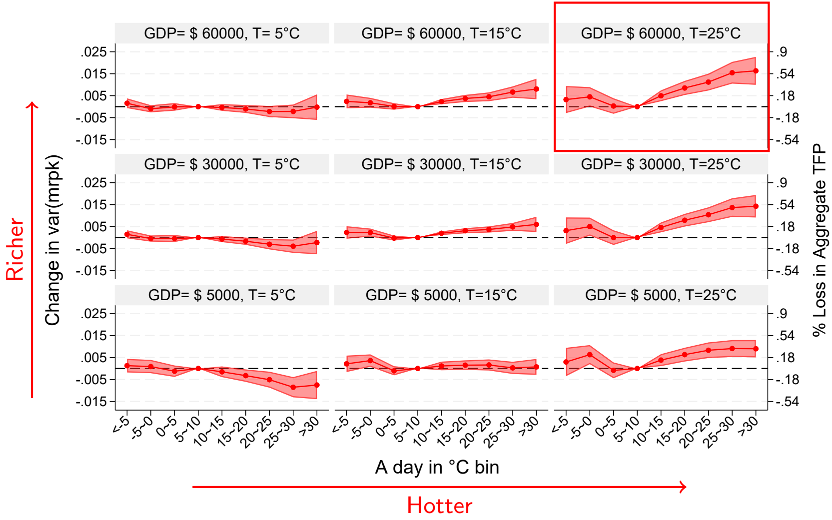


In terms of the misallocation channel:

- Hotter and more developed regions are more susceptible to heat shocks.
- Cooler regions could even benefit from heat shocks.

Regression Details

Heterogeneous Effect across Regional Income and Long-run Climate



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End-of-the-century Projections under SSP3-7.0 Warming Scenario

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Under the assumption that $\frac{\partial \, \text{var}_{mrpk_{ni}}(\tilde{\mathbf{T}}_{rt}, \cdot)}{\partial \tilde{\mathbf{T}}_{rt}} = f(\text{Long-run Climate}, \text{Income})$, 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 around the world.

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- The cost of climate-induced misallocation admits the following reduced-form decomposition:

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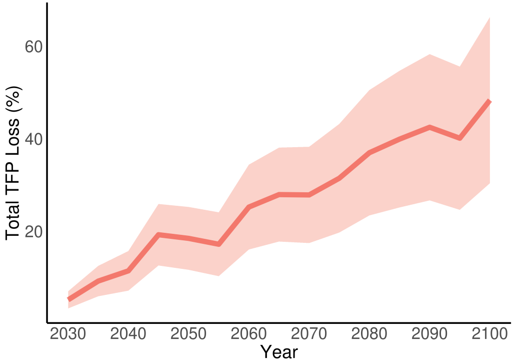
- The cost of climate-induced misallocation admits the following reduced-form decomposition:

$$\underbrace{\Delta^{\text{Loss}} \ln \text{TFP}}_{\text{Total Effect}=42.69\%} = \underbrace{\text{Weather Shock Effect}}_{4.99\%} + \underbrace{\text{Climatic Effect}}_{20.0\%} + \underbrace{\text{Income Effect}}_{17.7\%},$$

▸ Equation ▸ Data

Figure: Global TFP Loss from the Misallocation Channel



Future TFP Loss under SSP3-7.0 Warming Scenario

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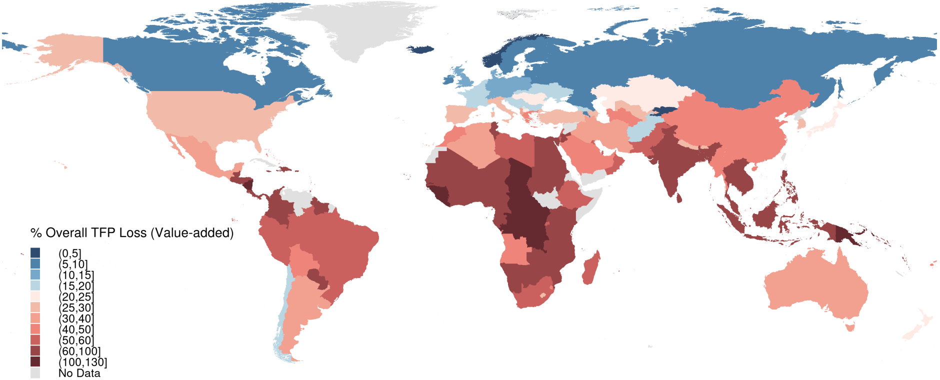

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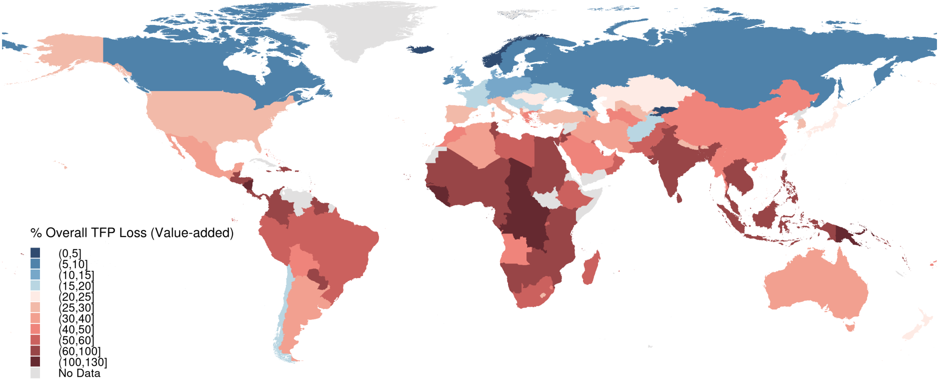

→ Large spatial heterogeneity in projected damages from the misallocation channel:

- Above 60 %: Guinea, Congo, Malaysia, and India.
- 25-30 %: United States, Turkey, and Spain.
- Below 15 % : Norway, Finland, Canada, and Germany.

A Simple Model of Firm Dynamics

- We want to explain why both the levels and shocks of temperature matter for misallocation.
- A simple model with minimal ingredients: focusing on activities within (r, s).
- Similar aggregation as the accounting framework: Iso-elastic demand + Cobb-Douglas Production
- Equilibrium revenue function: $P_{it} Y_{it} = \hat{A}_{it} K_{it}^{\alpha_K} N_{it}^{\alpha_N}$.

A Firm's productivity is heterogeneously impacted by temperature:

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

sensitivity ($\hat{\beta}_{it}$) — deviation from optimal T^* ($T_t - T^*$)

- 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: e.g. products and adaptability.
  - $\rightarrow$ $\hat{\xi}_{it} \sim \mathcal{N}\left(0, \sigma^2_{\hat{\xi}}\right)$ is i.i.d.: likelihood of extreme events scales with $(T_t - T^*)$.

MRPK and Temperature

- "Time-to-build" Capital $\rightarrow$ 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:

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

- Who gets lower *mrpk* with a heat shock in a warm place? ($\eta_t > 0$, $T_t - T^* > 0$):
  - $\rightarrow$ Heat-averse firms with $\hat{\beta}_i < \overline{\hat{\beta}_i}$: failed to expect the low productivity caused by the temperature shock η_t.
  - $\rightarrow$ Unlucky firms with $\hat{\xi}_{it} > 0$: failed to expect the low productivity caused by the damage sensitivity shock $\hat{\xi}_{it}$.

Firm-Level Evidence 1

MRPK Dispersion

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

$$\sigma^2_{mrpk,(r,s),t} = \left(\frac{1}{1-\alpha_N}\right)^2 \text{Var}(\hat{a}_{nit} - \mathbb{E}_{t-1}[\hat{a}_{nit}])$$

$$= \left(\frac{1}{1-\alpha_N}\right)^2 \Bigg[\underbrace{(T_{r,t} - T^*)^2 \sigma^2_{\xi,(r,s)}}_{\substack{\text{Damage Volatility} \\ \text{(Level Effect)}}} + \underbrace{(T_{t+1} - \mathbb{E}_t[T_{t+1}])^2 \sigma^2_{\beta,(r,s)}}_{\substack{\text{Climate Volatility} \\ \text{(Forecast Error Effect)}}} + \sigma^2_{\varepsilon,(r,s)} \Bigg]$$

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

How would climate change lead to larger misallocation?

- Larger deviation from optimal temperature: $(T_{r,t} - T^*)^2$
- Larger unexpected temperature shocks: $(T_{t+1} - \mathbb{E}_t[T_{t+1}])^2$

▸ Firm-Level Evidence 2

Forecast Error Effect: Climate Volatility

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

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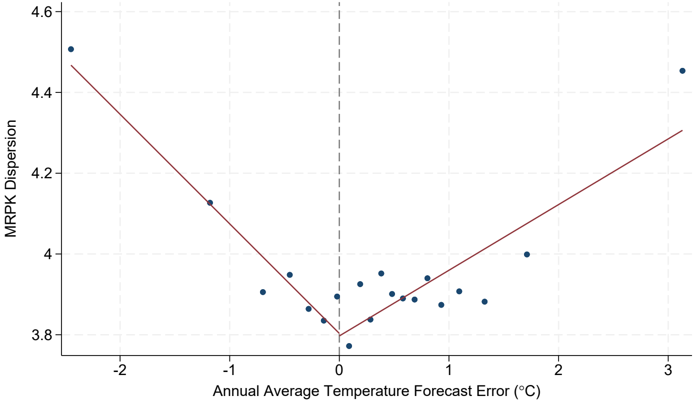
- Mid-range temperature forecast data (1-month ahead forecast) from ECMWF.
- Misallocation is worse if the temperature forecast is overly cold or overly hot



Forecast Error Effect: Climate Volatility

$$\sigma^2_{mrpk,(s,r),t} = \sum_{q \in \{\text{summer, winter, annual}\}} \theta_q \cdot \text{MSFE}_{q,r,t} + \gamma_1 T_{rt} + \gamma_2 T^2_{rt} + \eta_{s,r} + \delta_{c(r),t} + \varepsilon_{s,r,t},$$

- $\text{MSFE}_{q,r,t}$: Mean Squared Forecast Error of monthly temperature.

$\text{MSFE}_{\text{annual},r,t}$	0.019114***	0.016249**		
	(0.006675)	(0.006561)		
$\text{MSFE}_{\text{summer},r,t}$			0.014908**	0.016592**
			(0.007115)	(0.007084)
$\text{MSFE}_{\text{winter},r,t}$			0.008536**	0.006096
			(0.004017)	(0.003882)
Quadratic Temperature Control	No	Yes	No	Yes
Region-Sector FE	Yes	Yes	Yes	Yes
Country-Year FE	Yes	Yes	Yes	Yes
Observations	124,065	124,065	124,065	124,065
R^2	0.876	0.876	0.876	0.876

- Forcast Errors are costly!
  - → a 1°C error in temperature forecast for all months → 0.58 % annual aggregate TFP loss

Level Effect: Temperature as volatility shock

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

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

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

by using the "first-differenced" TFPR shocks.

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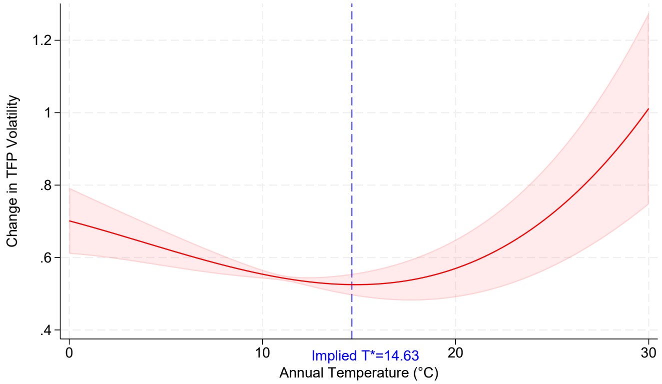

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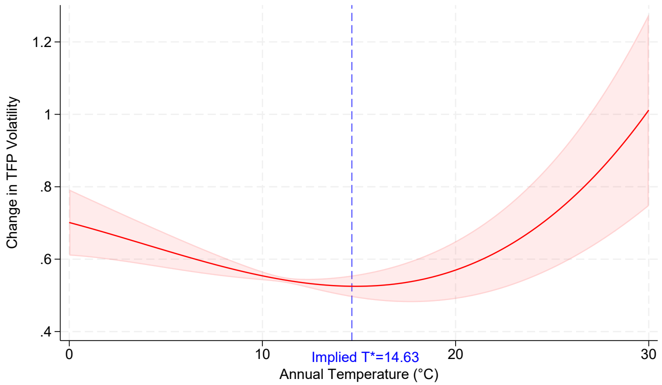
- Firms' TFP volatility goes up in regions that are too hot or too cold.
- Optimal level of temperature is around 13 - 15°C ▸ Burke, Hsiang and Miguel 2015



Does climate matter? Yes!

Our model-implied regressions imply that:

- Climate-induced misallocation can explain 3.81% of TFP on average:

$$
\begin{aligned}
\Delta \log TFP_{(s,r),t} &= -\underbrace{\frac{\tilde{\alpha}_K + \tilde{\alpha}_K^2(\sigma - 1)}{2}}_{0.359} \Delta\sigma^2_{mrpk,(s,r),t} \\
&= -\underbrace{\frac{\tilde{\alpha}_K + \tilde{\alpha}_K^2(\sigma - 1)}{2} \frac{\hat{\sigma}^2_{\hat{\xi},(s,r)}}{(1-\alpha_N)^2} \overline{(T_{r,t} - T^*)^2}}_{\substack{\text{Level Effect} \\ =3.00\%}} \\
&\quad - \underbrace{\frac{\tilde{\alpha}_K + \tilde{\alpha}_K^2(\sigma - 1)}{2} \frac{\hat{\sigma}^2_{\hat{\beta},(s,r)}}{(1-\alpha_N)^2} \overline{FE^{T2}_{r,t}}}_{\substack{\text{Forecast Error Effect} \\ =0.81\%}} \\
&= 3.81\%
\end{aligned}
$$

- Volatility associated with temperature Levels account for 10% of the difference in aggregate TFP between India and EU.

Conclusions and Policy Implications

Conclusions and Policy Implications

- Established the first causal estimates and projections of the misallocation channel of climate change.
- Quantified the role of climate-induced volatility and weather forecasts in a firm dynamics model.
- Policies to manage climate-induced misallocation:
  - $\rightarrow$ Mitigating global warming: $\approx$ 15% TFP loss can be avoided under RCP 2.6 compared to RCP 7.
  - $\rightarrow$ Improving mid-range temperature forecast accuracy
  - $\rightarrow$ Reducing damage heterogeneity across units: "mind the laggards"!
    - More "equity" across firms $\rightarrow$ higher aggregate efficiency

The (Mis)Allocation Channel of Climate Change

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Identification of the Causal Elasticities

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

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- $\mathbf{X}_{s,r,t}$ 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..

Go Back

Heterogeneous Regression Identification

- The same hot/cold day shock is likely to have heterogeneous across region-sectors.

  ▸ Het. effect across sectors

- Effect might be ambiguous:

  → Heat-sensitive firms in hotter region might have greater incentives to adapt.
  → But the marginal effect of hot temperatures in already hot locations might be worse.
  → Firms in more developed regions find it easier to cope with weather damage
  → But firm heterogeneity is larger in developed regions.

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

$$
\begin{aligned}
\sigma^2_{mrpk_{s,r,t}} = & \sum_{b \in B_{/(5\sim 10^\circ C)}} \lambda^b_{\sigma^2_{mrpk}} \times \text{Tbin}^b_{r,t} + \sum_{b \in B_{/(5\sim 10^\circ C)}} \lambda^{b,\bar{T}}_{\sigma^2_{mrpk}} \times \text{Tbin}^b_{r,t} \times \overline{T}_r \\
& + \sum_{b \in B_{/(5\sim 10^\circ C)}} \lambda^b_{\text{GDP}_{pc}} \times \text{Tbin}^b_{r,t} \times \ln \overline{\text{GDP}_{pc,r}} + \delta_{\sigma^2_{mrpk}} \times \tilde{\mathbf{X}}_{s,r,t} + \alpha_{c,t} + \eta_{s,r} + \varepsilon_{s,r,t},
\end{aligned} \tag{1}
$$

- Therefore, the first-order effect is region-specific:

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

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End-of-the-century Projection of the Misallocation Channel

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 around the world.

$$\underbrace{\Delta^{\text{Loss}} \ln \text{TFP}_r}_{\text{Total Effect}_r} = \frac{\alpha_{Kn} + \alpha_{Kn}^2(\sigma_n - 1)}{2} \Bigg[\underbrace{\sum_b \left(\lambda^b + \lambda^b_{\text{GDP}_{pc}} \ln \text{GDP}_{pc,r,2019} + \lambda^b_{\bar{T}} \bar{T}_{r,2019} \right) \times \Delta \text{Tbin}^b_r}_{\text{Weather Shock Effect}_r}$$

$$+ \underbrace{\sum_b \lambda_{b,\bar{T}} \text{Tbin}^b_{r,\text{EOC}} \times \Delta T_r}_{\text{Climatic Effect}_r}$$

$$+ \underbrace{\sum_b \lambda^b_{\text{GDP}_{pc}} \text{Tbin}^b_{r,\text{EOC}} \times \Delta \ln \text{GDP}_{pc,r}}_{\text{Income Effect}_r} \Bigg],$$

- Δ denotes changes between end-of-century (EOC) and 2019.
  - → *Weather Shock effect*: changes in daily temperature distributions
  - → *Climatic effect*: changes in elasticity due to shifts in long-run temperature
  - → *Income effect*: changes in elasticity due to economic development

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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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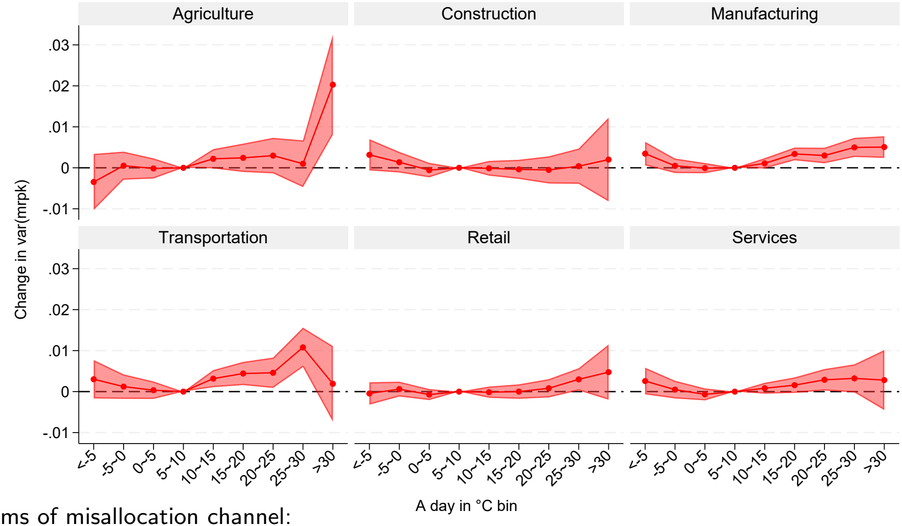
Heterogeneous Effect across Major Sectors



In terms of misallocation channel:

- The U-shaped pattern holds for all sectors.
- Agricultural and construction sector suffer the most. (a >30 $^\circ$C day $\approx$ 0.23% TFP loss)

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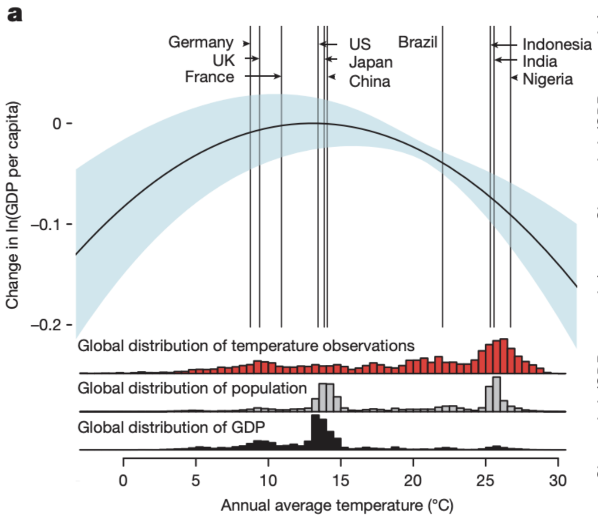
Burke, Hsiang and Miguel 2015

Their finding: ountry-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:

$$\begin{aligned} \log(MRPK_{r,s,i,t}) = & \sum_{b \in B/\{5-10^\circ C\}} \lambda_b \times \text{Tbin}_{r,t}^b \\ & + \sum_{b \in B/\{5-10^\circ C\}} \lambda_{b,\hat{\beta}\text{-proxy}} \times \text{Tbin}_{r,t} \times \hat{\beta}\text{-proxy}_{it}^{r,s} + \delta \mathbf{X}_{i,t} \\ & + \delta_i + \alpha_{s,c(r),t} + \varepsilon_{s,c(r),i,t}, \qquad \hat{\beta}\text{-proxy} \in \{\text{Relative Size, AC}\}. \end{aligned} \tag{2}$$

- 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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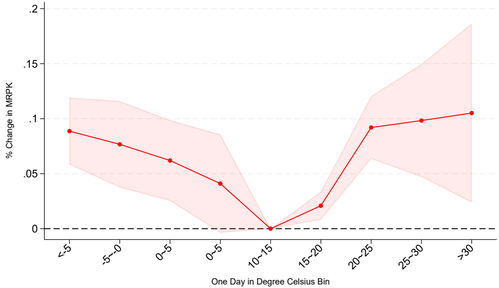
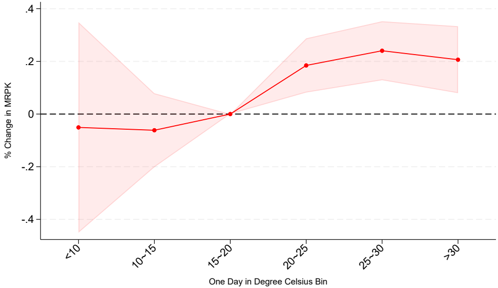
Firm-level Evidence: Heterogeneity of β_i and MRPK Responses



(a) Heterogeneous Effect from Firm Size



(b) Heterogeneous Effect from Firm Adaptability (AC)

- An additional 30°C day relative to baseline:
  - $\rightarrow$ makes a 1-SD larger firm having 0.1% higher MRPK compared to the average firm.
  - $\rightarrow$ 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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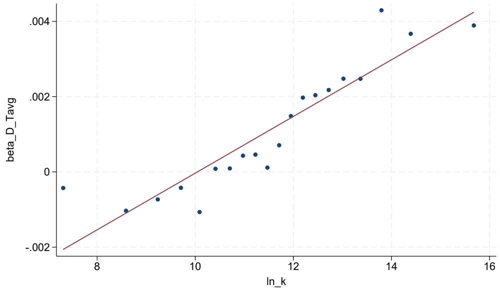
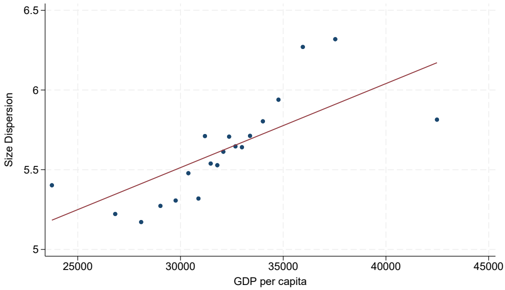
Firm-level Evidence: Heterogeneity of β_i and MRPK Responses

- This explains why richer regions suffer larger climate-induced misallocation $\rightarrow$ 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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