

# Extreme Heat and Directed Innovation

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- Impact of **Climate Change** is multifaceted: agriculture, human capital, labor supply and productivity, and human health
- **Adaptation** now sits at the center of the Climate Change agenda
- Yet the role of **innovation** as an adaptation margin remains underexplored

- Impact of **Climate Change** is multifaceted: agriculture, human capital, labor supply and productivity, and human health
- **Adaptation** now sits at the center of the Climate Change agenda
- Yet the role of **innovation** as an adaptation margin remains underexplored
- This paper asks the following questions
  1. **How does innovation respond to extreme heat shock?**
  2. **What is the role of innovation in adaptation to climate change?**

- Examines how extreme heat affects the direction of innovation for 9 EU countries from 2000-2020
- Provides new empirical evidence that firms use innovation as an adaptation margin to extreme heat outside of agriculture
- Constructs a Firm-level Production and Innovation Dataset: ORBIS + OECD REGPAT

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## Main Findings

1. Heat-to-productivity damage is concentrated among **labor-intensive** firms.
2. Extreme heat induces **capital-deepening adaptation**: more capital-intensive technology and more labor-saving patents
3. Heat-induced innovation **mitigates** the productivity damage by **28%**

1. **New empirical evidence on how *the direction of Innovation and technology change* respond to climate shocks**
  - Impact of Climate Change on Firms and Labor Productivity (Zivin and Neidell 2014, Somanathan et al 2021, Zhang et al 2018, Long and Wang 2025)
2. **First paper that evaluates the role of innovation as an adaptation margin to climate change outside of agriculture**
  - Measuring Climate Adaptation (Burke and Emerick 2016, Carleton and Hsiang 2016, Burke et al 2024)
  - Agriculture Evidence (Moscona and Sastry 2023)

- Heat Shock: **Climate (NOAA PSL)**

- Daily *maximum* temperature [▶ BINS vs CDD](#)

1. **8 TMAX BINS** [▶ Bin Distribution Shift](#) [▶ Hot Days Map](#)
2. **Cooling Degree Days (CDD) above 85°F** [▶ ΔCDD](#)

- Firm: **ORBIS**

- Firm-level balance sheet data
  - revenue/value added, labor cost, capital, employment. material costs, lon/lat
- Production Function Estimation: estimate firm TFP and Output Elasticity [▶ PFE](#)

- Innovation: **OECD REGPAT** [▶ Orbis-REGPAT Matching](#) [▶ Classification](#)

- EPO Patent application data, regionalized to NUTS-3
  - applicant names, addresses, CPC/IPC code, patent titles

- Final Sample

- Heat-Exposed Sectors:  
B(Mining), C(Manufacturing), D(Power&Utilities), F(Construction)
- 8.3 million firm-year observations (2000–2020)
- **9 European countries:** Austria, Belgium, Denmark, Germany, Spain, Finland, France, Italy, Luxembourg

# Descriptive Evidence on Factor-Biasedness of Heat Shock

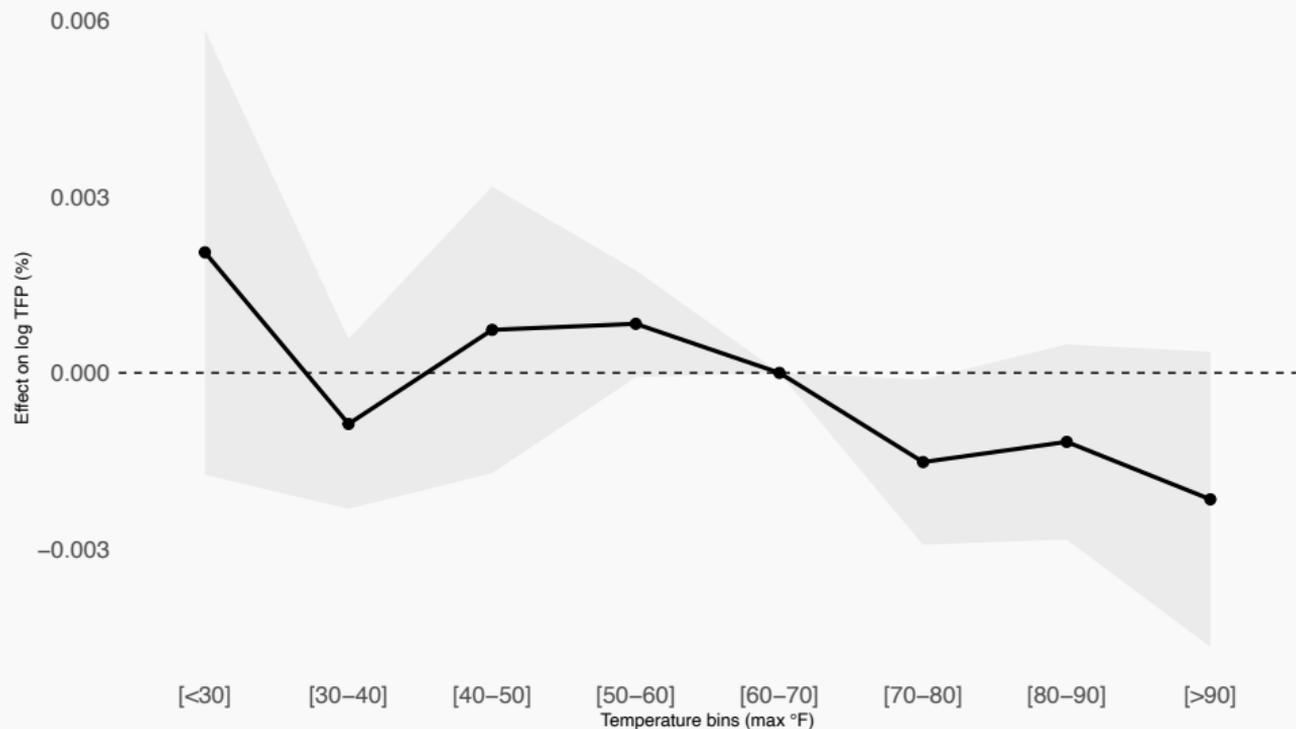
$$\ln(\text{TFP})_{it} = \sum_{b \neq [60-70^\circ\text{F}]} \beta_b \text{Bin}_{it}^b + \gamma \text{Prec}_{it} + \delta_i + \eta_{c(i),t} + \zeta_{s(i),t} + \varepsilon_{it},$$

- **Bins:** daily *max* 10 °F bins ([< 30]...[> 90]); omitted [60, 70)°F
- **Climate Controls:** precipitation
- **FE:** firm; country×year; sector×year. **SE** clustered by firm and country-year
- **Interpretation:**  $\beta_b =$  percent change from +1 day in bin  $b$  vs. [60, 70)°F
- **Heterogeneity:** High vs Low Labor Intensity firms within industry (based on Output Elasticity w.r.t labor estimates)

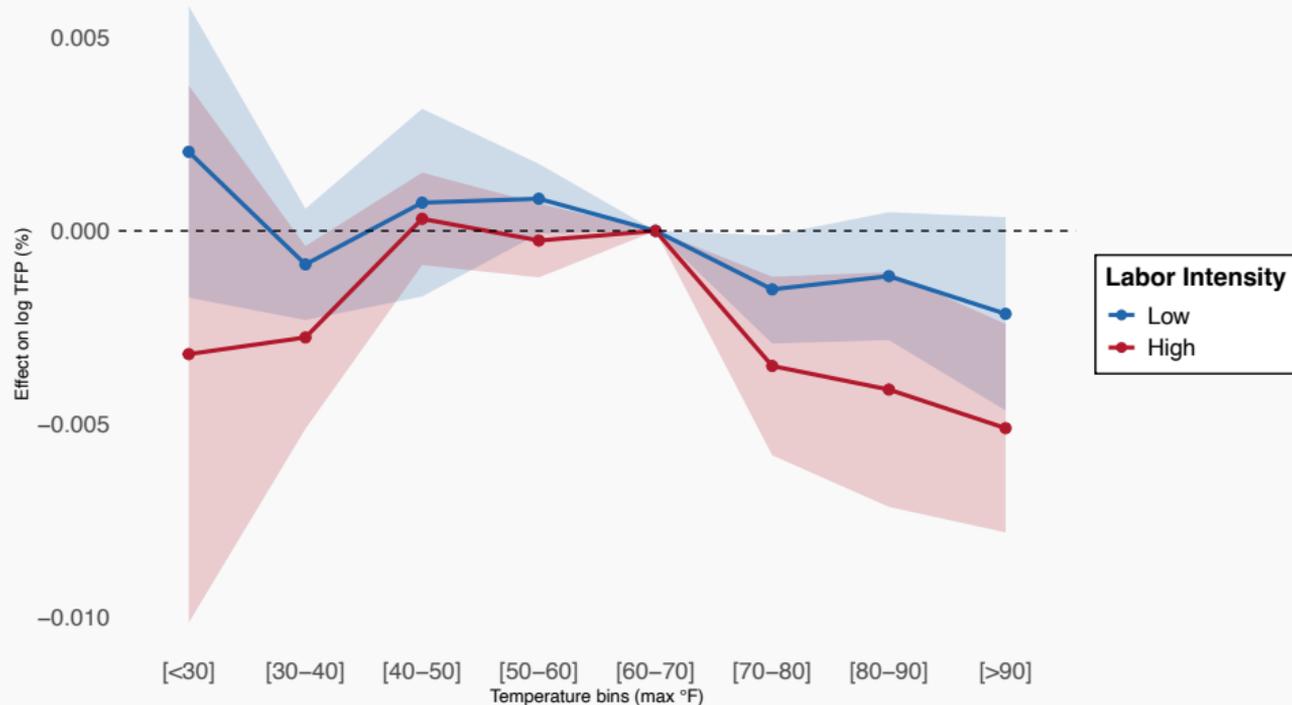
▶ PFE

▶ Heat Level Map

# Mild Negative Avg Effect



# Labor-Intensive Firms Suffer More Productivity Damage



# Evidence of Labor-Biased Heat Shock

- **Productivity** losses are concentrated among labor-intensive firms
  - Same pattern for cross-industry
- Similar results from **market share**: labor-intensive firms lose market share
  - ▶ Market Share Result
- Results are robust to controls of firm sizes

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But how do firms respond to such shock? What are the margins for adaptation?

1. Technology
2. Innovation

# How Does Technology Adjust to Heat?

- Technology Measure: **Output elasticity w.r.t. labor or capital (OE)** ▶ PFE
- How does technology responds to heat?

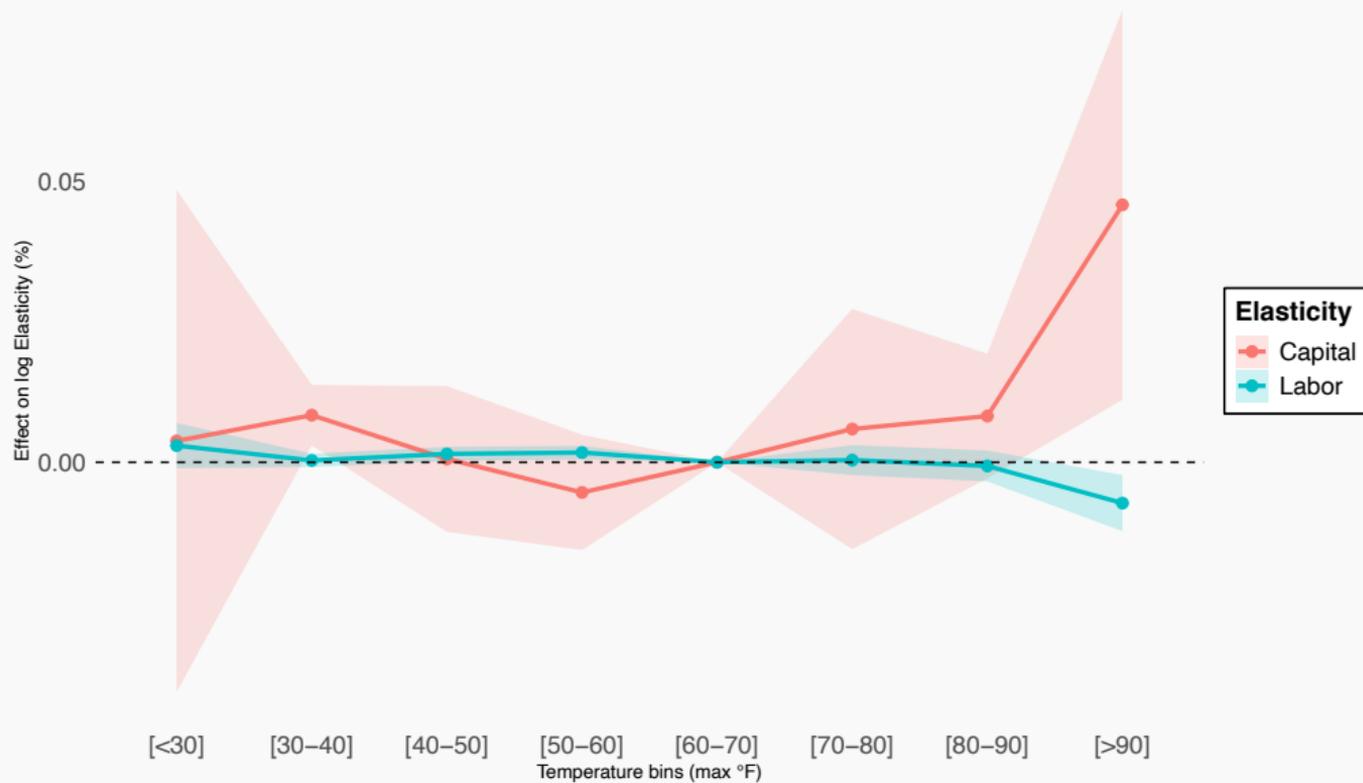
$$\ln(OE)_{it}^m = \sum_{b \neq [60-70^\circ F]} \beta_b^m \text{Bin}_{it}^b + \gamma^m \text{Prec}_{it} + \delta_i^m + \eta_{c(i),t}^m + \zeta_{s(i),t}^m + \varepsilon_{it}^m, \quad m \in \{K, L\}$$

▶ Labor OE trend

▶ LOE by industry

▶ COE by industry

# Heat $\Rightarrow$ More Capital-Intensive Technology



# How Does Innovation Respond to Heat?

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Poisson regression (i - industry, r - region, t - year)

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Region-industry specific exposure

$$\text{ExtremeExposure}_{i,r,t-2} \equiv \underbrace{\text{CDD}_{r,t-2}}_{\substack{\text{Spatial variation in heat shock} \\ \text{(across NUTS3 regions)}}} \times \underbrace{\text{LaborIntensity}_{i,0}}_{\substack{\text{Industry exposure to heat shock} \\ \text{(across industries)}}$$

» Avg DD map

» Patent Data

» Zolas Crosswalk

# How Does Innovation Respond to Heat?

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$$\text{Innovation}_{i,r,t} = \exp\left(\beta_1 \text{CDD}_{r,t-2} + \beta_2 \text{LI}_{i,0} + \beta_3 \text{CDD}_{r,t-2} \times \text{LI}_{i,0} + \alpha_{r,s(i)} + \alpha_t\right)$$

- Innovation<sub>i,r,t</sub>: **labor-saving patents count** » Snapshot » Classification
- SE Clustered at region(NUTS3)-year level
- Main coefficient of interest :  $\beta_3$ 
  - **Do more exposed industries develop more labor-saving patents under extreme heat?**

# Exposed Industries Develop more LS Patents Under Heat

**Table 1:** Heat and Labor-Saving Innovation

	Labor-saving patents (1)
CDD	-0.0069*** (0.0016)
Labor Intensity	-2.797*** (0.1440)
CDD × Labor Intensity	0.0144*** (0.0034)
Observations	76,400
Region-Sector fixed effects	✓
Year fixed effects	✓

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**Table 2:** Heat and Labor-Saving Innovation

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Example:

- **Spain:** +500 CDD  
(p95 firm-level  $\Delta$ CDD, 2000→2020)
- **Textiles (LI = 0.72)**
- $\Rightarrow$  LS patents  $\approx 5.7\times$  higher

- **Temp measure:** Bins vs CDD [▶ OE Bins](#) [▶ OE CDD](#) [▶ Definition](#)
- **Dynamics:** Lagged CDD (2–5) [▶ OE CDD Lags](#) [▶ Patents Lags](#)
- **Alternative innovation measure:** past patent stocks; shares instead of count  
[▶ All outcomes](#)
- **Long-Difference:** [▶ LD](#)

1. Extreme heat shocks disproportionately harm labor-intensive firms
2. Firms and industries respond through two margins:
  - **Technology**: more capital-intensive production technology.
  - **Redirected innovation**: more labor-saving innovation.

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Would induced innovation attenuate the damage from heat? Mechanisms?

Apply a standard DTC framework in a new context: **climate-induced labor shocks**

(Acemoglu et al 2012)

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- **Abundant Factor** attracts more innovations » estimates<sup>1</sup>
- Innovation can **improve productivity**

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In my model:

- Innovators choosing between **K** (Robots) or **L** (Energy efficient AC) sectors
- **Heat lowers effective labor:** effective labor =  $D(T) \cdot L$  with  $D(T) \downarrow$
- This makes labor more scarce  $\Rightarrow$  innovators tilt to capital sector (**labor-saving**).

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$$\Delta \text{Productivity} \approx \underbrace{\Delta D(T)}_{\text{Direct heat damage } <0} + \underbrace{\Delta \gamma(T)}_{\text{Induced innovation } >0}$$

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Can we innovate our way out of trouble?

## Do LS Patents Mitigate Heat-TFP Damage?

$$\ln \text{TFP}_{it} = \beta_1 \text{CDD}_{it} + \beta_2 \text{LS}_{i,t-2} + \beta_3 \text{CDD}_{it} \times \text{LS}_{i,t-2} + \Gamma \text{Prec}_{it} \\ + \mathbf{X}_{i,t-2} + \alpha_i + \alpha_{c(i),t} + \alpha_{s(i),t} + \varepsilon_{it}.$$

- **LS innovation indicator:**  $\text{LS}_{i,t-2} = 1\{\text{LS patent within past 2 yrs}\}$
- **Firm Controls:**  $\mathbf{X}_{i,t-2}$  includes lagged firm size
- Interpretation:  $\beta_3 > 0 \Rightarrow$  **LS innovation attenuates** heat-productivity damage (flattened damage function).

▶ LS firms

# LS Patents Flatten the Heat-TFP Damage

**Table 3:** TFP on CDD  $\times$  LS (lag 2)

	log TFP (1)
CDD	-0.0005** (0.0002)
Any LS (t-k)	-0.1638 (0.5309)
CDD $\times$ Any LS (t-k)	0.0061*** (0.0021)
Firm fixed effects	✓
Country-Year fixed effects	✓
Sector-Year fixed effects	✓
Lag Revenue Control	✓

# LS Patents Flatten the Heat-TFP Damage

	log TFP
	(1)
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Sector-Year fixed effects	✓
Lag Revenue Control	✓

- **Benchmark shocks (2000→2020):**

- **+500 CDD (Spain):**

- non-LS  $\approx [-0.25\%]$ , LS  $\approx [+2.8\%]$ .

- Directed innovation **attenuates** heat-induced productivity losses (consistent with model).

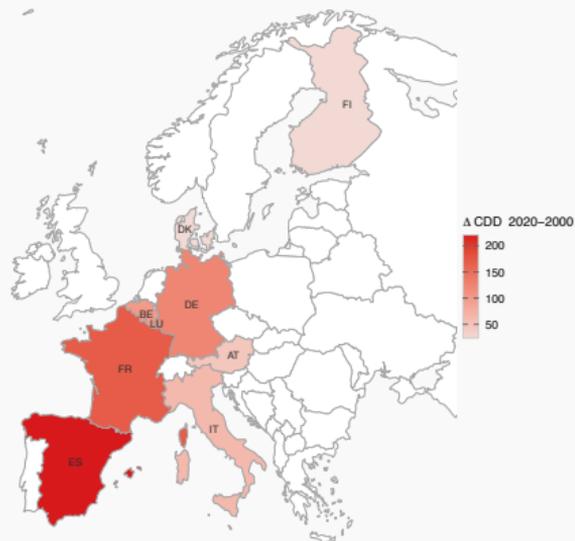
Result robust for  $k \in [1, 3]$ , though no significant contemporaneous effect  $k = 0$ ; stock variant similar. [▶ Lag figure](#)

## What if there were no induced innovations?

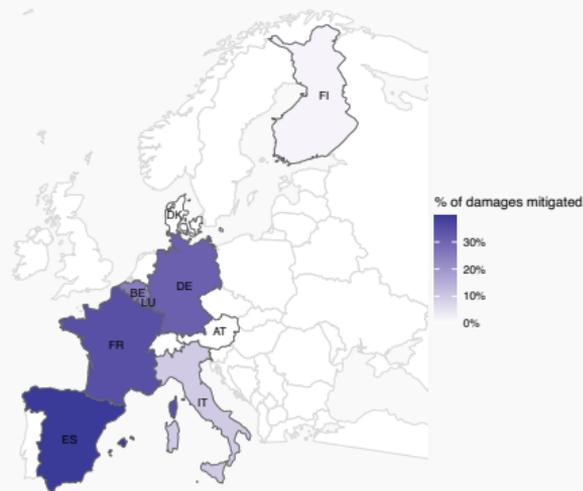
$$\text{Mitigation} = \frac{\Delta \text{TFP}_{\text{Climate Change}}^{\text{No Innovation}} - \Delta \text{TFP}_{\text{Climate Change}}^{\text{Innovation}}}{\Delta \text{TFP}_{\text{Climate Change}}^{\text{No Innovation}}}$$

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$$\text{Mitigation} = \frac{\Delta \text{TFP}_{\text{Climate Change}}^{\text{No Innovation}} - \Delta \text{TFP}_{\text{Climate Change}}^{\text{Innovation}}}{\Delta \text{TFP}_{\text{Climate Change}}^{\text{No Innovation}}}$$



(a) Heat Shock (2020–2000)



(b) Mitigation via LS innovation (2000–2020)

On avg, heat-induced LS innovation mitigates 28% of productivity damage

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- Heat shocks cause **labor-biased damage** (hits labor-intensive firms; production shifts toward capital)
- Innovation responds: **labor-saving patents rise**, mitigating productivity losses by **28%** (19% in Moscona & Sastry 2023, ag.)

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Upcoming projects

- **Who adapts?** Uneven adaptation – Winners, losers, and aggregate consequences
- **Developing economies:** Extending to India and China

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