Adapting to Heat Extremes with Unequal Access to Cooling: Evidence from India

Filippo Pavanello[1,2,3] Ian Sue Wing[4]

[1]Department of Economics, University of Bologna

[2]ECIP Division, Euro-Mediterranean Center on Climate Change (CMCC)

[3]Department of Economics, Ca' Foscari University of Venice

[4]Department of Earth & Environment, Boston University

Preliminary Version. Please do not cite.

Introduction

Motivation

- Large evidence about the **welfare costs** of extreme heat for individuals
  (e.g., Deschenes and Greenstone 2011, AEJ; Park et al. 2020, AEJ; Somanathan et al. 2021, JPE; Carleton et al. 2022, QJE)

Motivation

- Large evidence about the **welfare costs** of extreme heat for individuals
  (e.g., Deschenes and Greenstone 2011, AEJ; Park et al. 2020, AEJ; Somanathan et al. 2021, JPE; Carleton et al. 2022, QJE)

- Air-conditioning proved to be highly effective against extreme heat
  (e.g., Barreca et al. 2016, JPE; Park et al. 2020, AEJ; Somanathan et al. 2021, JPE)

Motivation

- Large evidence about the **welfare costs** of **extreme heat** for individuals
  (e.g., Deschenes and Greenstone 2011, AEJ; Park et al. 2020, AEJ; Somanathan et al. 2021, JPE; Carleton et al. 2022, QJE)

- **Air-conditioning** proved to be highly **effective** against extreme heat
  (e.g., Barreca et al. 2016, JPE; Park et al. 2020, AEJ; Somanathan et al. 2021, JPE)

- Problem 1.: air conditioners are **expensive** $\Rightarrow$ high upfront and operational costs

Motivation

- Large evidence about the **welfare costs** of extreme heat for individuals
  (e.g., Deschenes and Greenstone 2011, AEJ; Park et al. 2020, AEJ; Somanathan et al. 2021, JPE; Carleton et al. 2022, QJE)

- Air-conditioning proved to be highly effective against extreme heat
  (e.g., Barreca et al. 2016, JPE; Park et al. 2020, AEJ; Somanathan et al. 2021, JPE)

- Problem 1.: air conditioners are **expensive** $\Rightarrow$ high upfront and operational costs

  $\hookrightarrow$ Unequal distribution of air-conditioning, especially in **developing economies**
  (Davis et al. 2021, GEC; Pavanello et al. 2021, NC)

Motivation

- Large evidence about the **welfare costs** of extreme heat for individuals
  (e.g., Deschenes and Greenstone 2011, AEJ; Park et al. 2020, AEJ; Somanathan et al. 2021, JPE; Carleton et al. 2022, QJE)

- Air-conditioning proved to be highly effective against extreme heat
  (e.g., Barreca et al. 2016, JPE; Park et al. 2020, AEJ; Somanathan et al. 2021, JPE)

- Problem 1.: air conditioners are **expensive** $\Rightarrow$ high upfront and operational costs

  $\hookrightarrow$ Unequal distribution of air-conditioning, especially in **developing economies**
  (Davis et al. 2021, GEC; Pavanello et al. 2021, NC)

- Emergence of **cheaper (but possibly less effective)** alternatives $\Rightarrow$ evaporative coolers

Motivation

- Large evidence about the **welfare costs** of extreme heat for individuals
  (e.g., Deschenes and Greenstone 2011, AEJ; Park et al. 2020, AEJ; Somanathan et al. 2021, JPE; Carleton et al. 2022, QJE)

- Air-conditioning proved to be highly effective against extreme heat
  (e.g., Barreca et al. 2016, JPE; Park et al. 2020, AEJ; Somanathan et al. 2021, JPE)

- Problem 1.: air conditioners are **expensive** $\Rightarrow$ high upfront and operational costs

  $\hookrightarrow$ Unequal distribution of air-conditioning, especially in **developing economies**
  (Davis et al. 2021, GEC; Pavanello et al. 2021, NC)

- Emergence of **cheaper (but possibly less effective)** alternatives $\Rightarrow$ evaporative coolers

- Problem 2.: The extent to which these technologies are substitute is **unclear**

Motivation

- Large evidence about the **welfare costs** of extreme heat for individuals
  (e.g., Deschenes and Greenstone 2011, AEJ; Park et al. 2020, AEJ; Somanathan et al. 2021, JPE; Carleton et al. 2022, QJE)

- Air-conditioning proved to be highly effective against extreme heat
  (e.g., Barreca et al. 2016, JPE; Park et al. 2020, AEJ; Somanathan et al. 2021, JPE)

- Problem 1.: air conditioners are **expensive** $\Rightarrow$ high upfront and operational costs

  $\hookrightarrow$ Unequal distribution of air-conditioning, especially in **developing economies**
  (Davis et al. 2021, GEC; Pavanello et al. 2021, NC)

- Emergence of **cheaper (but possibly less effective)** alternatives $\Rightarrow$ evaporative coolers

- Problem 2.: The extent to which these technologies are substitute is **unclear**

  $\hookrightarrow$ Do agents face a **trade-off** cost vs protection?

Motivation

- Large evidence about the **welfare costs** of extreme heat for individuals
  (e.g., Deschenes and Greenstone 2011, AEJ; Park et al. 2020, AEJ; Somanathan et al. 2021, JPE; Carleton et al. 2022, QJE)

- Air-conditioning proved to be highly effective against extreme heat
  (e.g., Barreca et al. 2016, JPE; Park et al. 2020, AEJ; Somanathan et al. 2021, JPE)

- Problem 1.: air conditioners are **expensive** $\Rightarrow$ high upfront and operational costs
  - $\hookrightarrow$ Unequal distribution of air-conditioning, especially in **developing economies**
    (Davis et al. 2021, GEC; Pavanello et al. 2021, NC)

- Emergence of **cheaper (but possibly less effective)** alternatives $\Rightarrow$ evaporative coolers

- Problem 2.: The extent to which these technologies are substitute is **unclear**
  - $\hookrightarrow$ Do agents face a **trade-off** cost vs protection?
  - $\hookrightarrow$ If there is **imperfect** substitution $\Rightarrow$ inequality in exposure to extreme heat

Research Questions

Do these competing technologies contribute to inequality in adaptation to extreme heat?

Research Questions

Do these competing technologies contribute to inequality in adaptation to extreme heat?

$\Rightarrow$ Q1. Is there heterogeneous technological response of households to extreme heat?

Research Questions

Do these competing technologies contribute to inequality in adaptation to extreme heat?

$\Rightarrow$ Q1. Is there heterogeneous technological response of households to extreme heat?

$\Rightarrow$ Q2. Do air conditioners and evaporative coolers provide different level of protection?

This Paper

1. Examine the heterogeneous technological responses of households to hot days
    - **Household ($>$ 200k) panel** data from India combined with high-quality **weather** information
    - Document the **extensive margin** response: technology adoption
    - Document the **intensive margin** response: electricity consumption

This Paper

1. Examine the heterogeneous technological responses of households to hot days
    - **Household ($>$ 200k) panel** data from India combined with high-quality **weather** information
    - Document the **extensive margin** response: technology adoption
    - Document the **intensive margin** response: electricity consumption
2. Test whether technology determines the level of protection from extreme heat
    - Administrative **district-level** annual **mortality** data (all-age, all-causes)
    - Re-construct district-level **ownership rates** of air conditioners and evaporative coolers
    - Evaluate the **interactions** between ownership rates and extreme heat

This Paper

1. Examine the heterogeneous technological responses of households to hot days
    - **Household ($>$ 200k) panel** data from India combined with high-quality **weather** information
    - Document the **extensive margin** response: technology adoption
    - Document the **intensive margin** response: electricity consumption
2. Test whether technology determines the level of protection from extreme heat
    - Administrative **district-level** annual **mortality** data (all-age, all-causes)
    - Re-construct district-level **ownership rates** of air conditioners and evaporative coolers
    - Evaluate the **interactions** between ownership rates and extreme heat
3. Determine the consequences of technological inequality in heat adaptation
    - Number of **prevented deaths**
    - Implications for policy: back-to-the-envelope **cost-benefit analysis**

India

- **Extreme heat**:
  - ↪ Between March and May 2022: temperature reached 51°C
  - ↪ Future: estimated up to 20 times more likely relative to 2022
    (Zachariah et al. 2022)

India

- **Extreme heat**:
  - ↪ Between March and May 2022: temperature reached 51°C
  - ↪ Future: estimated up to 20 times more likely relative to 2022
    (Zachariah et al. 2022)
- **Consequences** of extreme heat:
  - ↪ Historical: about 4-6 deaths per 100k people per year
  - ↪ Future: estimated 10-60 deaths per 100k people per year by 2100
    (Carleton et al. 2022, QJE)

India

- **Extreme heat**:
  - ↪ Between March and May 2022: temperature reached 51°C
  - ↪ Future: estimated up to 20 times more likely relative to 2022
    (Zachariah et al. 2022)
- **Consequences** of extreme heat:
  - ↪ Historical: about 4-6 deaths per 100k people per year
  - ↪ Future: estimated 10-60 deaths per 100k people per year by 2100
    (Carleton et al. 2022, QJE)
- **Cooling adaptation**:
  - ↪ Rising incomes and temperatures ⇒ boost in cooling demand
    (IEA, 2018; Davis et al. 2021; Pavanello et al. 2021, NC)
  - ↪ One of the first countries to develop a Cooling Action Plan (2019)

Preview of the Results

- Majority of households has no access to any form of cooling

Preview of the Results

- Majority of households has **no access** to any form of cooling
- When they do:

Preview of the Results

- Majority of households has **no access** to any form of cooling
- When they do:

  $\hookrightarrow$ **Poor and middle-income** households $\Rightarrow$ **evaporative coolers**

Preview of the Results

- Majority of households has **no access** to any form of cooling
- When they do:
  - $\hookrightarrow$ **Poor and middle-income** households $\Rightarrow$ **evaporative coolers**
  - $\hookrightarrow$ **High-income urban** families $\Rightarrow$ **air conditioners**

Preview of the Results

- Majority of households has no access to any form of cooling
- When they do:
  - $\hookrightarrow$ **Poor and middle-income** households $\Rightarrow$ evaporative coolers
  - $\hookrightarrow$ **High-income urban** families $\Rightarrow$ air conditioners
- This implies large disparities in electricity consumption during hot days

Preview of the Results

- Majority of households has no access to any form of cooling
- When they do:
  - $\hookrightarrow$ **Poor and middle-income** households $\Rightarrow$ evaporative coolers
  - $\hookrightarrow$ **High-income urban** families $\Rightarrow$ air conditioners
- This implies large disparities in electricity consumption during hot days
- Air conditioners are the only effective appliance against extreme heat

Preview of the Results

- Majority of households has no access to any form of cooling
- When they do:
  - $\hookrightarrow$ **Poor and middle-income** households $\Rightarrow$ evaporative coolers
  - $\hookrightarrow$ **High-income urban** families $\Rightarrow$ air conditioners
- This implies large disparities in electricity consumption during hot days
- Air conditioners are the only effective appliance against extreme heat
  - $\hookrightarrow$ **Evaporative coolers** prevented 14% of heat-related deaths
  - $\hookrightarrow$ If similarly widespread, **air conditioners** would have prevented 47% of heat-related deaths

Preview of the Results

- Majority of households has no access to any form of cooling
- When they do:
  - $\hookrightarrow$ **Poor and middle-income** households $\Rightarrow$ evaporative coolers
  - $\hookrightarrow$ **High-income urban** families $\Rightarrow$ air conditioners
- This implies large disparities in electricity consumption during hot days
- Air conditioners are the only effective appliance against extreme heat
  - $\hookrightarrow$ **Evaporative coolers** prevented 14% of heat-related deaths
  - $\hookrightarrow$ If similarly widespread, **air conditioners** would have prevented 47% of heat-related deaths
- **Subsidising** air conditioners results as a cost-effective strategy to reduce heat-related mortality

Related Literature

1. Air-conditioning adoption, temperature and income
   (Davis and Gertler 2015, PNAS; Davis et al. 2021, GEC; Pavanello 2021, NC; Randazzo et al. 2023, JEEM)

   $\hookrightarrow$ Contributions: alternative technologies, prevalence and adoption, heterogeneity

Related Literature

1. Air-conditioning adoption, temperature and income
   (Davis and Gertler 2015, PNAS; Davis et al. 2021, GEC; Pavanello 2021, NC; Randazzo et al. 2023, JEEM)

   ↪ **Contributions**: alternative technologies, prevalence and adoption, heterogeneity

2. Residential electricity consumption and temperature
   (Deschenes and Greenstone 2011, AEJ; Davis and Gertler 2015, PNAS; Auffhammer 2022, JEEM)

   ↪ **Contributions**: technological dimension, first response function for India, heterogeneity

Related Literature

1. Air-conditioning adoption, temperature and income
   (Davis and Gertler 2015, PNAS; Davis et al. 2021, GEC; Pavanello 2021, NC; Randazzo et al. 2023, JEEM)

   ↪ **Contributions**: alternative technologies, prevalence and adoption, heterogeneity

2. Residential electricity consumption and temperature
   (Deschenes and Greenstone 2011, AEJ; Davis and Gertler 2015, PNAS; Auffhammer 2022, JEEM)

   ↪ **Contributions**: technological dimension, first response function for India, heterogeneity

3. Mortality and extreme heat
   (Deschenes and Greenstone 2011, AEJ; Burgess et al. 2017; Carleton et al. 2022, QJE)

   ↪ **Contributions**: more recent response function for India, heterogeneity

Related Literature

1. Air-conditioning adoption, temperature and income
   (Davis and Gertler 2015, PNAS; Davis et al. 2021, GEC; Pavanello 2021, NC; Randazzo et al. 2023, JEEM)

   $\hookrightarrow$ **Contributions**: alternative technologies, prevalence and adoption, heterogeneity

2. Residential electricity consumption and temperature
   (Deschenes and Greenstone 2011, AEJ; Davis and Gertler 2015, PNAS; Auffhammer 2022, JEEM)

   $\hookrightarrow$ **Contributions**: technological dimension, first response function for India, heterogeneity

3. Mortality and extreme heat
   (Deschenes and Greenstone 2011, AEJ; Burgess et al. 2017; Carleton et al. 2022, QJE)

   $\hookrightarrow$ **Contributions**: more recent response function for India, heterogeneity

4. Mediator effect of cooling technologies
   (Barreca et al 2016, JPE; Park et al. 2020, AEJ; Somanathan et al. 2021, JPE; Hua et al. 2022, JPopE)

   $\hookrightarrow$ **Contributions**: technological dimension, first application to mortality in India, cost-benefit analysis

Data

- **Household panel data**: Consumer Pyramid Dx survey (2014-2019):
  - Four-month air-conditioning and coolers ownership
  - Monthly electricity expenditure
  - Households' socio-economic and demographic characteristics
- District-level annual **mortality data**: Civil Registration System (2014-2019)
  - Digitalise the reports
  - All-age and all-causes, distinction between total, urban and rural deaths
- District-level data on **heat adaptation**: Consumer Pyramid Dx survey (2014-2019)
  - District and state-level penetration rates of air conditioners and evaporative coolers
- Population-weighted **climate data** from ERA5 ($0.25^\circ \times 0.25^\circ$ cells):
  - Daily average temperature, daily total precipitation, daily specific humidity

Theoretical Framework

Set-up

A representative household maximises its utility function:

$$\max_{q_S, q_N, k, x} u = D\left[T, a, q_S, k\right] \cdot z\left[q_N, x\right] \quad \text{s.t. } y \geq p\left[q_S + q_N\right] + rk + x$$

$\hookrightarrow$ Assumption: (1) $\partial u / \partial D < 0$ (2) $\partial u / \partial z > 0$

- T = ambient temperature (°C)
- q_S = electricity for cooling (kWh)
- k = space conditioning capital (total capacity, kWh)
- p = electricity price, r = discounted capital cost
- y = income, q_N = electricity for other uses, x = numeraire good
- a = loss of effectiveness (°C / kWh)

Damage Function

The damage function is defined as follows:

- Higher-than-optimal indoor temperatures T^* incur a linear utility penalty D with marginal disutility coefficient δ

$$D = 1 - \delta \left(\frac{1}{A\left[q_S, k\right]} T - T^* \right)$$

  where we assume that $A^{(-1)} T \geq T^*$

- For simplicity, let A being a **Leontieff** function

$$A = a^{(-1)} \ \mathbf{min} \left[q_S, k\right]$$

Solution

Solve the model:

- Closed-form solution for electricity consumption and cooling capital

$$q_S^*, \bar{k}, q_S^* = k^* \propto \sqrt{T}\sqrt{Y}$$

$\hookrightarrow$ importance of **temperature-income interactions**

$\hookrightarrow$ diminishing returns to adaptation

- **Income inequality** $\Rightarrow$ how much a household can adapt
- Current assumption: no technological differences

Technology

- Assume that there exists two type of technologies $\theta \Rightarrow$ conditional **maximisation utility problem**
- Household invests only on one technology
- The two technologies only differ in loss of effectiveness a and cost r
- The optimal disutility due to temperature becomes:

$$D_\theta^* \propto \sqrt{r_\theta}, \sqrt{a_\theta}$$

- Coolers are cheaper than air conditioners ($r_C < r_{AC}$)
- If coolers are less effective at bringing thermal comfort ($a_{AC} < a_C$)

$\hookrightarrow$ There is a **trade-off**

Moving to Empirical Analysis

Our empirical analysis:

1. Identify how Indian households are adapting and through which technology

   $\hookrightarrow$ revealed preferences

2. Estimate the **marginal disutility** $\partial D / \partial T$

   $\hookrightarrow$ mortality—temperature relationship

3. Determine **differences at reducing thermal discomfort** a_θ

   $\hookrightarrow$ mortality—(temperature $\times$ technology)

Heat Adaptation

The Choice of the Heat Adaptation Technology

- Our data feature allows to look at both ownership and adoption of cooling appliances
- The investment decision is a **slow adjustment** process $\Rightarrow$ long lifetimes of cooling appliances
- Households invest based on expectations about climate $\Rightarrow$ average weather over long periods (Cohen et al. 2017)
- In our setting **adoption** occurs in a short period of time
  $\hookrightarrow$ driven only by economic development but **conditional on climatic conditions** Trend State
- How we model **unobserved heterogeneity** determines the dimension of study

Empirical Framework

Estimating the impact of **temperature and income** on the **ownership** and **adoption** of the cooling appliances:

$$C_{ciw} = \gamma_0 + \gamma_1 \overline{CDD}_{d(i)w} + \gamma_2 I_{iw} + \gamma_3 g(P_{d(i)w}) + \lambda X_{iw} + \mu_k + \delta_w + \theta_{s(i)} y + \theta^2_{s(i)} y^2 + \zeta_{iw}$$

- C_{ciw}: dummy if household i in wave w has a cooling appliance c
- $\overline{CDD}_{d(i)w}$: 10-year moving average of quarterly CDD in the previous decade
- I_{iw}: natural logarithm of quarterly income of household i
- Controls: second-degree polynomial of precipitation and household characteristics
- μ_k: unobserved heterogeneity (state or household FE)
- Additional fixed-effects: wave FE, quadratic state-year trend
- All regressions are weighted using survey weights that also correct for attrition

Ownership Het

Evaporative coolers are climate sensitive, air conditioners respond only to income

	Both Appliances	Air Conditioner	Evaporative Cooler
	(1)	(2)	(3)
$\overline{\text{CDD}}$ (100s)	0.0146***	0.0000375	0.0145***
	(0.002)	(0.001)	(0.003)
Log(Income)	0.0863***	0.0592***	0.0611***
	(0.007)	(0.006)	(0.010)
Precipitations Controls	Yes	Yes	Yes
Household Controls	Yes	Yes	Yes
State FE, Wave FE	Yes	Yes	Yes
Quadratic State $\times$ Year Trend	Yes	Yes	Yes
R^2	0.51	0.21	0.51
Observations	2442730	2442730	2442730

Notes: (1)-(3) clustered standard errors at district level in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regressions are conducted using survey weights.

Additional Drivers

Air conditioners:

- **Living in an urban area** (⇑⇑)
- Hours of power availability during the day and ownership of generators (⇑)
- **Education level** (⇑⇑), female head (⇓), house materials (⇑), head age (⇓)

Coolers:

- Hours of **power availability** during the day and **ownership of generators** (⇑⇑)
- Education level (⇑), female head (⇓), house materials (⇑), head age (⇑)

Adoption is a matter of **economic development**

	Both Appliances (1)	Air-conditioning (2)	Evaporative Cooler (3)
$\overline{\text{CDD}}$ (100s)	-0.000666	0.000216	-0.000764*
	(0.000)	(0.000)	(0.000)
Log(Income)	0.0410***	0.0135***	0.0344***
	(0.003)	(0.001)	(0.003)
Precipitations Controls	Yes	Yes	Yes
Household Controls	Yes	Yes	Yes
Household FE, Wave FE	Yes	Yes	Yes
Quadratic Trend $\times$ State	Yes	Yes	Yes
R^2	0.05	0.02	0.06
Observations	2432366	2432366	2432366

Notes: (1)-(6) clustered standard errors at district level in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regressions are conducted using survey weights..

Robustness

Our results remain **robust** to several alternative specifications:

- Alternative time and time-invarying fixed-effects
- Clustering standard errors at state level
- Changing CDD thresholds
- Specifying CDD up to degree 3 polynomials
- Logit and multinomial logit specification (for ownership)

Electricity Consumption

- Consumption electricity in response to temperature is a short-term decision
- Technology modulates household response
- Using the monthly information we observe the **causal effect** of short-term variation in temperature
- **Heterogeneity** in the response should be confirmatory of the **distribution** of the technologies

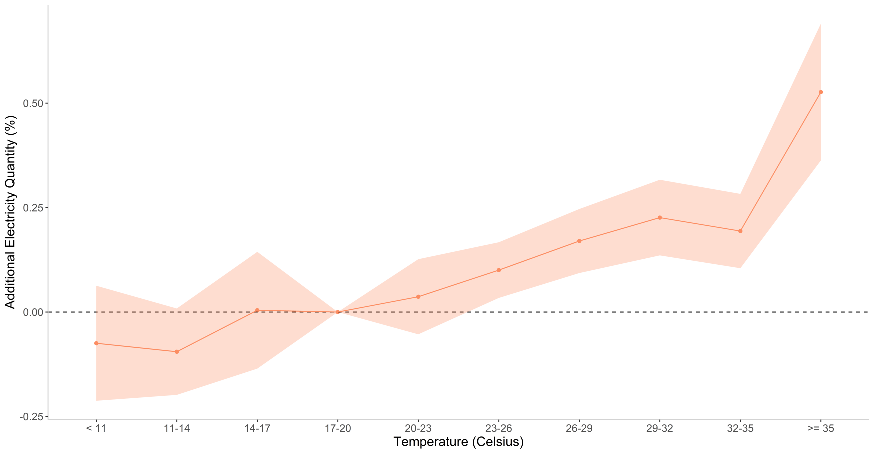
Empirical Framework

Estimating the impact of **temperature** on electricity quantity:

$$Q_{imy} = \alpha + \sum_{j=1}^{k} \theta_j T^j_{d(i)my} + \beta_2 f(P_{d(i)my}) + \beta_3 I_{imy} + \mu_i + \delta_{my} + \epsilon_{imy}$$

- Q_{imy}: natural logarithm of electricity quantity of household i in month m and year y
- $T_{d(i)my}$: 3°C bins of daily average temperature in district d (17-20 as reference category)
- Controls: second-degree polynomial of total precipitation and natural logarithm of monthly income
- Fixed-effects: household FE (μ_i) and month-year FE (δ_{my})
- All regressions are weighted using survey weights that also correct for attrition

Temperature-electricity



An additional day $\geq 35\ ^\circ$C (wrt $17 - 20$) increases electricity consumption by **0.53%**

Heterogeneity Het II Het III

We test the heterogeneity of the response across different sub-samples

	Rural			Urban		
	Poor	Middle	Rich	Poor	Middle	Rich
	(1)	(2)	(3)	(4)	(5)	(6)
≥ 35	0.00387***	0.00329***	0.00530***	0.00607***	0.00749***	0.00973***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Household FE	Yes	Yes	Yes	Yes	Yes	Yes
Month-Year FE	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.02	0.01	0.01	0.05	0.04	0.09
Observations	550374	1636916	414634	511879	3242848	1960647
Avg. kWh	59.85	92.59	148.77	75.37	116.80	208.83
Δ(kWh)	+0.23	+0.30	+0.79	+0.40	+0.87	+2.03

Notes: (1) to (6) clustered standard errors at district level in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regressions are conducted using survey weights.

Robustness

Our results remain **robust** to alternative specifications:

- Alternative time and time-invarying fixed-effects
- Electricity quantity in levels
- Clustering standard errors at state level
- Specifying temperature as 5-degree bins, up to degree 3 polynomials, as Cooling Degree Days (CDD)
- CRU rather than ERA5 climate data

Protective Effects

Empirical Framework

Estimating the impact of **temperature** on mortality:

$$M_{dt} = \alpha_0 + \sum_j \theta_j T_{dtj} + \sum_k \delta_k P_{dtk} + \sum_h \beta_h H_{dth} + \mu_d + \rho_t + \lambda_{r(d)} t + \lambda^2_{r(d)} t^2 + \epsilon_{dt}$$

- M_{dt}: natural logarithm of mortality rate in district d and year y
- $T_{d(i)my}$: 5°C bins of daily average temperature in district d (15-20 as reference category)
- Fixed-effects: district FE (μ_d), year FE (ρ_t), climatic region × quadratic trend ($\lambda_{s(d)} t + \lambda^2_{s(d)} t^2$)
- Square root of district population used as weight for the regression
  (Barreca et al. 2016, JPE; Burgess et al. 2017)
- Additional regressions: (1) interaction **warmest × most humid bin**

The Role of Cooling

Estimate **an augmented regression model**:

$$M_{dt} = \alpha_0 + \sum_{j=1}^{8} \theta_j T_{dtj} + \sum_{l=1}^{2} \gamma_l T_{dt}^{\geq 35} \times C_{dtl} + \sum_{l=1}^{2} \phi_l C_{dtl} +$$
$$+ \sum_{k} \delta_k P_{dtk} + \sum_{h} \beta_h H_{dth} + \mu_d + \rho_t + \lambda_{r(d)} t + \lambda_{r(d)}^2 t^2 + \epsilon_{dt}$$

- C_{dtl}: penetration rate in district d of technology l
- Additional regressions: interactions with (1) bins of humidity, (2) warmest × most humid bin
- **Drawback**: no quasi-experimental design

↪ **Key for identification**: the two shares do not have to correlate with other drivers of mortality

↪ **Robustness**: log of income per capita, log of income per capita × all bins, ownership rates × with all bins

Protective Effects

Only air conditioners are effective against extreme heat

	Air conditioner	Evaporative Cooler	Both Appliances
	(1)	(2)	(3)
AC $\times$ T ($\geq$ 35)	-0.0270***		-0.0206**
	(0.009)		(0.009)
Cooler $\times$ T ($\geq$ 35)		-0.00769*	-0.00629
		(0.004)	(0.005)
District FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Quadratic Trend $\times$ Region	Yes	Yes	Yes
R^2	0.05	0.05	0.05
Observations	2753	2753	2753

Notes: (1)-(3) clustered standard errors at district level in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regressions are weighted by the square root of district population.

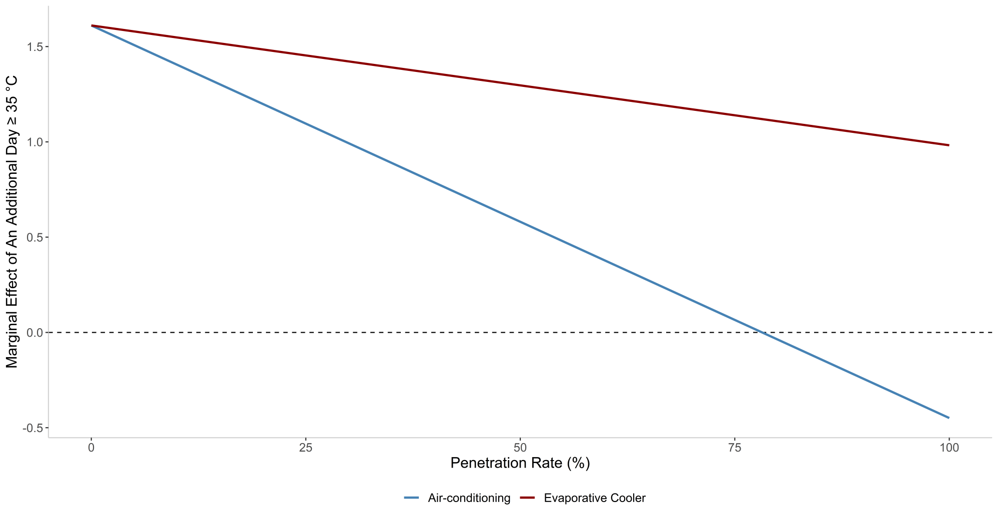
Robustness

Our results remain **robust** to alternative specifications:

- Temperature $\times$ Humidity Humidity
- State-level ownership rates State
- Clustering standard errors at state level
- Interactions with all temperature bins All Bins
- Including district-level income per capita, and interactions of income with temperature bins Income

Discussion

Residual Effect of Extreme Heat



Residual Effect of Extreme Heat

Let's make an example:

Residual Effect of Extreme Heat

Let's make an example:

- **Delhi**:
  - $\hookrightarrow$ income = 42183 rupees, CDD = 465 degree-days

Residual Effect of Extreme Heat

Let's make an example:

- **Delhi**:
  - $\hookrightarrow$ income = 42183 rupees, CDD = 465 degree-days
  - $\hookrightarrow$ increase by **30% p.p. in air-conditioning** penetration rate (25% to 55%)

Residual Effect of Extreme Heat

Let's make an example:

- **Delhi**:
  - ↪ income = 42183 rupees, CDD = 465 degree-days
  - ↪ increase by **30% p.p. in air-conditioning** penetration rate (25% to 55%)
  - ↪ heat-related mortality from extreme heat reduced by 52%

Residual Effect of Extreme Heat

Let’s make an example:

- **Delhi**:
  - ↪ income = 42183 rupees, CDD = 465 degree-days
  - ↪ increase by **30% p.p. in air-conditioning** penetration rate (25% to 55%)
  - ↪ heat-related mortality from extreme heat reduced by 52%
- **Uttar Pradesh**:
  - ↪ income = 14844 rupees, CDD = 454 degree-days

Residual Effect of Extreme Heat

Let's make an example:

- **Delhi**:
  - $\hookrightarrow$ income = 42183 rupees, CDD = 465 degree-days
  - $\hookrightarrow$ increase by **30% p.p. in air-conditioning** penetration rate (25% to 55%)
  - $\hookrightarrow$ heat-related mortality from extreme heat reduced by 52%
- **Uttar Pradesh**:
  - $\hookrightarrow$ income = 14844 rupees, CDD = 454 degree-days
  - $\hookrightarrow$ increase by **30% p.p. in evaporative cooler** penetration rate (25% to 55%)

Residual Effect of Extreme Heat

Let's make an example:

- **Delhi**:
  - $\hookrightarrow$ income = 42183 rupees, CDD = 465 degree-days
  - $\hookrightarrow$ increase by **30% p.p. in air-conditioning** penetration rate (25% to 55%)
  - $\hookrightarrow$ heat-related mortality from extreme heat reduced by 52%
- **Uttar Pradesh**:
  - $\hookrightarrow$ income = 14844 rupees, CDD = 454 degree-days
  - $\hookrightarrow$ increase by **30% p.p. in evaporative cooler** penetration rate (25% to 55%)
  - $\hookrightarrow$ heat-related mortality from extreme heat reduced by 12%

Avoided Deaths

Without adaptation $\Rightarrow$ **0.865 million annual excess deaths** due to extreme heat ($\geq 35\ ^{\circ}$C)

Avoided Deaths

Without adaptation $\Rightarrow$ **0.865 million annual excess deaths** due to extreme heat ($\geq 35\,^{\circ}$C)

- Annual percentage of **avoided deaths** in the period 2014-2019:

Avoided Deaths

Without adaptation $\Rightarrow$ **0.865 million annual excess deaths** due to extreme heat ($\geq 35\,^{\circ}$C)

- Annual percentage of **avoided deaths** in the period 2014-2019:

  $\hookrightarrow$ With heat adaptation $\Rightarrow$ 21%

Avoided Deaths

Without adaptation $\Rightarrow$ **0.865 million annual excess deaths** due to extreme heat ($\geq 35\ ^\circ$C)

- Annual percentage of **avoided deaths** in the period 2014-2019:

  $\hookrightarrow$ With heat adaptation $\Rightarrow$ **21%**

- **Annual gross welfare gains** from heat adaptation in the period 2014-2019

  $\hookrightarrow$ $0.865 \times 21\% \times VSL = \$33$ billion $\Rightarrow$ **2.18% of the annual GDP**

  $\hookrightarrow$ **66%** of these benefits is due to evaporative coolers $\Rightarrow$ 6 times more widespread than air conditioners

Avoided Deaths

Without adaptation $\Rightarrow$ **0.865 million annual excess deaths** due to extreme heat (≥ 35 °C)

- Annual percentage of **avoided deaths** in the period 2014-2019:
  - $\hookrightarrow$ With heat adaptation $\Rightarrow$ 21%
- **Annual gross welfare gains** from heat adaptation in the period 2014-2019
  - $\hookrightarrow$ $0.865 \times 21\% \times VSL$ = \$33 billion $\Rightarrow$ **2.18% of the annual GDP**
  - $\hookrightarrow$ **66%** of these benefits is due to evaporative coolers $\Rightarrow$ 6 times more widespread than air conditioners
- What would have happened if air conditioners were **as widespread as** evaporative cooler?
  - $\hookrightarrow$ Air-conditioning **alone** $\Rightarrow$ Annual percentage of **avoided deaths** = 47%
  - $\hookrightarrow$ Annual gross welfare gains = \$73 **billion** $\Rightarrow$ **4.9% of the annual GDP**
  - $\hookrightarrow$ Estimates for the United States = \$85 – \$185 billion (Barreca et al. 2016, JPE)

Implications for Policy

- Subsidise air conditioners may be a very **expensive policy**
  - ↪ The annualised cost is around 3083 rupees ($37)
  - ↪ **100% subsidy** for having same rate of coolers = $3.02 **billion**
  - ↪ Annual cost of additional **electricity expenditure** = $0.57 **billion**
  - ↪ Annual **social cost of additional emissions** = $0.003 **billion**
- But air conditioners appear as a cost-effective solution
  - ↪ **Benefits largely offset the costs**
  - ↪ Technology costs can be reduced with investment in innovation United States
- Evaporative coolers seems a **stop-gap** solution
  - ↪ Better an evaporative cooler than no cooling

Conclusion

Conclusion

- There exists a **trade-off** between accessibility to cooling and health protection
- **Technology layer** in the heat adaptation inequality for low- and middle-income households
- Only rich urban households adopt and use the most effective technology
- Trade-off also for policy makers
- **Questions**:
  - ↪ do competing strategies in other setting (e.g. agriculture) have similar inequality consequences?
  - ↪ is there a trade-off between adaptation and mitigation?
  - ↪ is the technological gap specific of India?

Thank you for your attention! **Any questions?**

Welfare Costs of Extreme

Back

Examples of evidence about the welfare costs of extreme heat:

- Mortality and morbidity
  (Deschenes and Greenstone 2011, AEJ; Barreca et al. 2016, JPE; Burgess et al. 2017; Heutel et al. 2021, RESTAT; Carleton et al. 2022, QJE)
- Learning
  (Park et al. 2020, AEJ; Zivin et al. 2020, JEEM; Park 2022, JHR)
- Mental health and mood
  (Noelke et al. 2016, ER; Baylis 2020, JPubE; Hua et al. 2022, JPopE)
- Labour productivity
  (Dasgupta et al. 2021, Lancet; Somanathan et al. 2021, JPE)
- Aggressive behaviour and crime
  (Ranson et al. 2015, JEEM; Baysan et al. 2019; JEBO; Blakeslee et al. 2021; JEBO)

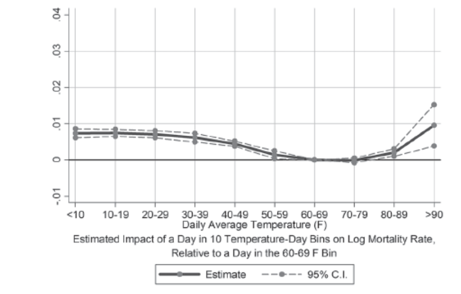
Mediating Effects of Air-conditioning

Back

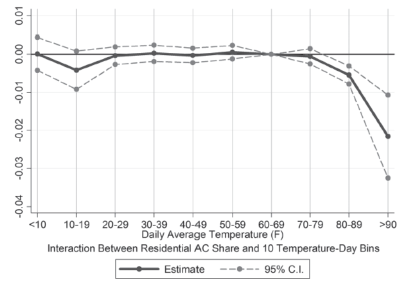
Mortality

(Barreca et al. 2016, JPE)

Without Air-conditioning



With Air-conditioning

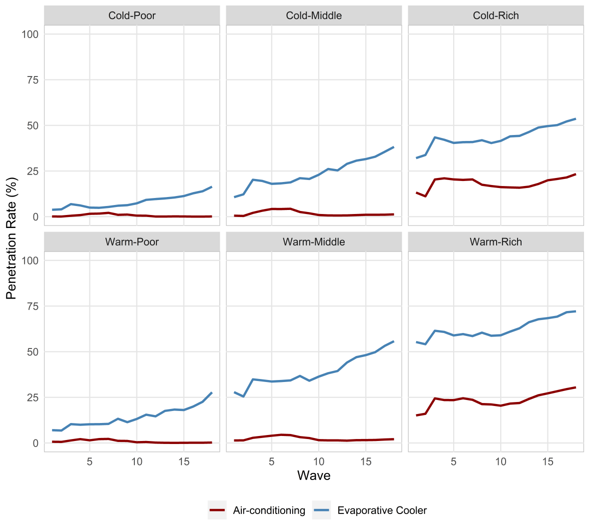


Further evidence: learning achievements, labour productivity and mental health

(Park et al. 2020, AEJ; Somanathan et al. 2021, JPE; Hua et al. 2022, JPopE)

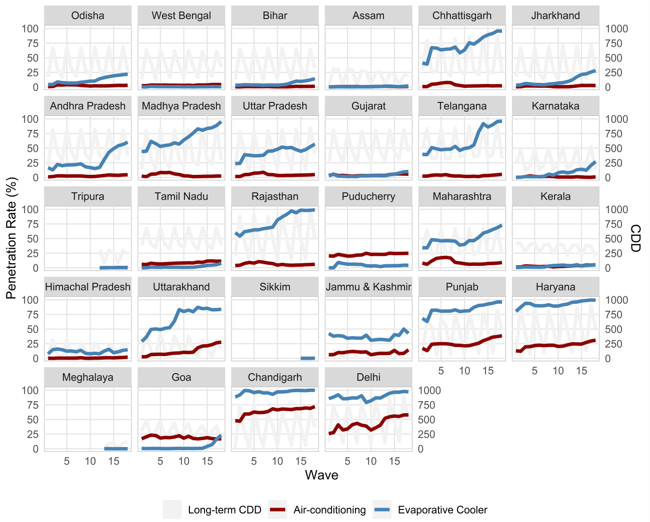
Trends in Ownership Rates by Income and Climate

Back State



Trends in Ownership Rates by States

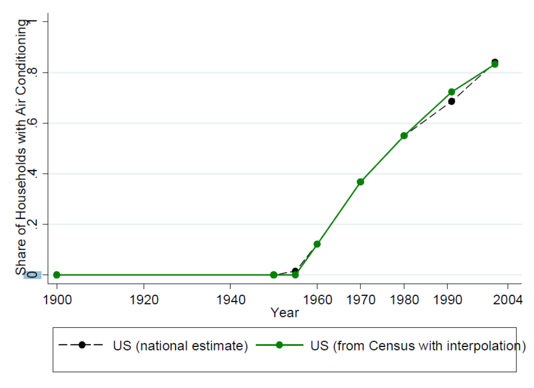
Back Trend Zoom



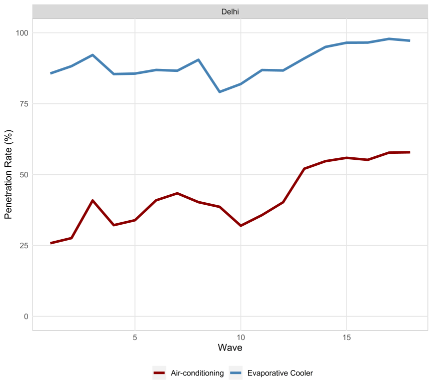
Zooming In

Back Trend State

United States (1900-2004)



Delhi (2014-2019)



Ownership - Heterogeneity

Back

Air-conditioners is not climate sensitive even for high-income families

	Both Appliances	Air Conditioner	Evaporative Cooler
	(1)	(2)	(3)
$\overline{\text{CDD}}$ (100s)	-0.0373***	-0.0101	-0.0423***
	(0.010)	(0.001)	(0.013)
Log(Income)	0.0637***	0.0547***	0.0363**
	(0.010)	(0.006)	(0.015)
$\overline{\text{CDD}} \times$ Log(Income)	0.00548***	0.00107	0.00600***
	(0.001)	(0.001)	(0.002)
Precipitations, Household Controls	Yes	Yes	Yes
State FE, Wave FE	Yes	Yes	Yes
Quadratic State $\times$ Year Trend	Yes	Yes	Yes
R^2	0.51	0.21	0.51
Observations	2442730	2442730	2442730

Notes: (1)-(3) clustered standard errors at district level in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regressions are conducted using survey weights.

Adoption - Interaction

Back

Still climatic conditions do not matter for adoption

	Both Appliances	Air Conditioner	Evaporative Cooler
	(1)	(2)	(3)
$\overline{\text{CDD}}$ (100s)	-0.00723**	0.00151	-0.00943***
	(0.003)	(0.001)	(0.003)
Log(Income)	0.0383***	0.0140***	0.0310***
	(0.003)	(0.002)	(0.003)
$\overline{\text{CDD}} \times$ Log(Income)	0.000693**	-0.000137	0.000914***
	(0.000)	(0.000)	(0.000)
Precipitations, Household Controls	Yes	Yes	Yes
Household FE, Wave FE	Yes	Yes	Yes
Quadratic State $\times$ Year Trend	Yes	Yes	Yes
R^2	0.05	0.02	0.05
Observations	2442730	2442730	2442730

Notes: (1)-(3) clustered standard errors at district level in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regressions are conducted using survey weights.

Adoption - Heterogeneity I

Back

Middle-income households adopt evaporative coolers

	Air Conditioner			Evaporative Cooler		
	Poor	Middle	Rich	Poor	Middle	Rich
	(1)	(2)	(3)	(4)	(5)	(6)
Log(Income)	0.00320***	0.00752***	0.0437***	0.0184***	0.0324***	0.0159***
	(0.001)	(0.001)	(0.003)	(0.004)	(0.004)	(0.004)
Precipitations, Household, CDD Controls	Yes	Yes	Yes	Yes	Yes	Yes
Household FE, Wave FE	Yes	Yes	Yes	Yes	Yes	Yes
Quadratic Trend $\times$ State	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.01	0.01	0.03	0.10	0.07	0.02
Observations	485084	1219147	485420	485084	1219147	485420

Notes: (1)-(6) clustered standard errors at district level in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regressions are conducted using survey weights.

Adoption - Heterogeneity II

Back

Income elasticity **varies** between urban and rural areas

	Air Conditioner		Evaporative Cooler	
	Rural	Urban	Rural	Urban
	(1)	(2)	(3)	(4)
Log(Income)	0.00554***	0.0342***	0.0316***	0.0284***
	(0.001)	(0.003)	(0.003)	(0.004)
Precipitations, Household, CDD Controls	Yes	Yes	Yes	Yes
Household FE, Wave FE	Yes	Yes	Yes	Yes
Quadratic State $\times$ Year Trend	Yes	Yes	Yes	Yes
R^2	0.01	0.03	0.07	0.06
Observations	786354	1646012	786354	1646012

Notes: (1)-(4) clustered standard errors at district level in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regressions are conducted using survey weights.

Adoption - Heterogeneity III

Back

Income elasticity **varies** with climatic conditions

	Air Conditioner			Evaporative Cooler		
	Cold	Mild	Warm	Cold	Mild	Warm
	(1)	(2)	(3)	(4)	(5)	(6)
Log(Income)	0.0152***	0.0134***	0.0128***	0.0122***	0.0370***	0.0435***
	(0.003)	(0.002)	(0.002)	(0.005)	(0.004)	(0.005)
Precipitations, Household, CDD Controls	Yes	Yes	Yes	Yes	Yes	Yes
Household FE, Wave FE	Yes	Yes	Yes	Yes	Yes	Yes
Quadratic State $\times$ Year Trend	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.02	0.03	0.01	0.08	0.08	0.05
Observations	829670	739207	863489	829670	739207	863489

Notes: (1)-(6) clustered standard errors at district level in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regressions are conducted using survey weights.

Electricity - Heterogeneity II

Back

Heterogeneity based on **technology**

	Air Conditioner (1)	Evaporative Cooler (2)
≥ 35	0.0112***	0.00469***
	(0.002)	(0.001)
Precipitations Controls	Yes	Yes
Household Income	Yes	Yes
Household FE	Yes	Yes
Month-Year FE	Yes	Yes
R^2	0.05	0.01
Observations	785745	3707868
Avg. kWh	241.65	135.08
Δ(kWh)	+2.71	+0.63

Notes: (1) and (2) clustered standard errors at district level in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regressions are conducted using survey weights.

Electricity - Heterogeneity III

Back

Focusing on **high-income** families

	Poor-Middle		Rich	
	Air Conditioner	Evaporative Cooler	Air Conditioner	Evaporative Cooler
	(1)	(2)	(3)	(4)
≥ 35	0.00123	0.00350***	0.0147***	0.00909***
	(0.002)	(0.001)	(0.003)	(0.002)
Precipitations Controls	Yes	Yes	Yes	Yes
Household Income	Yes	Yes	Yes	Yes
Household FE	Yes	Yes	Yes	Yes
Month-Year FE	Yes	Yes	Yes	Yes
R^2	0.01	0.01	0.06	0.02
Observations	161766	226428	538787	1018452
Avg. kWh	130.99	110.46	278.43	185.33
Δ(kWh)	+ 0.16	+0.39	+4.09	+1.68

Notes: (1)-(4) clustered standard errors at district level in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regressions are conducted using survey weights.

Controlling for Humidity

Back

	FE (1)	FE (2)	FE (3)	FE (4)
T ($\geq$ 35)	0.00943***		0.00996***	0.000320
	(0.002)		(0.002)	(0.003)
H (0 − 3)		0.000660	-0.000505	-0.000102
		(0.003)	(0.003)	(0.003)
H ($\geq$ 18)		-0.000102	0.000756	0.000110
		(0.001)	(0.001)	(0.001)
T ($\geq$ 35) $\times$ H ($\geq$ 18)				0.000123***
				(0.000)
District FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Quadratic Trend $\times$ Region	Yes	Yes	Yes	Yes
R^2	0.03	0.02	0.03	0.04
Observations	3908	3908	3908	3908

Notes: (1)-(4) clustered standard errors at district level in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regressions are weighted by the square root of district population.

Heterogeneity I

Back

Heat-related deaths mostly occur in **rural areas**

	Rural		Urban	
	(1)	(2)	(3)	(4)
T ($\geq$ 35)	0.00909**	-0.00191	0.00549*	0.00229
	(0.004)	(0.005)	(0.003)	(0.004)
T ($\geq$ 35) $\times$ H ($\geq$ 18)		0.000153**		0.0000533
		(0.000)		(0.000)
District FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Quadratic Trend $\times$ Region	Yes	Yes	Yes	Yes
R^2	0.03	0.04	0.02	0.02
Observations	2520	2520	1549	1549

Notes: (1)-(4) clustered standard errors at district level in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regressions are weighted by the square root of district rural and urban population.

Heterogeneity II

Back

Heat-related deaths mostly occur in district with a **higher share of poor individuals**

	Below Median		Above Median	
	(1)	(2)	(3)	(4)
T ($\geq$ 35)	0.00430*	0.00410	0.0173***	0.00147
	(0.003)	(0.003)	(0.004)	(0.006)
T ($\geq$ 35) $\times$ H ($\geq$ 18)		0.0000199		0.000168**
		(0.000)		(0.000)
District FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Quadratic Trend $\times$ Region	Yes	Yes	Yes	Yes
R^2	0.04	0.04	0.06	0.07
Observations	1369	1369	1384	1384

Notes: (1)-(4) clustered standard errors at district level in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regressions are weighted by the square root of district population.

State-level Ownership Rates

Back

	Temperature			Humidity			Temperature × Humidity		
	Air Conditioner (1)	Cooler (2)	Both (3)	Air Conditioner (4)	Cooler (5)	Both (6)	Air Conditioner (7)	Cooler (8)	Both (9)
AC × T (≥ 35)	-0.0444***		-0.0373***						
	(0.013)		(0.014)						
Cooler × T (≥ 35)		-0.0109**	-0.00770						
		(0.005)	(0.005)						
AC × H (≥ 18)				-0.00228		-0.00521			
				(0.005)		(0.005)			
Cooler × H (≥ 18)					-0.000857	-0.000746			
					(0.002)	(0.002)			
AC × T (≥ 35) × H (≥ 18)							-0.000390**		-0.000397**
							(0.000)		(0.000)
Cooler × T (≥ 35) × H (≥ 18)								-0.0000427	-0.00000122
								(0.000)	(0.000)
District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Quadratic Trend × Region	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.05	0.06	0.06	0.05	0.06	0.07	0.05	0.06	0.06
Observations	2753	2753	2753	2753	2753	2753	2753	2753	2753

Notes: (1)-(9) clustered standard errors at district level in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regressions are weighted by the square root of district population.

Performance during Very Hot and Humid Days

Back

Again only air conditioners are effective against extreme hot and humid days

	Humidity			Temperature × Humidity		
	Air conditioner	Cooler	Both	Air conditioner	Cooler	Both
	(1)	(2)	(3)	(4)	(5)	(6)
AC × H (≥ 18)	-0.000662		-0.000685			
	(0.002)		(0.002)			
Cooler × H (≥ 18)		0.000507	0.000538			
		(0.001)	(0.001)			
AC × T (≥ 35) × H (≥ 18)				-0.000422***		-0.000384***
				(0.000)		(0.000)
Cooler × T (≥ 35) × H (≥ 18)					-0.0000512	-0.0000238
					(0.000)	(0.000)
District FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Quadratic Trend × Region	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.05	0.05	0.05	0.06	0.06	0.06
Observations	2753	2753	2753	2753	2753	2753

Notes: (1)-(6) clustered standard errors at district level in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regressions are weighted by the square root of district population.

Interactions with all Temperature Bins

Back

	Air Conditioner (1)	Evaporative Cooler (2)	Both (3)
AC × T($\leq$ 10)	0.00109		-0.000206
	(0.009)		(0.009)
Cooler × T($\leq$ 10)		0.0000828	0.000279
		(0.003)	(0.003)
AC × T(10 — 15)	-0.0114*		-0.0102
	(0.006)		(0.007)
Cooler × T(10 — 15)		-0.00219	-0.000694
		(0.004)	(0.004)
AC × T(20 — 25)	-0.00499		-0.00523
	(0.004)		(0.004)
Cooler × T(20 — 25)		-0.00195	-0.00153
		(0.002)	(0.002)
AC × T(25 — 30)	-0.00293		-0.00278
	(0.005)		(0.005)
Cooler × T(25 — 30)		0.000724	0.00104
		(0.002)	(0.002)
AC × T(30 — 35)	-0.00903		-0.0101
	(0.006)		(0.006)
Cooler × T(30 — 35)		0.00309	0.00365*
		(0.002)	(0.002)
AC × T($\geq$ 35)	-0.0246**		-0.0155
	(0.010)		(0.011)
Cooler × T($\geq$ 35)		-0.00752	-0.00646
		(0.005)	(0.005)
Precipitation Terciles	Yes	Yes	Yes
Humdity Bins	Yes	Yes	Yes
District FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Quadratic Trend × Region	Yes	Yes	Yes
R^2	0.05	0.06	0.06
Observations	2753	2753	2753

Notes: (1)-(3) clustered standard errors at district level in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regressions are weighted by the square root of district population.

Controlling for Income

Back

	FE (1)	FE (2)
AC $\times$ T ($\geq$ 35)	-0.0208**	-0.0178*
	(0.009)	(0.010)
Cooler $\times$ T ($\geq$ 35)	-0.00636	-0.00629
	(0.005)	(0.005)
Income Per Capita	Yes	Yes
Income $\times$ Temperature Bins	No	Yes
District FE	Yes	Yes
Year FE	Yes	Yes
Quadratic Trend $\times$ Region	Yes	Yes
R^2	0.05	0.06
Observations	2753	2753

Notes: (1)-(2) clustered standard errors at district level in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All regressions are weighted by the square root of district population.

Innovation in the United States

Back

Rapson (2014, JEEM)