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 of University

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Introduction

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- Evidence of the **protective effects** of air conditioners
  - $\hookrightarrow$ e.g., 80% reduction in heat-related mortality in US Graph
    (Barreca et al. 2016, JPE)
- **Problem**: access to air conditioning is **unequally distributed**
  (Davis et al. 2021, GEC; Pavanello et al. 2021, NC; Romitti et al. 2022, PNAS Nexus)
  - $\hookrightarrow$ especially in **developing economies**
  - $\hookrightarrow$ air conditioners are too **expensive** $\Rightarrow$ high operational and capital costs

Cooling, Inequality and Technology

Are there any alternative cooling appliances affordable for **poorer** households?

Cooling, Inequality and Technology

Air conditioner

Evaporative cooler

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Evaporative cooler

- Policymakers **promote** **evaporative coolers** as a sustainable and cheap option
- Evaporative coolers ⇒ low upfront and operational costs

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$\hookrightarrow$ **Trade-off (?)** $\Rightarrow$ **cost and accessibility — health protection effectiveness**

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    - **Household** ($>$ 200k) panel data from **India**
    - Information on **technology** and **electricity consumption**

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2. Test whether the choice of the technology determines **the level of protection** from extreme heat
   - **District-level** annual **mortality** data
3. Determine the consequences of **technological inequality** in heat adaptation
   - Number of **prevented deaths**
   - Implications for **policy**

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  ↪ Evaporative coolers prevented **23%** of heat-related deaths between 2014-2019

  ↪ At the same rate air conditioners would have prevented **46%** of heat-related deaths

Contributions

1. Air-conditioning adoption, temperature and income

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3. Mortality and extreme heat
   (Deschenes and Greenstone 2011, AEJ; Burgess et al. 2017; Carleton et al. 2022, QJE)
4. Mediator effect of cooling
   (Barreca et al 2016, JPE; Park et al. 2020, AEJ; Somanathan et al. 2021, JPE; Hua et al. 2022, JPopE)

$\hookrightarrow$ **Main contribution**: add the technological dimension

India

- **Extreme heat**:
  - Between March and May 2022: temperature reached 51°C
  - In a +2°C scenario: 2-20 times more likely and 0.5-1.5°C hotter relative to 2022
    (Zachariah et al. 2022)

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- **Consequences** of extreme heat:
  - Historical: about 4-6 deaths per 100k people per year
  - Future: 10-60 deaths per 100k people per year by 2100

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- **Cooling adaptation**:
  - Rising incomes and temperatures $\Rightarrow$ boost in cooling demand

    (IEA, 2018)
  - Demand for cooler raising even in remote areas
  - Air-conditioning spread is still low (9%, in 2019)

    (Davis et al. 2021; Pavanello et al. 2021, NC)
  - One of the first countries to develop a **Cooling Action Plan** (2019)

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

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

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

Solution

Solve the model:

- Closed-form solution for electricity consumption and cooling capital

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

  $\hookrightarrow$ 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 utility
- 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)

Cooling Adaptation

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

- Actualised **electricity prices**: 2011 National Socio-Economic Survey
    - Aggregated at the district-urban/rural level

- Population-weighted **climate data** from ERA5 ($0.25^\circ \times 0.25^\circ$ cells):
    - Daily average temperature
    - Daily total precipitation

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 ⇒ long lifetimes of cooling appliances
- Households invest based on expectations about climatic conditions ⇒ average weather over long periods
  (Cohen et al. 2017)
- Adoption in short period of time ⇒ 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:

$$C_{ciw} = \gamma_0 + \beta_1 \overline{CDD}_{d(i)w} + \beta_2 I_{iw} + \gamma_2 g(P_{d(i)w}) + \lambda X_{iw} + \mu_k + \delta_w + \theta_{s(i)} y + \theta^2_{s(i)} y^2 + \zeta_{iw}$$

- 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

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***	0.0000542	0.0145***
	(0.002)	(0.001)	(0.003)
Log(Income)	0.0861***	0.0607***	0.0597***
	(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** ($\Uparrow\Uparrow$)
- Hours of power availability during the day and ownership of generators ($\Uparrow$)
- **Education level** ($\Uparrow\Uparrow$), female head ($\Downarrow$), house materials ($\Uparrow$), head age ($\Downarrow$)

Coolers:

- Hours of **power availability** during the day and **ownership of generators** ($\Uparrow\Uparrow$)
- Education level ($\Uparrow$), female head ($\Downarrow$), house materials ($\Uparrow$), head age ($\Uparrow$)

Adoption

Adoption is a matter of **economic development**

	Both Appliances	Air-conditioning	Evaporative Cooler
	(1)	(2)	(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 alternative specifications:

- Alternative time and time-invarying fixed-effects
- Clustering standard errors at state level
- Changing CDD thresholds
- Specifying temperature up to degree 3 polynomials
- GLDAS rather than ERA5 climate data

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 response to temperature
- Heterogeneity in the response should be confirmatory of the distribution of the technologies

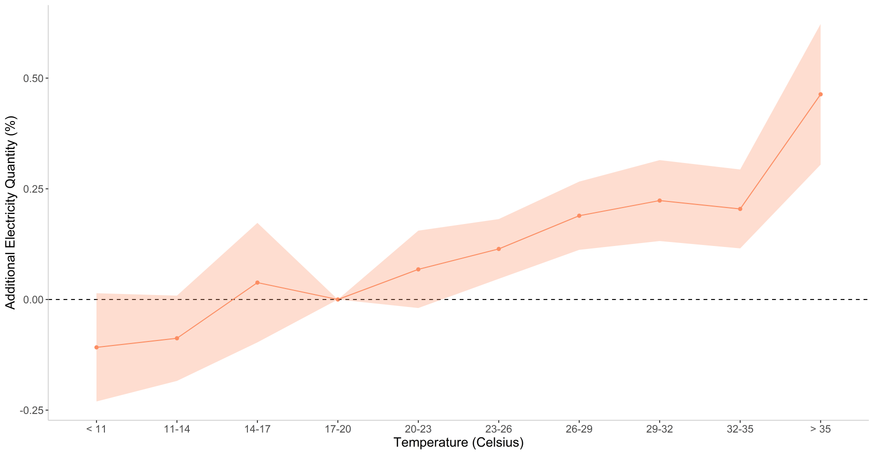
Empirical Framework

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 ≥ 35 °C (wrt $17-20$) increases electricity consumption by 0.46%

Heterogeneity

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	0.00345***	0.00271***	0.00422***	0.00566***	0.00748***	0.00779***
	(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	0.04	0.04	0.09
Observations	791899	1293061	236447	854902	2698269	1297719
Avg. kWh	69.35	103.86	171.59	83.37	117.99	195.08
Δ(kWh)	+0.24	+0.28	+0.72	+0.47	+0.88	+1.51

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.

Het II Het III

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

Health and Extreme Heat

Data

- District-level annual **mortality data**: Civil Registration System (2009-2019)
  - 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

Empirical Framework

Estimating the impact of temperature on mortality:

$$M_{dt} = \alpha_0 + \sum_{j=1}^{8} \theta_j T_{dt} + \sum_{r} \delta_r \{P_{dt} \in tercile\ r\} + \mu_d + \rho_t + \lambda_{r(d)} t + \lambda^2_{r(d)} t^2 + \epsilon_{dt}$$

- 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)
- Trend: 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) bins of humidity, (2) interaction **warmest** × **most humid bin**

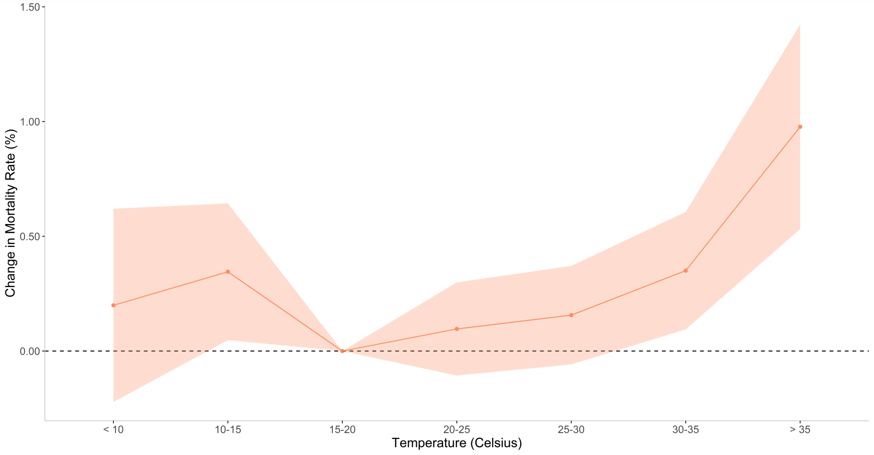
The Role of Cooling

Estimate **an augmented regression model**:

$$M_{dt} = \alpha_0 + \sum_{j=1}^{8} \theta_j T_{dt} + \sum_{j=1}^{8} \sum_{l=1}^{2} \gamma_j T_{dt} \times C_{dtl} + \sum_{l=1}^{2} \phi_l C_{dtl} +$$
$$+ \sum_{r} \delta_r \{P_{dt} \in tercile\ r\} + \mu_d + \rho_t + \lambda_{r(d)} t + \lambda^2_{r(d)} t^2 + \epsilon_{dt}$$

- C_{dtl}: penetration rate in district d of technology l
- Additional regressions: interactions with (1) bins of **humidity**, (2) warmest $\times$ most humid bin
- **Drawback**: no quasi-experimental design
  $\hookrightarrow$ the two shares do not have to correlate with other drivers of mortality

Temperature-mortality



An additional day $\geq 35\ ^\circ$C (wrt $15-20$) increases mortality rates by 1%

Controlling for Humidity

	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

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

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.

Evaporative Cooler vs Air conditioner

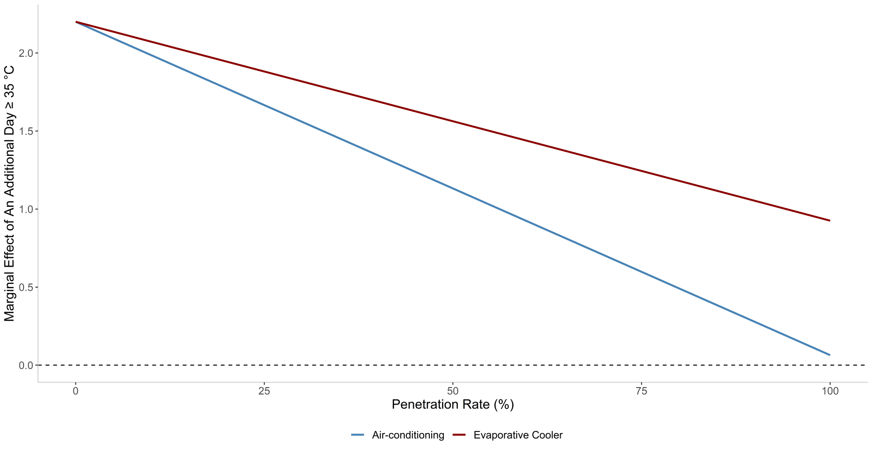
Evaporative coolers are more than two times less effective than air conditioners

	Temperature			Humidity			Temperature × Humidity		
	Air conditioner	Cooler	Both	Air conditioner	Cooler	Both	Air conditioner	Cooler	Both
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
AC × T ($\geq$ 35)	-0.0302***		-0.0268***						
	(0.009)		(0.009)						
Cooler × T ($\geq$ 35)		-0.0132**	-0.0123**						
		(0.005)	(0.005)						
AC × H ($\geq$ 18)				-0.000661		-0.000685			
				(0.002)		(0.002)			
Cooler × H ($\geq$ 18)					0.000506	0.000538			
					(0.001)	(0.001)			
AC × T ($\geq$ 35) × H ($\geq$ 18)							-0.000436***		-0.000368***
							(0.000)		(0.000)
Cooler × T ($\geq$ 35) × H ($\geq$ 18)								-0.000131**	-0.000113**
								(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	0.05	0.05	0.05	0.05	0.05	0.06	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.

Discussion

Residual Effect of Extreme Heat



Residual Effect of Extreme Heat

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- **Uttar Pradesh**:
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  - $\hookrightarrow$ increase by 30% p.p. in evaporative cooler penetration rate (25% to 55%)
  - $\hookrightarrow$ heat-related mortality from extreme heat reduced by 19%

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Without adaptation $\Rightarrow$ **1.01 million people** excess deaths due to extreme heat

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  $\hookrightarrow$ $1.05 \times 30\% \times VSL \Rightarrow$ 55 billion \$

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- What would have happened if air conditioners were **as spread as** evaporative cooler?

  - air-conditioning **alone** $\Rightarrow$ **46%**

  $\hookrightarrow$ gross welfare gains $\Rightarrow$ **14 billion \$** $\Rightarrow$ **0.46% of the annual GDP**

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 ⇒ 252 billion rupees (**3 billion \$**)
- Evaporative coolers seems a **stop-gap** solution
  - ↪ better an evaporative cooler than no cooling
- Air conditioners are likely the solution in the **long-term**
  - ↪ **extreme heat** will become more intense and frequent
  - ↪ **income** is expected to largely increase in the next years
  - ↪ need for investment in **innovation** United States

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
- **Future research agenda**:
  - $\hookrightarrow$ **projections** $\Rightarrow$ how will the situation evolve in the next 30 years?
  - $\hookrightarrow$ is there a trade-off between adaptation and mitigation?
  - $\hookrightarrow$ is the technological gap specific of India?

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

Welfare Costs of Extreme Heat

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)

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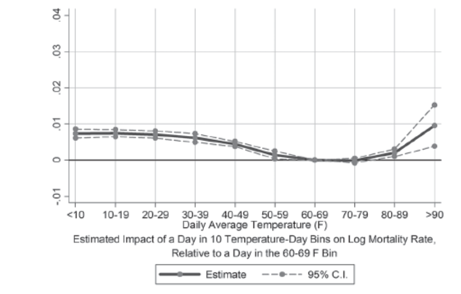
Mediating Effects of Air-conditioning

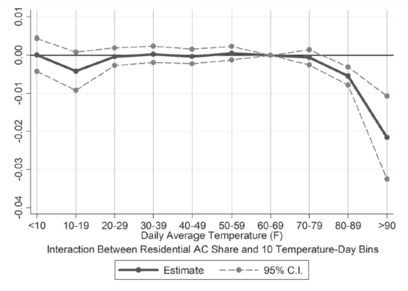
Mortality

(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)

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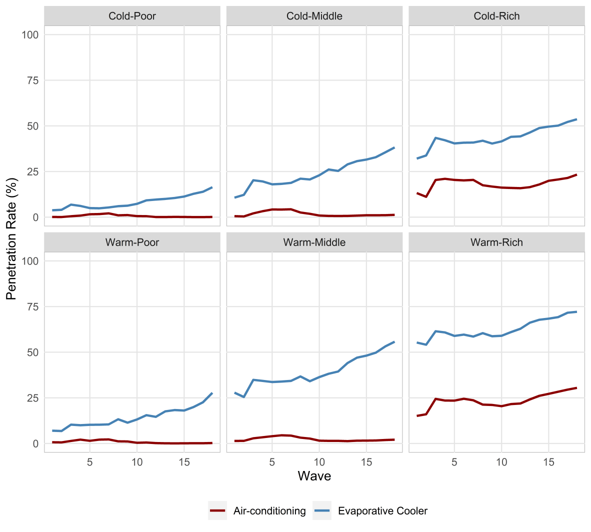
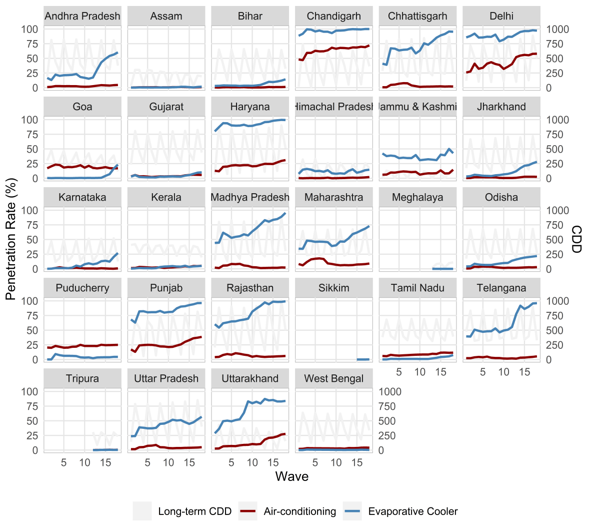
Trends in Ownership Rates by Income and Climate



Back State

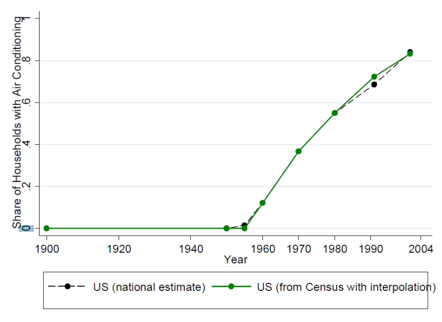
Trends in Ownership Rates by States



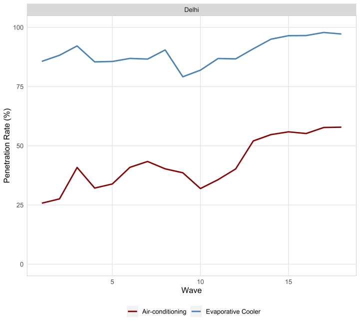
Back Trend Zoom

Zooming In

United States (1900-2004)



Delhi (2014-2019)



Back Trend State

Electricity - Heterogeneity II

Heterogeneity based on technology

	Air Conditioner	Evaporative Cooler
	(1)	(2)
≥ 35	0.00726***	0.00429***
	(0.002)	(0.001)
Precipitations Controls	Yes	Yes
Household FE	Yes	Yes
Month-Year FE	Yes	Yes
R^2	0.04	0.01
Observations	724127	3648335

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.

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Electricity - Heterogeneity III

Focusing on high-income families

	Air Conditioner	Evaporative Cooler
	(1)	(2)
≥ 35	0.00939***	0.00677***
	(0.002)	(0.001)
Precipitations Controls	Yes	Yes
Household FE	Yes	Yes
Month-Year FE	Yes	Yes
Within R^2	0.05	0.02
Observations	490613	995301

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.

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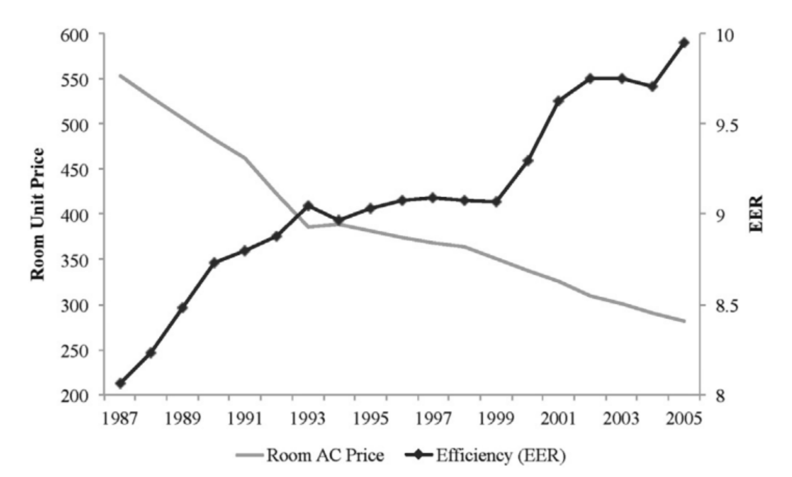
Innovation in the United States

Rapson (2014, JEEM)



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