

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

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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

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



# Cooling, Inequality and Technology

Air conditioner



Evaporative cooler



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

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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

## 1. Air-conditioning adoption, temperature and income

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## 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)

↪ **Main contribution:** add the technological dimension

- **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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- 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

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A representative household maximises its utility function:

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

↪ 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  $\delta$

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

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

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

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

Solve the model:

- Closed-form solution for electricity consumption and cooling capital

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

↪ importance of **temperature-income interactions**

↪ diminishing returns to adaptation

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

- 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

↪ revealed preferences

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

↪ mortality—temperature relationship

3. Determine **differences at reducing thermal discomfort**  $a_\theta$

↪ mortality—(temperature  $\times$  technology)

# Cooling Adaptation

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

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

- $C_{ciw}$ : 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
- $\mu_k$ : 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

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

	Both Appliances (1)	Air Conditioner (2)	Evaporative Cooler (3)
$\overline{\text{CDD}}$ (100s)	0.0146*** (0.002)	0.0000542 (0.001)	0.0145*** (0.003)
Log(Income)	0.0861*** (0.007)	0.0607*** (0.006)	0.0597*** (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 <sup>2</sup>	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.

## 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 (0.000)	0.000216 (0.000)	-0.000764* (0.000)
Log(Income)	0.0410*** (0.003)	0.0135*** (0.001)	0.0344*** (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 <sup>2</sup>	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..

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

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

- 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

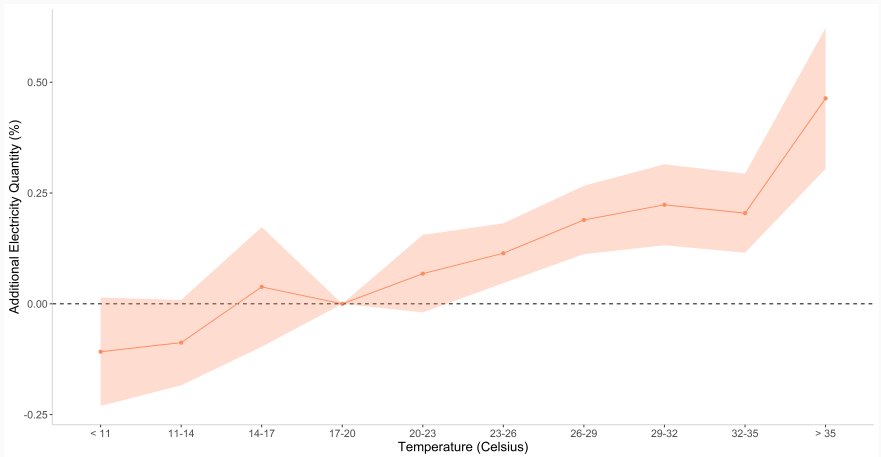


Estimating the impact of **temperature** on electricity quantity:

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

- $Q_{imy}$ : 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 ( $\mu_i$ ) and month-year FE ( $\delta_{my}$ )
- All regressions are weighted using survey weights that also correct for attrition

# Temperature-electricity



An additional day  $\geq 35^{\circ}\text{C}$  (wrt 17 – 20) increases electricity consumption by **0.46%**

# Heterogeneity

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

	Rural			Urban		
	Poor (1)	Middle (2)	Rich (3)	Poor (4)	Middle (5)	Rich (6)
$\geq 35$	0.00345*** (0.001)	0.00271*** (0.001)	0.00422*** (0.001)	0.00566*** (0.001)	0.00748*** (0.001)	0.00779*** (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 <sup>2</sup>	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
$\Delta(\text{kWh})$	+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.

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

- Alternative time and time-invariant 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

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- 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:

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

- $M_{dt}$ : 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 ( $\mu_d$ ), year FE ( $\rho_t$ )
- Trend: climatic region  $\times$  quadratic trend ( $\lambda_{s(d)} t + \lambda_{s(d)}^2 t^2$ )
- 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**  $\times$  **most humid bin**

# The Role of Cooling

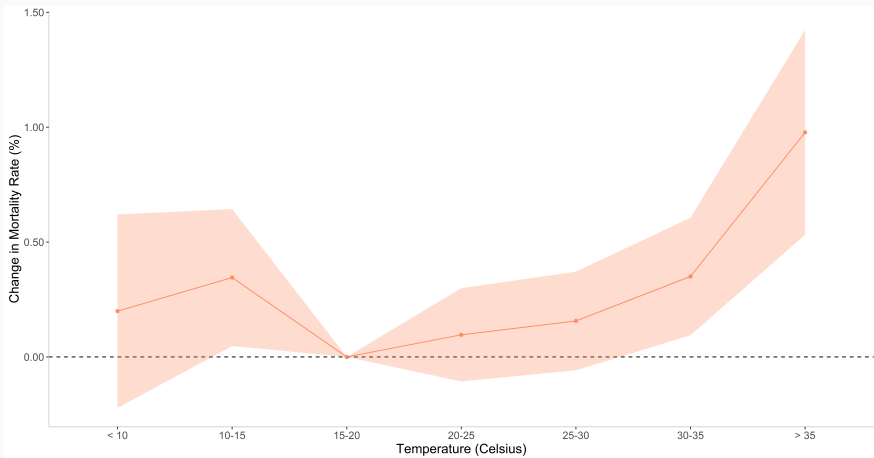
Estimate an augmented regression model:

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

- $C_{dtl}$ : penetration rate in district  $d$  of technology  $l$
- Additional regressions: interactions with (1) bins of **humidity**, (2) warmest  $\times$  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  $\geq 35$  °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*** (0.002)		0.00996*** (0.002)	0.000320 (0.003)
H (0 – 3)		0.000660 (0.003)	-0.000505 (0.003)	-0.000102 (0.003)
H ( $\geq 18$ )		-0.000102 (0.001)	0.000756 (0.001)	0.000110 (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 <sup>2</sup>	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.

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

	Rural		Urban	
	(1)	(2)	(3)	(4)
T ( $\geq 35$ )	0.00909** (0.004)	-0.00191 (0.005)	0.00549* (0.003)	0.00229 (0.004)
T ( $\geq 35$ ) $\times$ H ( $\geq 18$ )		0.000153** (0.000)		0.0000533 (0.000)
District FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Quadratic Trend $\times$ Region	Yes	Yes	Yes	Yes
R <sup>2</sup>	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 <sup>2</sup>	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

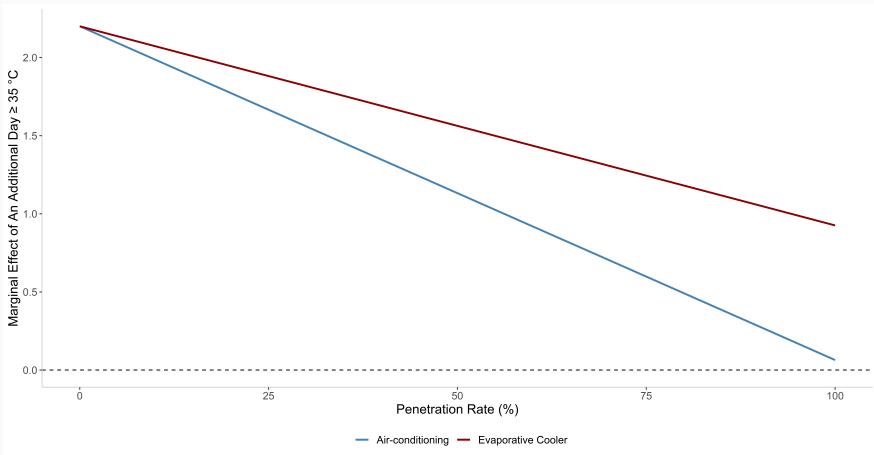
	Temperature			Humidity			Temperature $\times$ Humidity		
	Air conditioner (1)	Cooler (2)	Both (3)	Air conditioner (4)	Cooler (5)	Both (6)	Air conditioner (7)	Cooler (8)	Both (9)
AC $\times$ T ( $\geq 35$ )	-0.0302*** (0.009)		-0.0268*** (0.009)						
Cooler $\times$ T ( $\geq 35$ )		-0.0132** (0.005)	-0.0123** (0.005)						
AC $\times$ H ( $\geq 18$ )				-0.000661 (0.002)		-0.000685 (0.002)			
Cooler $\times$ H ( $\geq 18$ )					0.000506 (0.001)	0.000538 (0.001)			
AC $\times$ T ( $\geq 35$ ) $\times$ H ( $\geq 18$ )							-0.000436*** (0.000)		-0.000368*** (0.000)
Cooler $\times$ T ( $\geq 35$ ) $\times$ H ( $\geq 18$ )								-0.000131** (0.000)	-0.000113** (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 $\times$ Region	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R <sup>2</sup>	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

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# Residual Effect of Extreme Heat



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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  $\Rightarrow$  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

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- 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:**
  - ↪ **projections** ⇒ how will the situation evolve in the next 30 years?
  - ↪ 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 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)

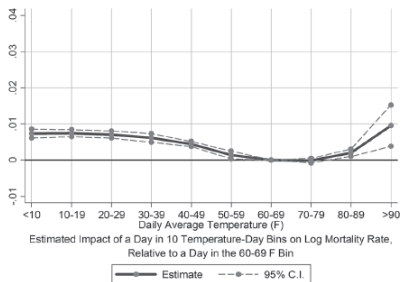


# Mediating Effects of Air-conditioning

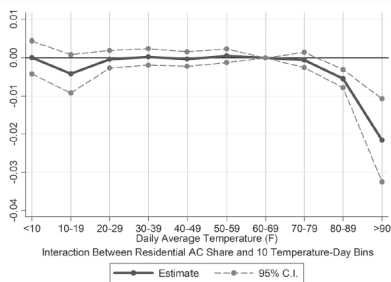
## Mortality

(Barreca et al. 2016, JPE)

### Without Air-conditioning



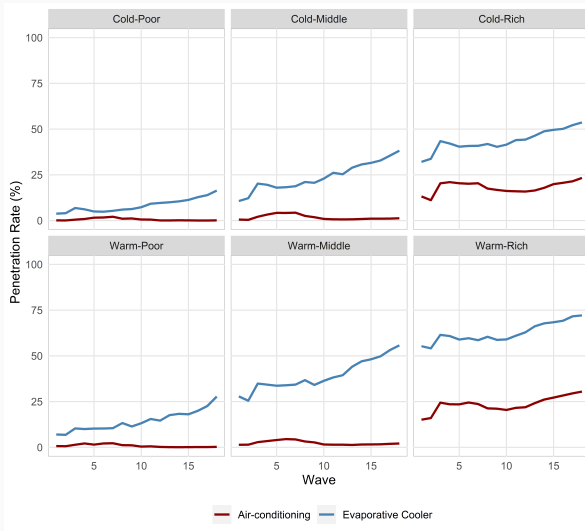
### With Air-conditioning



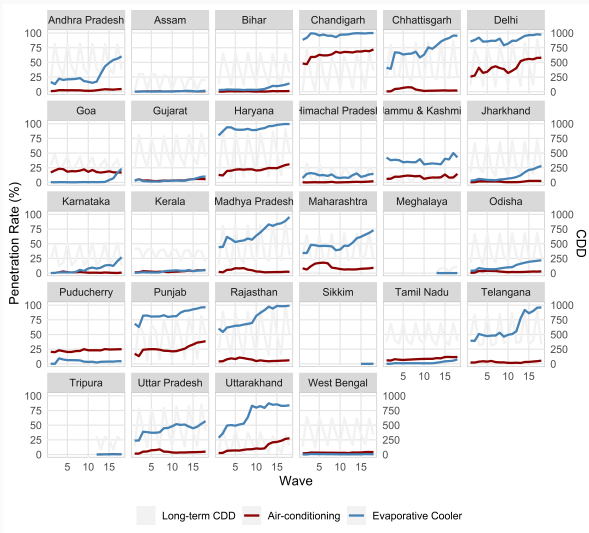
## Further evidence: learning achievements, labour productivity and mental health

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

# Trends in Ownership Rates by Income and Climate

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# Trends in Ownership Rates by States



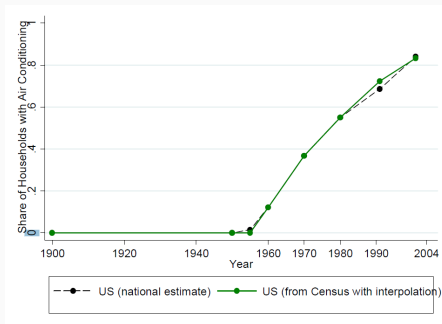
Back

Trend

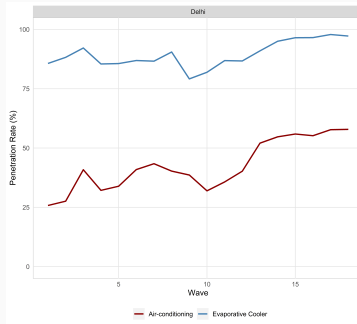
Zoom

# Zooming In

## United States (1900-2004)



## Delhi (2014-2019)



Back

Trend

State

# Electricity - Heterogeneity II

## Heterogeneity based on technology

	Air Conditioner (1)	Evaporative Cooler (2)
$\geq 35$	0.00726*** (0.002)	0.00429*** (0.001)
Precipitations Controls	Yes	Yes
Household FE	Yes	Yes
Month-Year FE	Yes	Yes
R <sup>2</sup>	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.

# Electricity - Heterogeneity III

Focusing on high-income families

	Air Conditioner (1)	Evaporative Cooler (2)
$\geq 35$	0.00939*** (0.002)	0.00677*** (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.

# Innovation in the United States

Rapson (2014, JEEM)

