The Long-run Effect of Air Pollution on Survival

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How bad is air pollution for adult health?

- Air pollution harms health in both the short and long run

- But, the magnitude of the effect remains uncertain
  - Observational estimates are prone to bias
  - Quasi-experimental studies focus on short-run effects

- Identifying the **long-run** effect of **chronic** exposure is hard
  - Limited data on long-run outcomes
  - Variation in long-run exposure hard to find
How do we address these challenges?

1. Use variation in wind direction as instrument for daily pollution
   - Trace out mortality patterns up to one month following acute exposure
   - Limited to short-run effects of acute exposure

2. Integrate empirical estimates into dynamic production model of health
   - Can be internally validated using quasi-experimental estimates

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Research questions

- Pollutant: sulfur dioxide (SO$_2$)

1. What is the short-run causal effect of acute (one-day) exposure to SO$_2$?
   - Instrumental variables research design
   - Main outcome: monthly (28-day) mortality

2. What is the long-run effect of chronic exposure to SO$_2$?
   - Production model of health from Lleras-Muney and Moreau (2022)
   - Main outcome: life expectancy
Main results

- A 1-day, 10% increase in $\text{SO}_2$ increases same-day mortality by 0.3 percent

- In the month following exposure:
  - Cumulative effect for cancer deaths falls to zero ("mortality displacement")
  - Cumulative effect for other diseases more than triples ("accelerated aging")
  - On net, cumulative mortality more than doubles

- Benefit of reducing lifetime $\text{SO}_2$ exposure by 10% is 1.2 years of extra life
  - 90% of benefits occur after age 50
Contributions to the literature

- Framework for estimating long-run survival effects of chronic exposure
  - Model calculations differ from IV extrapolation
  - Approach is similar in spirit to Athey, Chetty, and Imbens (2020)

- Health effects of air pollution (Chay and Greenstone 2003; Currie and Neidell 2005; Schlenker and Walker 2016; Hollingsworth and Rudik 2021; Alexander and Schwandt 2022; Heo, Ito, and Kotamarthi 2023)
  - We are the largest quasi-experimental study (17 years, 18 million deaths)
  - We focus on mortality dynamics
Background and Data
EPA regulates six air pollutants

- Carbon monoxide (CO)
- Ozone (O₃)
- Nitrogen dioxide (NO₂)
- Lead
- Particulate matter (PM)
- Sulfur dioxide (SO₂)

We focus on SO₂, which is well-measured during our 1972–1988 time period
  - Regulated at the daily and annual levels
SO$_2$ has immediate and delayed effects

- Direct exposure to SO$_2$ impairs respiratory function

- SO$_2$ leads to formation of sulfates, a component of PM 2.5 (fine particulates)
  - Acute exposure to PM 2.5 causes premature death

- Chronic exposure to air pollution associated with “accelerated aging”
  - Risk factors for cardiovascular disease (eg, coronary artery calcification)
  - Initiation and promotion of lung cancer
Daily environmental data

- Data on SO$_2$ obtained from EPA site monitors
  - Not available for all counties → limiting factor in the final size of our sample

- Temperature and precipitation obtained from Schlenker and Roberts (2009)

- Wind direction and wind speed obtained from Japan Meteorological Agency

- All data are aggregated to the county-day level
Daily mortality data

  - Exact date of death
  - County of occurrence
  - Cause of death
  - Age, sex, and race of decedent

- Merge with environmental data at the county-day level
  - Main specification includes 2.03 million county-day observations
SO$_2$ levels are declining during our sample period.
## Summary statistics

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<tbody>
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<td>Std. Dev.</td>
<td>Observations</td>
</tr>
<tr>
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<td></td>
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</tr>
<tr>
<td>SO$_2$, ppb</td>
<td>8.96</td>
<td>12.62</td>
<td>2,032,338</td>
</tr>
<tr>
<td>NO$_2$, ppb</td>
<td>21.25</td>
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<tr>
<td>CO, ppm</td>
<td>1.64</td>
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Empirical Analysis

Short-run effects of acute exposure
Empirical strategy: instrumental variables (2SLS)

- Wind carries pollutants over long distances

- Key insight: no need to isolate the pollution source! (Deryugina et al. 2019)
  - Maximizes the size of our estimation sample

- Identifying assumption:
  - Wind direction unrelated to health except through pollution
How do we construct our instruments?

- Use clustering algorithm to assign pollution monitors to 50 regional groups

- First stage is group-specific relationship between wind direction and pollution

- Allow pollution transport patterns to vary across groups
  - Wind blowing from west has different effect in California than in Massachusetts
Black dots are SO₂ monitors
Wind direction and SO₂ in Southern California area

Blue shading depicts 95% confidence intervals
Black dots on map are SO₂ monitors
Wind direction and SO$_2$ in Southern California area

SO$_2$ (ppb)

Windward direction

Blue shading depicts 95% confidence intervals
Black dots on map are SO$_2$ monitors

Dirty
Clean

Pacific Ocean
Wind direction and SO$_2$ in Greater Philadelphia area

Blue shading depicts 95% confidence intervals
Black dots on map are SO$_2$ monitors
Wind direction and $\text{SO}_2$ in Greater Philadelphia area

Windward direction

$\text{SO}_2$ (ppb)

Blue shading depicts 95% confidence intervals
Black dots on map are $\text{SO}_2$ monitors
First stage: excluded instrument is wind direction

\[ \text{SO2}_{cd} = \sum_{g=1}^{50} f^g(\theta_{cd}) + \delta + \alpha_{cm} + \alpha_{my} + \varepsilon_{cd} \]

- Dependent variable is level of SO2 in county \( c \) on day \( d \)

- Effect of wind direction, \( \theta_{cd} \), varies across 50 geographic groups, \( g \)

- Consider two functional forms for \( f^g(\theta_{cd}) \)
  - Non-parametric 10-degree bins (1750 instruments)
  - Parametric sin function (100 instruments, preferred specification)
Second-stage regression

\[ Y_{cd}^k = \beta^k \widehat{SO}_2_{cd} + X_{cd}^k \delta + \alpha_{cm} + \alpha_{my} + \varepsilon_{cd} \]

- Estimate effect of 1-day exposure on \( k \)-day mortality rate (up to \( k = 28 \))
- Control for county-by-month (\( \alpha_{cm} \)) and month-by-year (\( \alpha_{my} \)) fixed effects
- **Flexibly control** for max temperature, precipitation, and wind speed
- Cluster standard errors at the county level, weight by county population
Cumulative mortality effect grows over time

(deaths per million)

Days since exposure
Divergent patterns by cause of death

Days since exposure

Cardio Other Cancer External

(deaths per million)

Accelerated aging

Mortality displacement
1-day mortality by age group (relative effect)

Age group

-1
-0.2
0
0.2
0.4
0.6
0.8%

<1
1-19
20-44
45-59
60-64
65-69
70-74
74-79
80-84
85+

Mortality rates:

- <1: 0.197
- 1-19: 0.188
- 20-44: 0.381
- 45-59: 0.215
- 60-64: 0.211
- 65-69: 0.441
- 70-74: 0.217
- 74-79: 0.306
- 80-84: 0.435
- 85+: 0.513
Alternative specifications and robustness checks

- Accounting for other air pollutants

- Sensitivity check: alternative weather controls

- **Falsification test**: SO$_2$ on day $t$ has no effect on mortality on day $t - 1$

- **Placebo test**: random wind direction produce weak first stage ($F \leq 2$)
Long-run Survival
Model: Lleras-Muney and Moreau (2022)

Health capital for individual $i$ at age $t$:

$$H_{it} = H_{i,t-1} - \delta t^\alpha + I + \varepsilon_{it}$$

where:

$$H_{i0} = H_{i0}^* \sim N(\mu_H, 1)$$

$$\varepsilon_{it} \sim N(0, \sigma_\varepsilon^2)$$
Model: Lleras-Muney and Moreau (2022)

\[ H_{it} = H_{i,t-1} - \delta t^\alpha + I + \varepsilon_{it} \]

- Death occurs when health capital falls below threshold \( H = 0 \):
  
  \[
  D_{i0} = 1 \left[ H_{i0} < H \right], \\
  D_{it} = 1 \left[ H_{it} < H \mid D_{i,t-1} = 0 \right], \ t > 0
  \]

- Simulate model for \( N \) agents \( \rightarrow \) survival curve

- Model captures a variety of real-world mortality dynamics
  - Mortality displacement
  - Accelerated aging
Calibrate baseline parameters using 1972 period life table

Life expectancy (life table): 71.2 years
Life expectancy (model): 71.3 years
Key structural assumption for incorporating IV estimates

- Effect of pollution on model parameters depends only on current exposure
  - Effect on parameters is same for old and young
  - Effect on parameters is independent of exposure history

- Thus, we can calibrate the effect of exposure using any age group

- Testable implication: calibration from one age predicts survival for other ages
Calibrate using 1-day IV estimates

\[ H_{it} = H_{i,t-1} - \delta t^\alpha + I + \varepsilon_{it} \]
\[ D_{it} = 1 \left[ H_{it} < \tilde{H} \mid D_{i,t-1} = 0 \right] , \ t > 0 \]

Acute exposure affects mortality through two channels:

1. Raises depreciation for 1 day, \( \delta \to \tilde{\delta} \)
   - accelerated aging effect
   - calibrate using 1-day non-cancer IV estimate

2. Raises death threshold for 1 day, \( \tilde{H} \to \tilde{\tilde{H}} \)
   - mortality displacement
   - calibrate using 1-day cancer IV estimate
Calibration steps for age group $a$

1. Solve for $\tilde{H}_a$ such that 1-day mortality increases by $\hat{\beta}^1_{a,cancer}$

2. Solve for $\tilde{\delta}_a$ such that 1-day mortality effect of $\{\tilde{H}_a, \tilde{\delta}_a\}$ equals $\hat{\beta}^1_{a,all}$

Do calibration for older age groups only (65 and over)

Any pair $\{\tilde{H}_a, \tilde{\delta}_a\}$ can be used for predictions
→ Preferred estimate uses average of all older age groups
### Example: ages 65–69

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<th>Cancer-related causes</th>
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Notes: Dependent variable is deaths per million on the day of exposure.
Example: ages 65–69

IV estimates (deaths per million)

Days since exposure

0.31 (all causes)
Example: ages 65–69

(deaths per million)

Days since exposure

IV estimates

Own-age prediction
"Leave-one-out" validation: calibrate using other ages

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Example: ages 65–69

(deaths per million)

- IV estimates
- Own-age prediction
- Leave-one-out prediction

Days since exposure

1 4 7 10 13 16 19 22 25 28
Example: ages 65–69

(deaths per million)

Days since exposure

IV estimates
Own-age prediction
Leave-one-out prediction
No-displacement prediction
All-displacement prediction

0% mortality displacement

100% mortality displacement
Survival benefit of 1-unit reduction in chronic exposure

Past survival gains

Future survival gains

2023

0.25

0.5

0.75

1

1.25

1.3 yrs

1.2 yrs

0.16 yrs

Age

Aging model 1 (δ)

Aging model 2 (α)

IV extrapolation

(years)
Interpreting long-run survival estimates

- Uncertainty in IV estimates produces uncertainty in long-run estimates
  - 5th and 95th percentiles from bootstrap yield range of $[0.3, 2.2]$ years

- $SO_2$ estimates may also include effects from particulate matter

- Survival model holds behavior fixed
  - We interpret estimates as gross benefits (Graff Zivin and Neidell 2012; Currie et al. 2014)
Conclusion

- Air pollution causes mortality displacement and accelerating aging

- Permanent, 10% reduction in exposure improves life expectancy by 1.2 yrs
  - 7 times larger than extrapolation of short-run estimate
  - Benefits concentrated in ages 50+
The End
First stage: parametric sin fit for Greater Philadelphia area

SO$_2$ (ppb)

Windward direction
Sensitivity check: alternative weather controls

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<td><strong>SO₂, parts per billion</strong></td>
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<td>0.084**</td>
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<td></td>
<td>(0.014)</td>
<td>(0.013)</td>
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<td>(0.012)</td>
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<td><strong>First-stage F-statistic</strong></td>
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<td>42</td>
<td>68</td>
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<tr>
<td><strong>Mean outcome</strong></td>
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<td><strong>Sample size</strong></td>
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Weather controls

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<td>Baseline weather variables</td>
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<td>Minimum temperature variables</td>
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<tr>
<td>More granular bins</td>
<td></td>
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<td>X</td>
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Notes: Dependent variable is 1-day mortality (deaths per million).
### IV estimates: accounting for multiple air pollutants (1/2)

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<td>81</td>
<td>21</td>
<td>17</td>
<td>11</td>
<td>20</td>
<td>10</td>
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<tr>
<td>Mean outcome</td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>Sample size</td>
<td>78,946</td>
<td>78,946</td>
<td>78,946</td>
<td>78,946</td>
<td>78,946</td>
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</tbody>
</table>

Notes: Dependent variable is 1-day mortality (deaths per million).
### IV estimates: accounting for multiple air pollutants (2/2)

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
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</thead>
<tbody>
<tr>
<td>( \text{SO}_2 ), ppb</td>
<td>0.079**</td>
<td>0.035*</td>
</tr>
<tr>
<td></td>
<td>(0.014)</td>
<td>(0.015)</td>
</tr>
<tr>
<td>( \text{TSP} ), ( \mu \text{g/m}^3 )</td>
<td></td>
<td>0.019**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0045)</td>
</tr>
<tr>
<td>First-stage ( F )-statistic</td>
<td>96</td>
<td>50</td>
</tr>
<tr>
<td>Mean outcome</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Sample size</td>
<td><strong>627,304</strong></td>
<td><strong>627,304</strong></td>
</tr>
</tbody>
</table>

Notes: Dependent variable is 1-day mortality (deaths per million). A */** indicates significance at the 5%/1% level. “TSP” is total suspended particulates.
# Placebo and falsification tests

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
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</thead>
<tbody>
<tr>
<td><strong>SO₂, ppb</strong></td>
<td>-0.079</td>
<td>0.18</td>
<td>-0.041</td>
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<td></td>
<td>(0.062)</td>
<td>(0.23)</td>
<td>(0.49)</td>
<td>-0.0036</td>
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<td><strong>SO₂ on day ( t + 1 ), ppb</strong></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.0036</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.0048)</td>
</tr>
<tr>
<td><strong>Outcome window, days</strong></td>
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<td>7</td>
<td>28</td>
<td>1</td>
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<tr>
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<td>1.9</td>
<td>1.9</td>
<td>28</td>
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<tr>
<td><strong>Mean outcome</strong></td>
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<td>173</td>
<td>691</td>
<td>25</td>
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<td><strong>Sample size</strong></td>
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<td>2,023,435</td>
<td>2,023,369</td>
<td>2,031,165</td>
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<td><strong>Placebo test</strong></td>
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<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td><strong>Falsification test</strong></td>
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<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

**Notes:** Dependent variable is number of deaths per million people over a window of 1, 7, or 28 days.