International Spillover Effects of Air Pollution: Evidence from Mortality and Health Data

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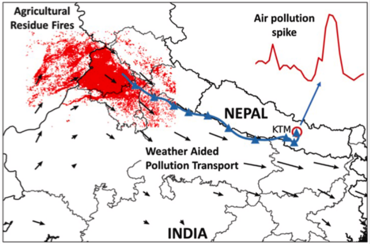
We would like to thank Keisuke Ito and David Xu for their exceptional research assistance.

International spillover effects are becoming important

AIRING ISSUES

India's noxious emissions are messing up neighbours' air, too



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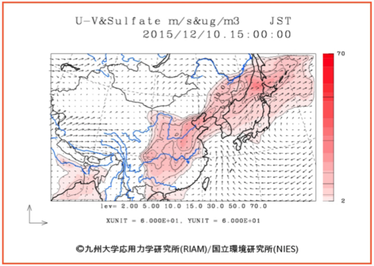
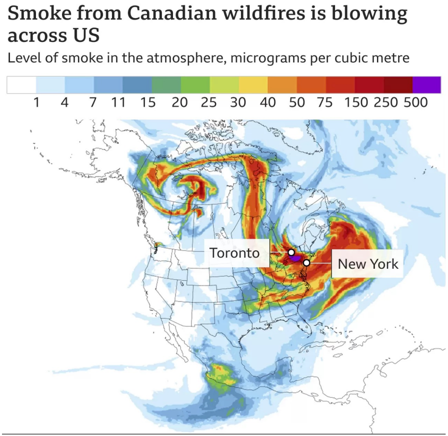
South Korea pollution: Is China the cause of 'fine dust'?

NATIONAL

Smog from Beijing may reach northern Japan



Including recent Canadian wildfires affecting US & Europe



Including recent Canadian wildfires affecting US & Europe

However, economic analysis rarely incorporate this effect

- Analyses of environmental policies usually focus on domestic benefits
  - e.g. Evaluations of environmental regulations in the United States
  - e.g. Evaluations of China's recent policy "War against pollution"
- We may have understated the benefits of environmental policies
  - e.g. China's environmental policy could benefit surrounding countries
  - In this case, conventional approaches may understate a policy's benefits
- Failure of international cooperation makes air pollution problems worse
  - Especially if countries make strategic decisions on where to emit pollution

In this paper, we study this international spillover effect

1. Integrate atmospheric science modeling with econometric estimation
   - Previous studies use indirect measures of transboundary air pollution
   - We use the HYSPLIT model to obtain direct measures at hour-city level
   - Bring these data to an econometric framework

2. Use the universe of individual-level mortality data in South Korea
   - We observe date, location, age, cause of death etc.
   - Estimate the mortality impact of transboundary air pollution

3. Quantify a hidden benefit of recent air quality improvements in China

4. Examine China's strategic pollution reductions and Coasian bargaining

Road map of the talk

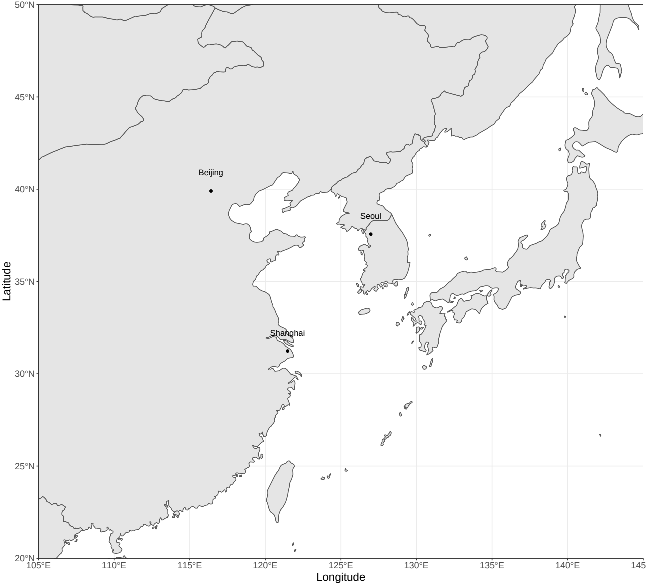
1. Introduction
2. Data and Descriptive Evidence
3. Empirical Analysis and Results
4. Strategic Reductions in Air Pollution and Policy Implications
5. Conclusion

Data and Descriptive Evidence

Data 1) $PM_{2.5}$ and weather data in China and South Korea

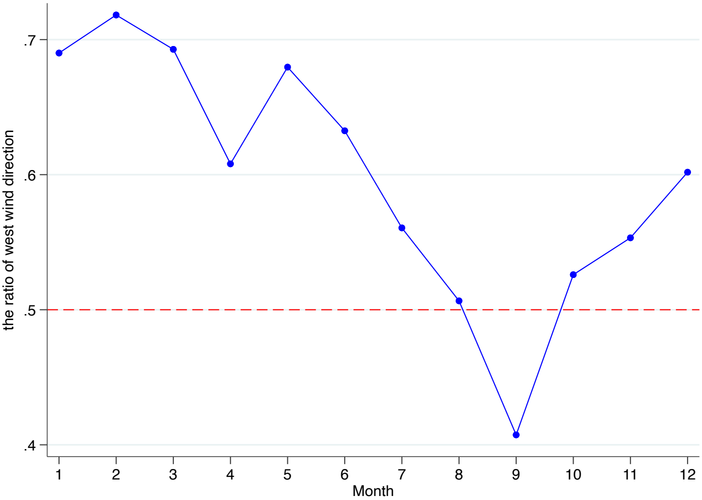
- Hourly $PM_{2.5}$ at the monitor level in China and South Korea
  - January 2015 to Decmber 2019
  - Sources: Korea Environment Corporation and Berkeley Earth
- Monitor-level weather data in South Korea
  - Source: Korea Meteorological Administration

Westerlies create strong wind from China to South Korea

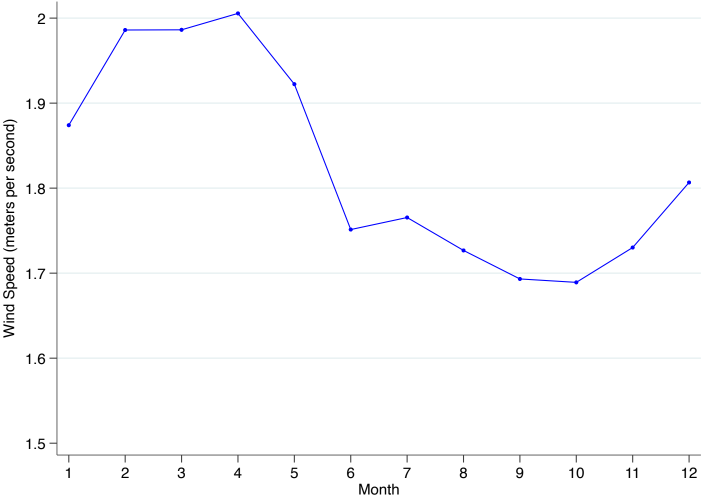


Winter and spring: Prevailing west wind in East Asia

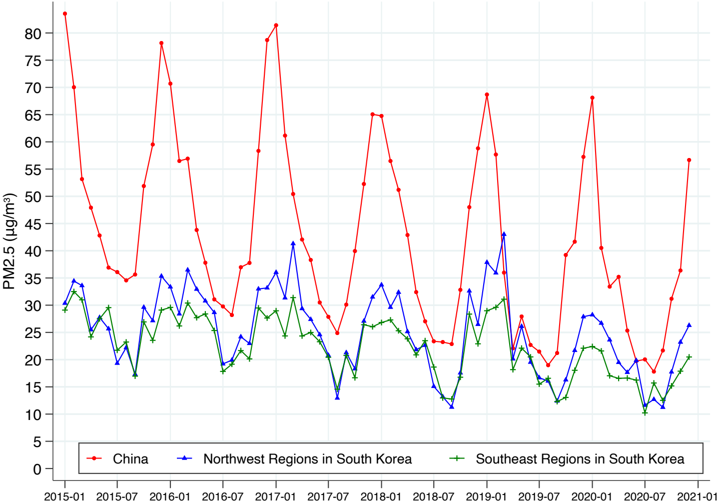
- The ratio of west wind in Seoul = west wind / (west + east wind)



Winter and spring: Wind speed is also higher



$PM_{2.5}$: Suggestive evidence of transboundary air pollution



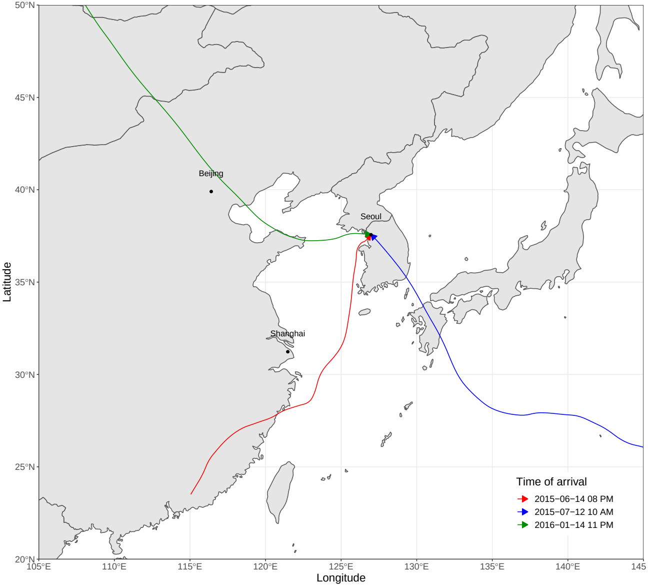
- Summer and fall: $PM_{2.5}$ is similar in NW and SW of South Korea
- Winter and spring: $PM_{2.5}$ is higher in NW than SW of South Korea

Data 2) Transboundary air pollution data from HYSPLIT

- Previous studies use indirect measures
  - e.g. an interaction between source location's pollution and wind direction

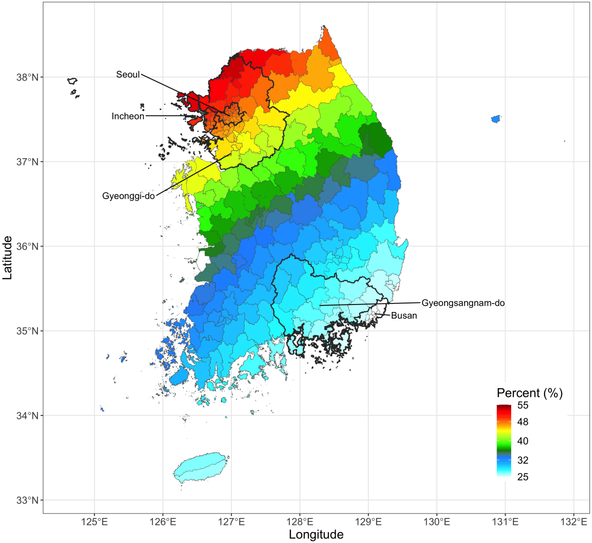
- We use NOAA's HYSPLIT model to obtain a direct measure
  1. Obtain backward particle trajectories for each hour for each city

Examples of backward trajectories



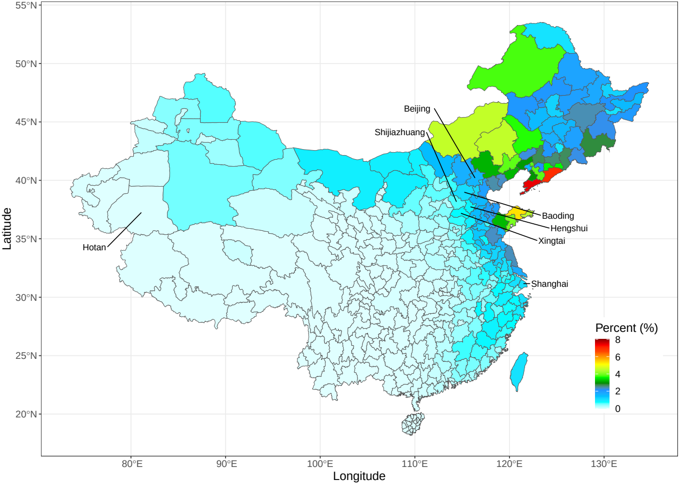
Frequency of trajectories coming from China

- For each city, we calculate % of hours that had trajectories from China



Where did these trajectories come from?

- For each city in China, we calculate % of hours that had trajectories to Korea



Data 2) Transboundary air pollution data from HYSPLIT

1. Obtain backward particle trajectories for each hour for each city
   - Need to obtain 6.57 million trajectories (24 hourly trajectories/day $\times$ 365 days/year $\times$ 5 years $\times$ 228 cities in South Korea)
2. For each trajectory, identify time and location when it hits China
   - We use 1 km height in China and check robustness with other heights
3. Identify $PM_{2.5}$ at this location (in China) and time
   - We call this $PM_{2.5}$ by "Transboundary $PM_{2.5}$"
   - i.e., Transboundary $PM_{2.5}$ is the level of $PM_{2.5}$ at the source location

Data 3) Mortality and ER visits

- The universe of mortality data in South Korea (1997-2019)
  - Date, hour, city, and cause of death. Age and gender.
  - Source: Statistics Korea
- Emergency hospital admissions in South Korea (2013-2017)
  - City-by-day data by symptoms
  - Source: National Health Insurance Service

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Empirical Analysis and Results

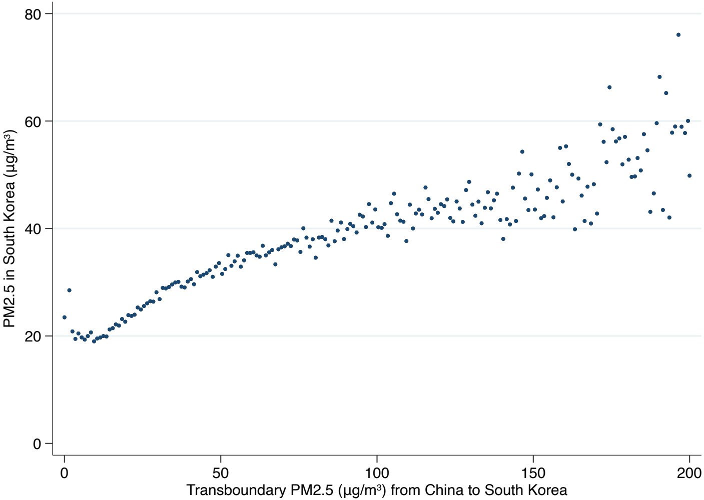
1st stage: Transboundary $PM_{2.5}$ & $PM_{2.5}$ in South Korea

$$\text{PM}_{ct} = \alpha_1 \text{TransboundaryPM}_{ct} + \alpha_2 X_{ct} + \theta_{ymc} + u_{ct}, \tag{1}$$

- Variables:
  - PM_{ct}: Hourly $PM_{2.5}$ in South Korean city c in hour t
  - $\text{TransboundaryPM}_{ct}$: Hourly transboundary $PM_{2.5}$ from China that reached South Korean city c in hour t
  - X_{ct}: A vector of control variables (weather etc.)
  - θ_{ymc}: Fixed effects (e.g., year-by-month-by-city FE)
  - We cluster standard errors at the city level

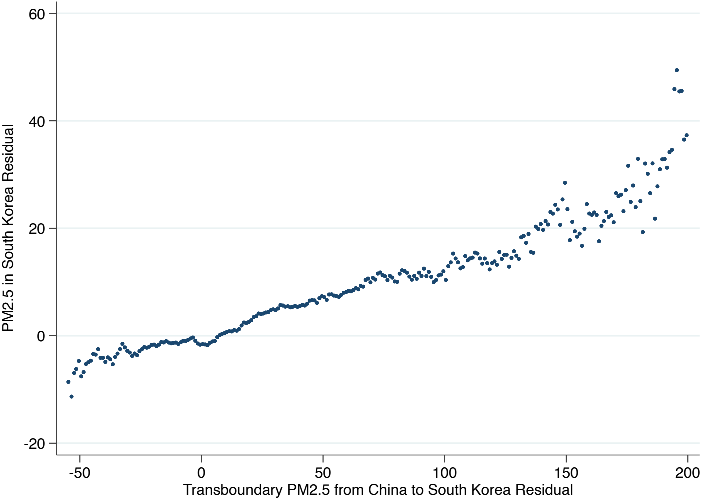
1st stage: Transboundary $PM_{2.5}$ & $PM_{2.5}$ in South Korea

- Raw data (hourly $PM_{2.5}$) with no control, with bin size = 1 unit of $PM_{2.5}$



1st stage: Transboundary $PM_{2.5}$ & $PM_{2.5}$ in South Korea

- Resisualized with fixed effects and controls used in last column of next table



1st stage: Transboundary $PM_{2.5}$ & $PM_{2.5}$ in South Korea

Dependent variable: Hourly $PM_{2.5}$ in South Korean cities

	(1)	(2)	(3)	(4)	(5)
Hourly Transboundary $PM_{2.5}$	0.170	0.129	0.129	0.129	0.122
	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	22.776				
	(0.221)				
Observations	9160118	9107025	9107025	9107025	9107025
KP F-stat	3885	5730	5819	5774	5812
Year-Month-City FE	No	No	Yes	Yes	Yes
Year-Month FE	No	Yes	No	No	No
Month-City FE	No	Yes	No	No	No
Day of week-City FE	No	Yes	Yes	Yes	Yes
Rainfall quartile-City FE	No	Yes	No	Yes	No
Temperature quartile-City FE	No	Yes	No	Yes	No
Rainfall decile-City FE	No	No	No	No	Yes
Temperature decile-City FE	No	No	No	No	Yes
Rainfall quartile FE	No	No	Yes	No	No
Temperature quartile FE	No	No	Yes	No	No

- 1 unit increase in transboundary $PM_{2.5}$ $\rightarrow$ 0.12 increase in $PM_{2.5}$ in Korea

Impacts on Mortality

Reduced-form: Transboundary $PM_{2.5}$ & Mortality

$$\text{Mortality}_{ct} = \sum_{j=0}^{J} \beta_j \text{TransboundaryPM}_{c,t-j} + \delta X_{ct} + \theta_{ymc} + u_{ct}, \qquad (2)$$

- Variables:
  - Mortality_{ct}: Hourly mortality in South Korean city c in hour t
  - $\text{TransboundaryPM}_{c,t-j}$: Hourly transboundary $PM_{2.5}$ from China that reached South Korean city c in hour $t-j$
  - X_{ct}: A vector of control variables (weather etc.)
  - θ_{ymc}: Fixed effects (e.g., year-by-month-by-city FE)
  - We cluster standard errors at the city level

Reduced-form: Transboundary $PM_{2.5}$ & Mortality

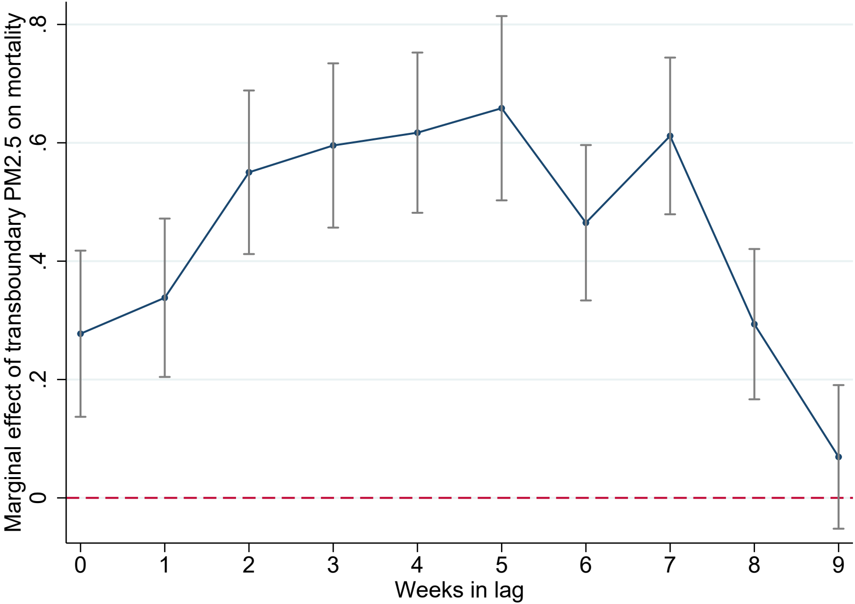
Dependent variable: Mortality at hour-city level (death per billion people)	Respiratory/ cardiovascular	Elderly	Infant	Overall
Transboundary $PM_{2.5}$ (past 0-70 days)	1.66	19.00	6.68	3.56
	(0.17)	(2.17)	(3.33)	(0.34)
Observations	9555368	9555368	9555368	9555368
Mean of dependent variable	148	3259	314	618
Marginal effect as % increase in mortality	1.1%	0.6%	2.1%	0.6%
Marginal effect on annual mortality/million	14.5	166.5	58.5	31.2

- 1 $\mu g/m^3$ increase in transboundary $PM_{2.5}$ from China in the past 70 days $\rightarrow$ an increase in hourly mortality in South Korea by 3.56 (per billion people)
- This is a 0.6% increase in mortality relative to mean hourly mortality
- This is also a 31.2 increase in mortality per million people

Reduced-form: Weekly lagged effects

	Respiratory/ cardiovascular	Elderly	Infant	Overall
Hourly Transboundary PM $_{2.5}$ (past 0-7 day)	0.14 (0.04)	1.35 (0.48)	0.90 (0.58)	0.28 (0.07)
Hourly Transboundary PM $_{2.5}$ (past 7-14 day)	0.21 (0.03)	1.93 (0.47)	0.37 (0.64)	0.34 (0.07)
Hourly Transboundary PM $_{2.5}$ (past 14-21 day)	0.25 (0.04)	3.16 (0.45)	2.02 (0.64)	0.55 (0.07)
Hourly Transboundary PM $_{2.5}$ (past 21-28 day)	0.25 (0.03)	3.59 (0.46)	-0.36 (0.59)	0.60 (0.07)
Hourly Transboundary PM $_{2.5}$ (past 28-35 day)	0.23 (0.04)	3.61 (0.49)	1.18 (0.70)	0.62 (0.07)
Hourly Transboundary PM $_{2.5}$ (past 35-42 day)	0.27 (0.04)	3.81 (0.51)	0.10 (0.69)	0.66 (0.08)
Hourly Transboundary PM $_{2.5}$ (past 42-49 day)	0.14 (0.03)	2.41 (0.44)	1.21 (0.75)	0.46 (0.07)
Hourly Transboundary PM $_{2.5}$ (past 49-56 day)	0.22 (0.03)	3.50 (0.45)	0.87 (0.70)	0.61 (0.07)
Hourly Transboundary PM $_{2.5}$ (past 56-63 day)	0.12 (0.03)	1.74 (0.40)	0.42 (0.57)	0.29 (0.06)
Hourly Transboundary PM $_{2.5}$ (past 63-70 day)	0.09 (0.03)	-0.09 (0.42)	0.67 (0.64)	0.07 (0.06)
Observations	9555318	9555318	9555318	9555318
Mean of dependent variable	148	3259	314	618

Reduced-form: Weekly lagged effects



By Age Group: Transboundary $PM_{2.5}$ & Mortality

Dependent variable: Mortality at hour-city level (death per billion people)

	Infant	1-9	10-19	20-29	30-39	40-49
Transboundary $PM_{2.5}$ (70 days)	6.68	0.18	-0.14	0.04	0.94	0.61
	(3.33)	(0.17)	(0.19)	(0.26)	(0.32)	(0.45)
Mean of dependent variable	314	12	18	42	79	169
Effect as % increase in mortality	2.1%	1.5%	-0.8%	0.1%	1.2%	0.4%
Effect on annual mortality/million	58.6	1.6	-1.3	0.3	8.2	5.3

	50-59	60-69	70-79	80-89	90-99	100-109
Transboundary $PM_{2.5}$ (70 days)	2.70	4.60	13.85	39.63	110.42	185.48
	(0.73)	(1.23)	(2.64)	(7.78)	(31.68)	(173.36)
Mean of dependent variable	364	746	2313	7324	19368	16318
Effect as % increase in mortality	0.7%	0.6%	0.6%	0.5%	0.6%	1.1%
Effect on annual mortality/million	23.6	40.3	121.3	347.1	967.3	1624.8

- We find larger impacts on infants, children, and elderly

2nd stage: $PM_{2.5}$ in South Korea & Mortality

$$\text{Mortality}_{ct} = \sum_{j=0}^{J} \beta_j \text{PM}_{c,t-j} + \delta X_{ct} + \theta_{ymc} + u_{ct}, \tag{3}$$

- Variables:
  - Mortality_{ct}: Hourly mortality in South Korean city c in hour t
  - $\text{PM}_{c,t-j}$: Hourly $PM_{2.5}$ in South Korean city c in hour $t-j$
  - Instrument = $\text{TransboundaryPM}_{c,t-j}$
  - X_{ct}: A vector of control variables (weather etc.)
  - θ_{ymc}: Fixed effects (e.g., year-by-month-by-city FE)
  - We cluster standard errors at the city level

2nd stage: $PM_{2.5}$ in South Korea & Mortality

Dependent variable: Mortality at hour-city level (death per billion people)

	Respiratory/ cardiovascular	Elderly	Infant	Overall
$PM_{2.5}$ (past 0-70 days)	4.24	48.60	17.44	9.09
	(0.47)	(5.72)	(8.63)	(0.94)
Observations	9528960	9528960	9528960	9528960
Mean of dependent variable	148	3258	314	618
Marginal effect as % increase in mortality	2.9%	1.5%	5.5%	1.5%
Marginal effect on annual mortality/million	37.2	425.8	152.8	79.7

- 1 $\mu g/m^3$ increase in local $PM_{2.5}$ in South Korea in the past 70 days $\rightarrow$ an increase in hourly mortality in South Korea by 9.09 per billion people
- This is a 1.47% increase in mortality relative to mean hourly mortality
- This is also a 79.7 increase in mortality per million people

Impacts on Emergency Room Visits

Reduced-form: Transboundary $PM_{2.5}$ & ER visits

Dependent variable: Counts of ER visits at day-city level (visit per billion people)

	Asthma	Rhinitis	Atopic
Transboundary $PM_{2.5}$ (past 0-60 days)	50.0	482.6	-2.8
	(10.2)	(54.3)	(1.6)
Observations	235388	235388	235388
Mean of dependent variable	9228.3	14053.4	363.5
Marginal effect as % increase in ER visits	0.5%	3.4%	-0.8%
Marginal effect on annual ER visits/million	18.3	176.1	-1.0

- We find increases for Asthma and Rhinitis but not for Atopic

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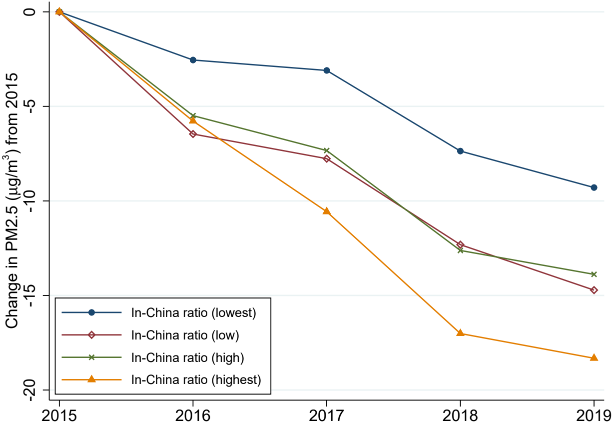
Strategic Reductions in Air Pollution and Policy Implications

Did China strategically choose where to reduce pollution?

- Hypothesis: China may prioritize pollution reductions for their citizens
  - Incentive is weaker to reduce transboundary pollution
  - Evidence was found in the water pollution litreature (Sigman, 2002; Lipscomb and Mobarak, 2016; Wang and Wang, 2021)
- Use the HYSPLIT to calculate "in-China ratio" of pollution trajectories
  - For each city & power plant, we obtain forward trajectories in each hour
  - Calculate how often this trajectory falls within China ("in-China ratio")
  - Test if the pollution reductions were correlated with "in-China ratio"

We find larger reductions where in-China ratio is higher



- Reductions in $PM_{2.5}$ ($\mu g/m^3$) from 2015 to 2019
  - Cities with quartile 1 of in-China ratio: 9.29 $\mu g/m^3$
  - Cities with quartile 4 of in-China ratio: 18.30 $\mu g/m^3$
  - ΔTransboundary $PM_{2.5}$ for South Korea: 9.63, similar to quartile 1

We find larger reductions where in-China ratio is higher

Dependent variable: Daily $PM_{2.5}$ in China at the city-level

	(1)	(2)	(3)	(4)
Annual trend	-4.29		-2.52	
	(0.12)		(0.16)	
Annual trend × in-China ratio	-8.70	-8.69		
	(0.98)	(0.98)		
Annual trend × Quartile 2 of in-China ratio			-1.71	-1.71
			(0.21)	(0.21)
Annual trend × Quartile 3 of in-China ratio			-1.70	-1.71
			(0.28)	(0.28)
Annual trend × Quartile 4 of in-China ratio			-3.52	-3.51
			(0.36)	(0.36)
N	1328053	1328026	1328053	1328026
Mean of dependent variable	47.83	47.83	47.83	47.83
City FE	Yes	Yes	Yes	Yes
Time FE	No	Yes	No	Yes

- Standard errors are clustered at the city level

What does this strategic reduction imply?

1. International spillover effects are affected by the strategic reduction
   - South Korea benefited from the spillover but potentially less
2. We could also consider a counterfactual scenario
   - What if China was more cooperative with South Korea?
   - This could be done by a negotiation/agreement
   - Coase (1960) states that one of the challenging issues of the Coasian bargaining in practice is measuring the bargaining benefit
   - We can use our results to estimate the benefit of such cooperation

International spillover benefits from pollution reductions

- We age-specific mortality impacts of transboundary pollution and VSLs
  - Quantify benefits ($ billion/year) for three scenarios
  - Actual: observed reductions in transboundary $PM_{2.5}$ (9.63 µg/m^3)
  - Counterfactual 1: what if it was at the China's average reduction (14.07)
  - Counterfactual 2: what if it was same as the quartile 4 of in-China ratio

	Overall	Infant < 1	Youth $1-19$	Adult $20-64$	Elderly ≥ 65
Actual:					
ΔTransboundary $PM_{2.5}$ by 9.63 µg/m^3	2.62	0.12	0.04	1.50	0.97
Counterfactual Scenario 1:					
ΔTransboundary $PM_{2.5}$ by 14.07 µg/m^3	3.83	0.18	0.05	2.19	1.41
Counterfactual Scenario 2:					
ΔTransboundary $PM_{2.5}$ by 18.3 µg/m^3	4.98	0.23	0.07	2.85	1.83

Conclusion

In this paper, we study this international spillover effect

1. Integrate atmospheric science modeling with econometric estimation
   - Previous studies use indirect measures of transboundary air pollution
   - We use the HYSPLIT model to obtain direct measures at hour-city level
   - Bring these data to an econometric framework
2. Use the universe of individual-level mortality data in South Korea
   - We observe date, location, age, cause of death etc.
   - Estimate the mortality impact of transboundary air pollution
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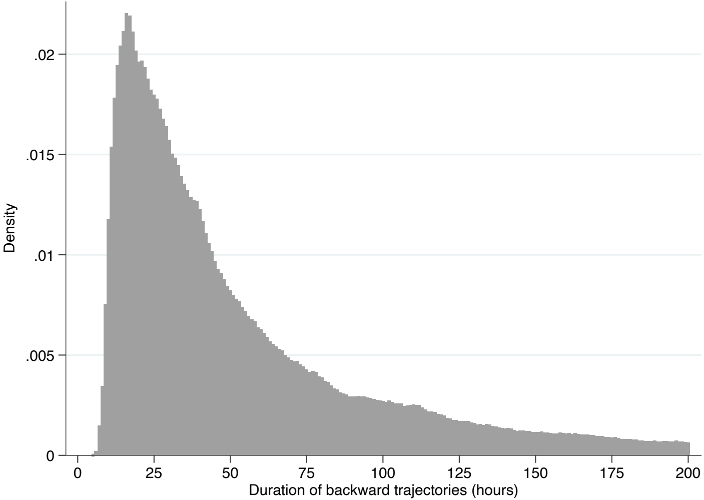
4. Examine China's strategic pollution reductions and Coasian bargaining

Appendix

How long does it take for particles to reach South Korea?



- The median is 38 hours

Table: Summary Statistics

	Mean	Standard deviation	Min	Max
$PM_{2.5}$ ($\mu g/m^3$) in Korean cities	24.99	18.06	0	843
Transboundary $PM_{2.5}$ ($\mu g/m^3$) from China to Korean cities	14.19	27.53	0	695
Transboundary trajectory indicator variable (1 or 0)	0.39	0.49	0	1
Mortality in Korean cities (hourly deaths per billion)				
Overall	894	3,800	0	200,501
Respiratory/Cardiovascular	231	1,954	0	117,689
Infant (age < 1)	327	27,702	0	14,084,507
Elderly (age ≥ 65)	3,576	14,197	0	928,505
City-level population (in thousands)				
Overall	232	240	10	1,700
Elderly (age ≥ 65)	32.16	25.27	2.10	181.83
Infant (age < 1)	1.68	1.91	0.03	12.92
Hourly Temperature (°C)	13.01	10.43	-25.27	40.50
Hourly Precipitation (mm)	0.13	1.00	0	109.50