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

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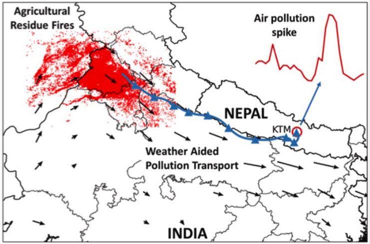
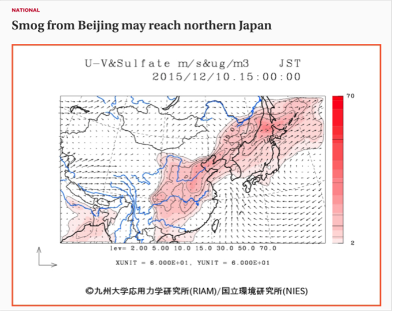
International spillover effects are becoming important





However, economic analysis rarely incorporate such effects

- 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

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

Road map of the talk

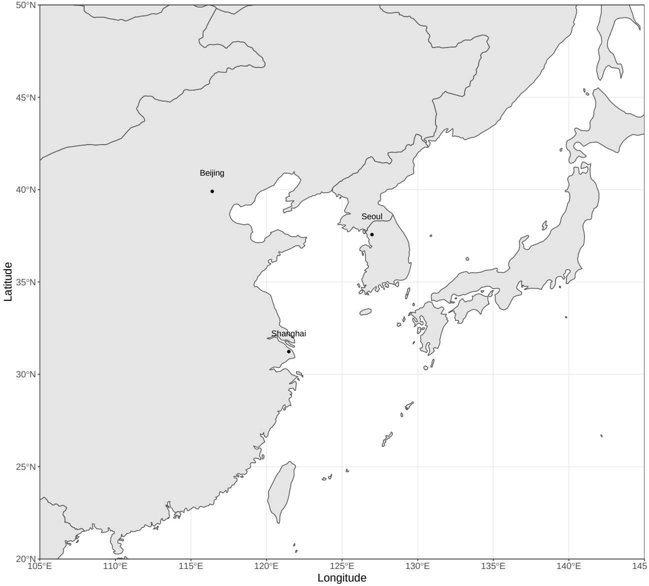
1. Data and Descriptive Evidence
2. Empirical Analysis and Results
3. Policy Implications

Data and Descriptive Evidence

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

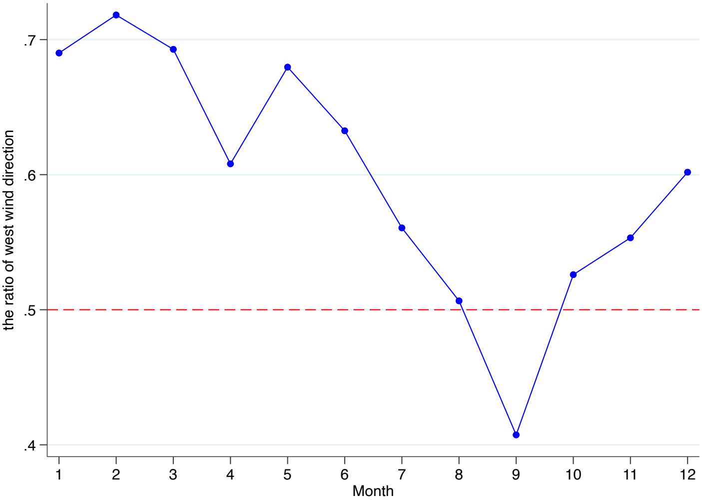
- Hourly $PM_{2.5}$ at the monitor level in China and South Korea
  - January 2015 to Decmber 2019
  - Sources: Korea Environment Corporation and Berkeley Earth
- Monitor-level weather data in South Korea
  - Source: Korea Meteorological Administration

Westerlies create strong wind from China to South Korea

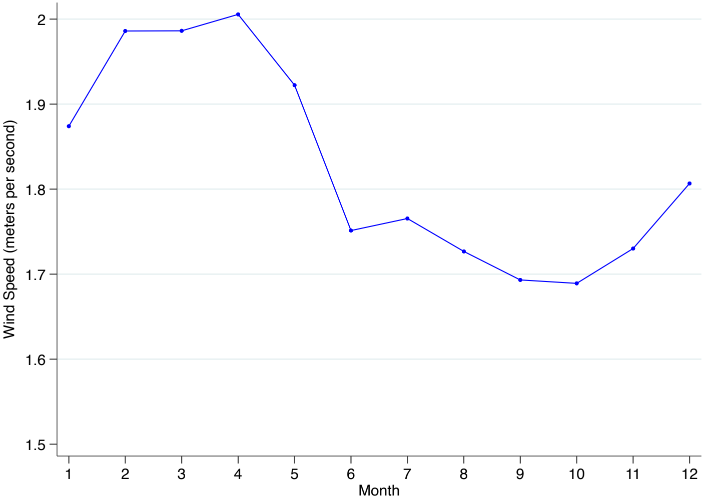


Winter and spring: Prevailing west wind in East Asia

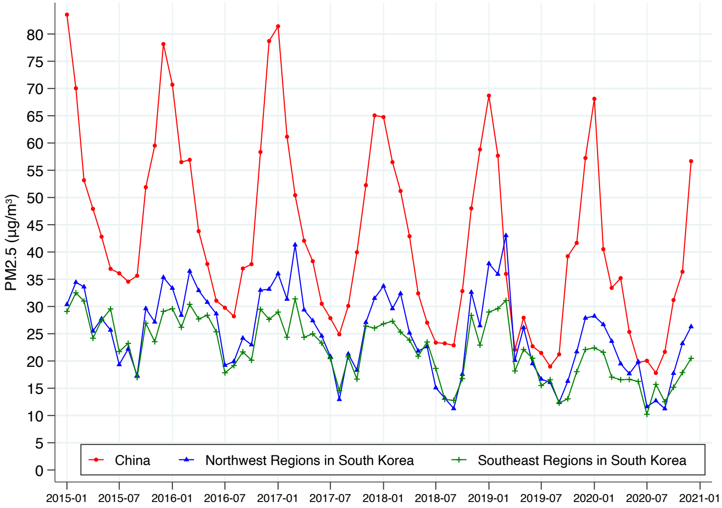
- The ratio of west wind in Seoul = west wind / (west + east wind)



Winter and spring: Wind speed is also higher



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

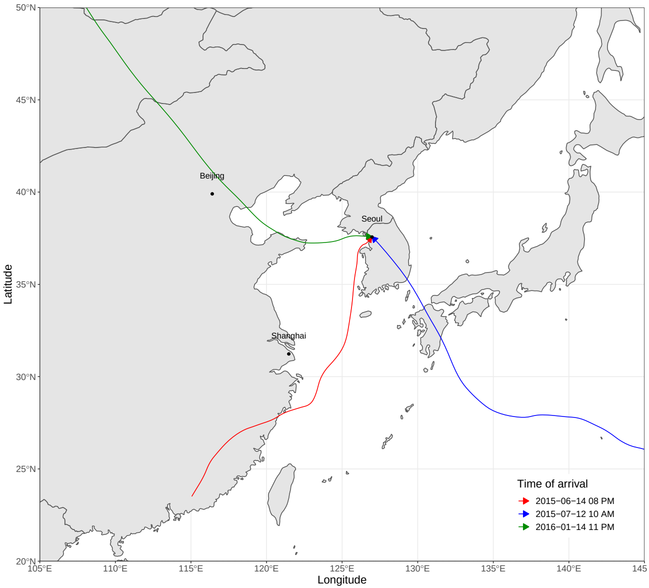


- Summer and fall: $PM_{2.5}$ is similar in NW and SW of South Korea
- Winter and spring: $PM_{2.5}$ is higher in NW than SW of South Korea

Data 2) Transboundary air pollution data from HYSPLIT

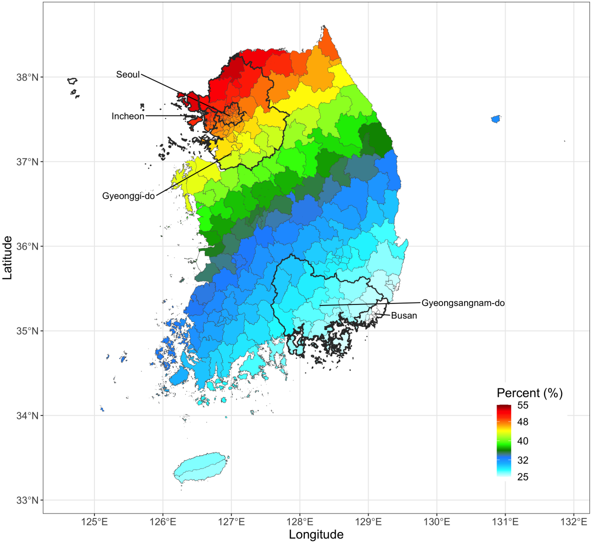
- Previous studies use indirect measures
  - e.g. an interaction between source location's pollution and wind direction
- We use NOAA's HYSPLIT model to obtain a direct measure
  1. Obtain backward particle trajectories for each hour for each city

Examples of backward trajectories



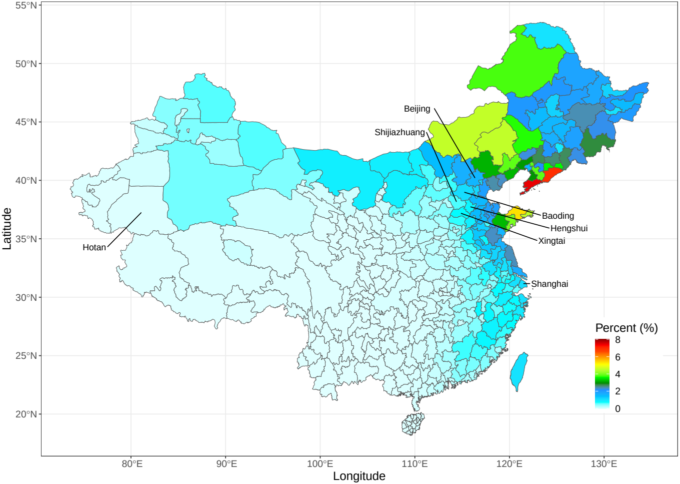
Frequency of trajectories coming from China

- 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

Road map of the talk

1. Data and Descriptive Evidence
2. Empirical Analysis and Results
3. Policy Implications

Empirical Analysis and Results

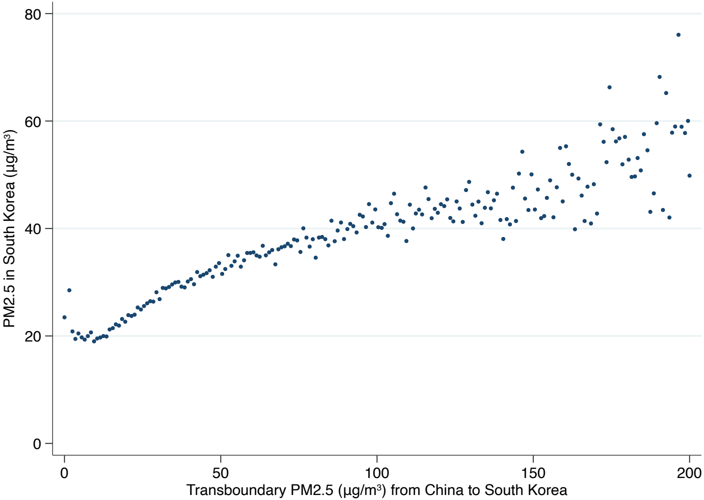
1st stage: Transboundary $PM_{2.5}$ & $PM_{2.5}$ in South Korea

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

- 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

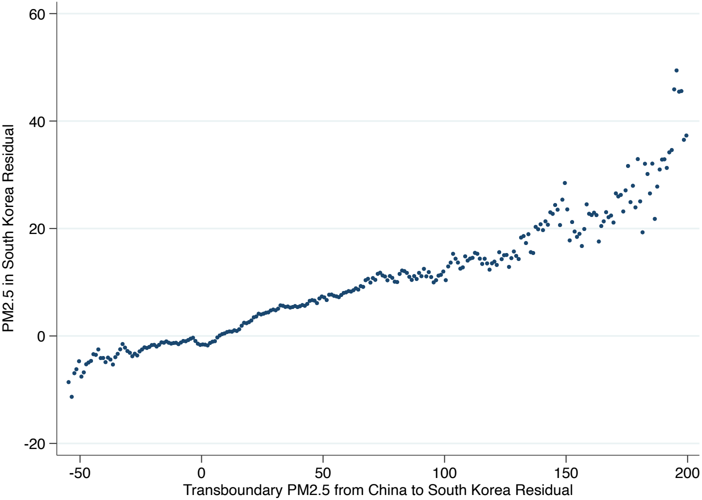
1st stage: Transboundary $PM_{2.5}$ & $PM_{2.5}$ in South Korea

- 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
Month-Province FE	No	No	No	No	No
City FE	No	No	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)

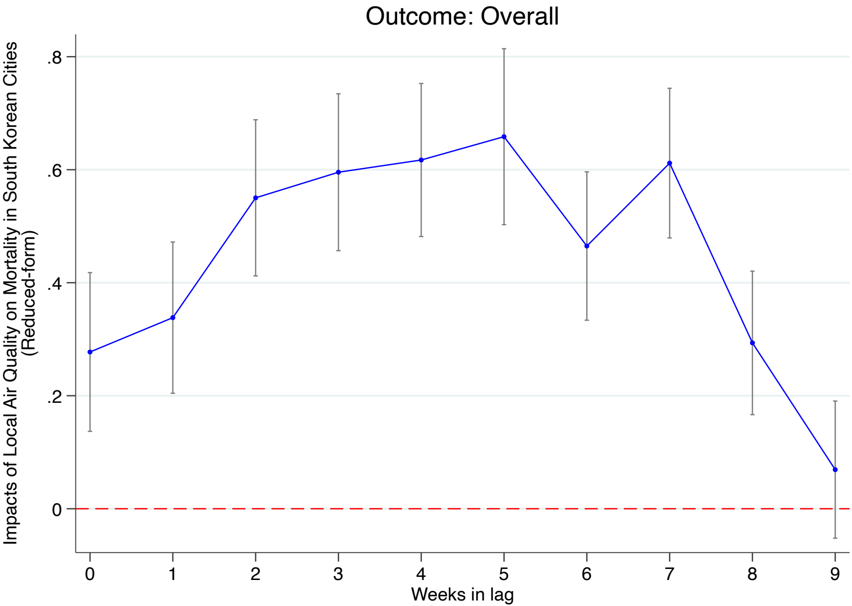
	Respiratory/ cardiovascular	Elderly	Infant	Overall
Hourly Transboundary PM $_{2.5}$	1.66	19.00	6.67	3.56
(past 0-70 days)	(0.17)	(2.17)	(3.33)	(0.34)
Observations	9555368	9555368	9555368	9555368
Mean of dependent variable	148	3259	314	618
Percent change relative to the mean	1.12	0.58	2.12	0.58

- 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

Reduced-form: Weekly lagged effects

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

Reduced-form: Weekly lagged effects



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

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

- 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
Hourly PM $_{2.5}$ (past 0-70 days)	4.24 (0.47)	48.60 (5.72)	17.44 (8.63)	9.09 (0.94)
Observations	9528960	9528960	9528960	9528960
Mean of dependent variable	148	3258	314	618
Percent change relative to the mean	2.86	1.49	5.55	1.47
KP F-stat	1816	1816	1816	1816

- 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

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
Daily Trans. $PM_{2.5}$	28.0	437.4	-3.5
(past 0-60 days)	(9.7)	(51.4)	(1.5)
Observations	235388	235388	235388
Mean of dependent variable	9228.3	14053.4	363.5
Percent change relative to the mean	0.30	3.11	-0.98

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

Suggestive Evidence on the Impact of Avoidance Behavior

Does the “pollution alert” change the damage function?

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

	Respiratory/ cardiovascular	Elderly	Infant	Overall
Hourly Transboundary PM $_{2.5}$ (past 0-70day)	2.04 (0.19)	25.46 (2.48)	5.13 (3.62)	4.47 (0.40)
Hourly Alert (past 0-70day)	-73.04 (59.64)	650.81 (758.45)	850.75 (1080.57)	176.44 (129.36)
Trans. PM $_{2.5}$ (past 0-70day) $\times$ Alert (past 0-70day)	-3.41 (2.77)	-124.71 (34.71)	-5.18 (45.80)	-20.50 (5.76)
Observations	9555368	9555368	9555368	9555368
Mean of dependent variable	148	3259	314	618

- The negative coefficient on the interaction term provides suggestive evidence that the marginal damage of pollution is reduced by the alert

Road map of the talk

1. Data and Descriptive Evidence

2. Empirical Analysis and Results

3. Policy Implications

Policy Implications (work in progress)

Policy implications

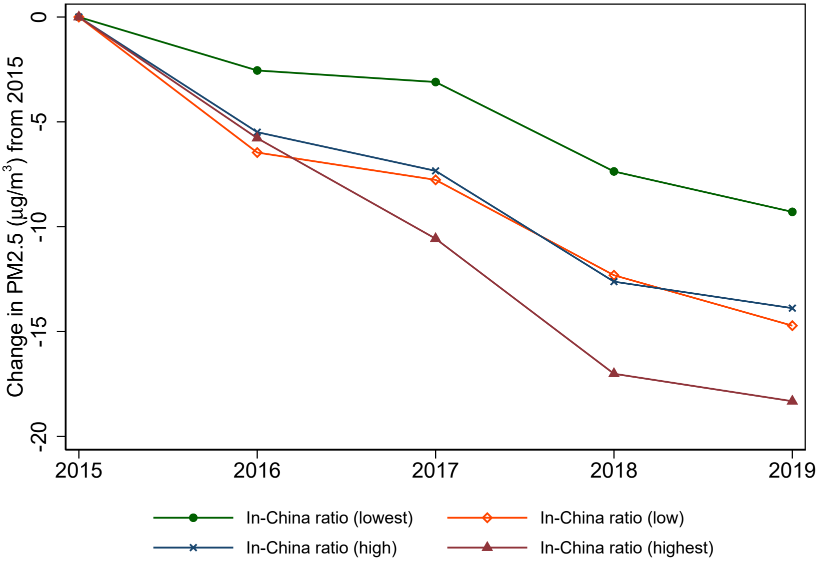
- China had a substantial improvement in air quality from 2015 to 2020
  - There was a decrease in average $PM_{2.5}$ by 10 μ/m^3
  - This is partly due to aggressive environmental policy "war on pollution"

- What is the international spillover benefit implied by our estimates?
  - One approach is to monetize our estimates by using the VSL
  - Estimate age-specific mortality impacts of transboundary pollution
  - Then use age-specific VSL estimates to obtain the values of life-years lost
  - Our current estimate implies that the 10 μ/m^3 reduction in $PM_{2.5}$ in China in 2015-20 provided an international spillover benefit of $8.05 billion per year for South Korea

Is this overestimated if China did strategic reductions?

- Hypothesis: China may have reduced pollution only for their citizens
  - China may have a weaker incentive to reduce transboundary pollution
- Use the HYSPLIT to calculate “in-China ratio”
  - 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



We find larger reductions where in-China ratio is higher

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

	(1)	(2)
Annual trend	-4.52	
	(0.12)	
Annual trend * in-China ratio	-8.15	-8.13
	(0.96)	(0.96)
Observations	235388	235388
Mean of dependent variable	47.30	47.30
City FE	Yes	Yes
Time FE	No	Yes

- Standard errors are clustered at the city level

What does this strategic reduction imply?

1. Our previous calculation was overestimated
   - We used China's average reductions in $PM_{2.5}$ (10 μ/m^3)
   - China's reductions that were relevant to South Korea was lower
   - We are updating our benefit calculation
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
   - A typical challenge: economic benefit of such cooperation is unmeasured
   - We could use our results to estimate the benefit of such cooperation

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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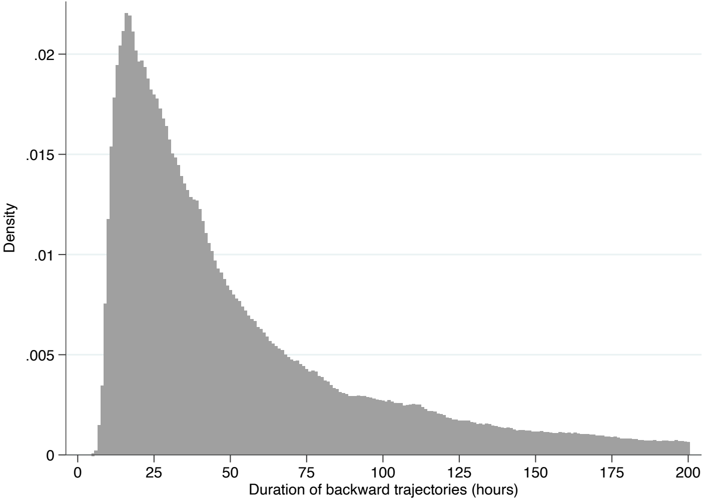
Appendix

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



- The median is 38 hours

Table: Summary Statistics

	Mean	Standard deviation	Min	Max
$PM_{2.5}$ ($\mu/$) in Korean cities	24.99	18.06	0	843
Transboundary $PM_{2.5}$ ($\mu/$) 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 ($^\circ C$)	13.01	10.43	-25.27	40.50
Hourly Precipitation (mm)	0.13	1.00	0	109.50