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IS CHINA'S POLLUTION THE CULPRIT FOR THE CHOKING OF SOUTH KOREA? EVIDENCE FROM THE ASIAN DUST*

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This paper studies the impact of air pollution spillover from China to South Korea. To isolate the effects of cross-border pollution spillover from that of locally generated pollution, we exploit within-South Korea and over-time variation in the incidence of Asian dust—a meteorological phenomenon exogenous to district–time cells in South Korea—together with temporal variations in China's air quality. We find that conditional on being exposed to Asian dust, increased pollution in China leads to increased mortality from respiratory and cardiovascular diseases in South Korean districts, with the most vulnerable being the elderly and children under five.

Economic growth, while bringing huge benefits, also has undesirable by-products such as pollution and environmental degradation. China is a prime example: its dramatic economic development was accompanied by severe air pollution that became a major threat to the health of millions of Chinese citizens (see, e.g., Chen *et al*., 2013; Zheng and Kahn, 2013, 2017; Ebenstein *et al*., 2015; Tanaka, 2015). Air pollution in China, however, is not only a domestic issue but a highly charged politico-economic one in East Asia and globally. In a recent scientific study, Lin *et al*. (2014) showed, based on data from 2006, that increased air pollution in China significantly elevates sulphate concentrations in the western U.S.A.[1] And it is reasonable to assume that the spillover impacts on nearby countries such as South Korea and Japan are even greater than for the U.S.A. Not surprisingly, China's air pollution is often blamed for the bad air quality in Seoul and Tokyo (see, e.g., Fackler, 2013; Slatter, 2013). Despite frequent public outcry in South Korea and Japan about the harmful effects of pollution spillover from China, as yet there is no direct causal evidence. This paper aims to provide evidence on the mortality impacts of Chinese pollution in South Korea, China's immediate eastern neighbour.

To establish a causal link between China's pollution and harmful effects in South Korea is not straightforward. The difficulty arises from the fact that in this region it is not just China who pollutes but also Japan (another neighbour) and South Korea itself. Moreover, emission cycles of China and South Korea may be correlated.[2] Therefore, just because the observed or measured air quality (i.e., pollution concentration) in Seoul or Tokyo increases in periods when China is more

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[1] Specifically, Lin *et al*. (2014) simulate the impact of export-related emissions in China on air quality in the U.S.A. using the GEOS-Chem model, a chemical transport model widely used in atmospheric chemistry. In contrast to the scientific literature, which is concerned mainly with understanding the spatial dispersion of chemical species based on simulations (which rely on a variety of model-specific assumptions), we focus on establishing a causal link from pollution in China to outcomes (mortality) in South Korea based on observational data and econometric techniques.

[2] In Figure 1, we plot the emission quantities of China, South Korea and Japan for major pollutants for 1970–2008.

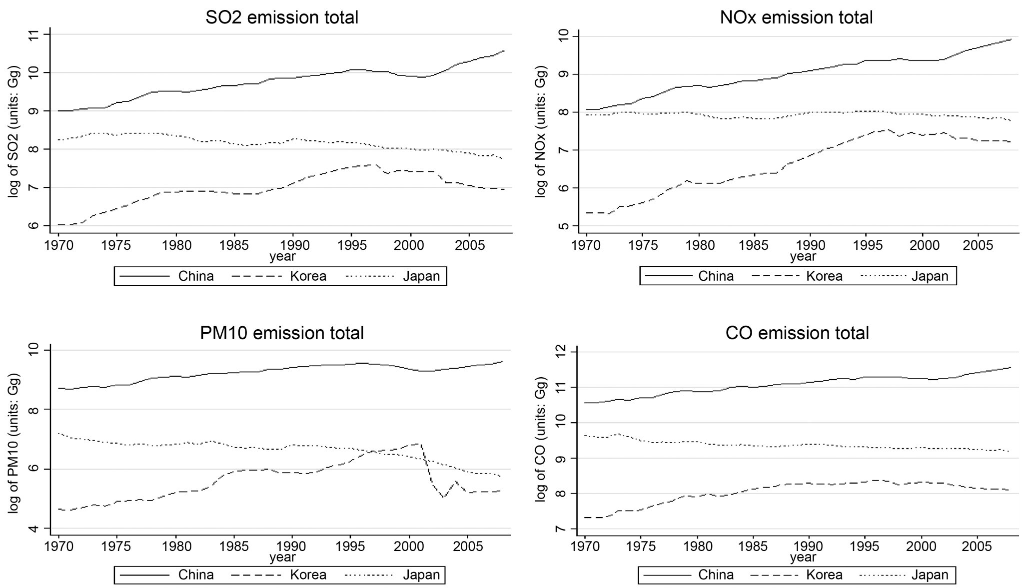


Fig. 1. *Trends in Emission Quantities in China, South Korea and Japan, 1970–2008.*
Source. Authors' calculations based on the European Commission, Joint Research Centre/PBL Netherlands Environmental Assessment Agency. Emission Database for Global Atmospheric Research (EDGAR), release version 4.2. http://edgar.jrc.ec.europe.eu, 2010 (units: Gg).

polluted, this does not mean that the pollution must have originated from China. One empirical strategy—used when studying the diffusion of pollution within relatively small local areas (e.g., Schlenker and Walker, 2016)—is to use wind directions as an identification device. One difficulty, however, is that over larger geographic areas as in our case (i.e., between China and South Korea), winds are not precisely traceable. In particular, tracing winds from the vast area of China to a specific district within South Korea is difficult and such data do not exist. Hence, when it comes to wind data, we are at best left with crude time variation (i.e., winds blowing over China), which makes it difficult to isolate China-to-South Korea pollution spillover from seasonal domestic shocks.

We propose an alternative strategy based on the phenomenon of Asian dust (also known as yellow dust or yellow sand), a meteorological event in which yellow dust clouds passing over China are carried eastwards to South Korea by strong and stable westerly winds (see Duce *et al.*, 1980; Chun *et al.*, 2001; and Bishop *et al.*, 2002, for details). Asian dust originates in the deserts of Mongolia, northern China, and Kazakhstan. Intense dust storms in the source regions, facilitated by high surface winds and low humidity, raise dense clouds of fine, dry soil particles, which are then carried eastwards by the prevailing westerlies across China, Korea, Japan and even the U.S.A. First documented in AD 174, the dust phenomena have a long history in Korea (Chun *et al.*, 2008). Before the industrialisation of China, the occurrence of Asian dust in South Korea merely signified strong westerly winds that happened to be visually salient (because of the yellow sand/dust particles blown in them). In recent decades, however, Asian dust has become an increasing public concern as scientific studies such as Choi *et al.* (2001) and

Li *et al.* (2012) suggest that Asian dust brings with it China's man-made pollution as well as its by-products.[3]

Our identification strategy is motivated by three primary features of the Asian dust occurrence. First, Asian dust has a clear directional aspect in that the wind underlying it blows from west (China) to east (South Korea), meaning that it can transport Chinese pollutants to Korea but not vice versa. Second, Asian dust is exogenous to South Korea's local activities. In particular, wind patterns and topography generate rich spatial and temporal variation in the incidence of Asian dust within South Korea and over time, for reasons unrelated to district- and time-specific local activities. Third, the occurrence of Asian dust—because of its visual salience—is monitored and recorded station by station in South Korea.[4] Such monitoring makes Asian dust a useful apparatus for determining which districts within South Korea are under the influence of China's pollution. In contrast, based on regular winds, such quantitative information on district-specific exposure to China's pollution is difficult to obtain, as variations in wind speeds and directions are highly volatile.[5]

In particular, to isolate measurable variations in South Korea's air quality that can be attributed to China, we exploit within-South Korea and over-time variations in the incidence of Asian dust together with temporal variations in China's air quality, as measured by the Air Quality Index (AQI) in 120 Chinese cities for 2000–11. Specifically, we interact the district-specific monthly incidence of Asian dust in South Korea with the intensity of China's air pollution and examine its effects on cause-specific monthly mortality in 232 South Korean districts, while conditioning on the direct effects of Asian dust and China's pollution, respectively.

We find that conditioning on the direct effects of Asian dust and China's pollution (along with a rich set of district- and time-level controls including weather), their interaction effect on South Korean mortality is significantly positive, in particular for deaths from respiratory and cardiovascular diseases (hereafter, respiratory and cardiovascular deaths). Specifically, our estimate shows that at the mean incidence of Asian dust (about one day per month), if China's average AQI increases by 12 (one standard deviation in the sample), respiratory and cardiovascular mortality rates in South Korea increase by 0.040 per 100,000, around 0.33% of the monthly mean. In contrast, we find no evidence for increased mortality due to cancer or accidents, which is unlikely to be affected by short-run variation in pollution. Looking at age group-specific effects, we find that the mortality effects are largely concentrated in children under five and the elderly, suggesting that these demographic groups are particularly vulnerable to Asian dust-induced Chinese pollution.

We next examine possible mechanisms for these outcomes. One natural explanation is that Asian dust and China's pollution elevate the pollution concentration in South Korea beyond what it would have been in the absence of spillovers from China. Although a variety of toxic materials can be carried via Asian dust (see the discussion in Subsection 1.1), we are limited to examining the impact on the common pollutants routinely measured by governments. We find

[3] See reports including 'China's Killer Yellow Dust Hits Korea, Japan' from Reuters (March 3, 2008) and 'Worries in the Path of China's Air' in the *New York Times* (December 25, 2013) for example.

[4] Appendix Figure A.1 presents a satellite image of Asian dust leaving China for Korea and Japan. When Asian dust arrives in an area, it is visible in the air.

[5] In contrast to our case, which deals with the identification of long-range pollution spillover from a large country (i.e., China) to a small country (i.e., South Korea), the exploitation of wind data can be more fruitful for research questions that address highly localised effects of pollution. See, e.g., the work of Anderson (2015) on the mortality effect of sustained downwind exposure from highways in the Los Angeles Basin.

that the interaction of Asian dust and China's pollution indeed raises the concentration of the major pollutants such as sulphur dioxide (SO_2) and nitrogen dioxide (NO_2).

One contribution of this paper is to provide concrete evidence on the mortality impacts of China's air pollution on South Korea, for which little causal evidence exists to date.[6] While our paper focuses on air pollution spillover from China to South Korea, possible harmful effects of transnational pollution spillover have been documented in other contexts previously. For instance, Almond *et al*. (2009) show that *in utero* exposure to the Chernobyl nuclear disaster in 1986 had adverse effects on Swedish children's test scores. Moreover, Black *et al*. (2013) show in the context of Norway that *in utero* exposure to radiation—due to nuclear weapon testing around the world in the 1950s and 1960s—had long-term consequences in terms of human capital and labour market outcomes. In the absence of such exogenous shocks, we focus instead on temporal variations in China's ambient air quality (which reflects China's industrial production and environmental policies) together with within-South Korea and over-time variation in the incidence of Asian dust. As an outcome, we focus on mortality, not because we think this is the only important outcome but because mortality data are consistently available for the whole of South Korea for the 12-year period we study.[7]

There exists an extensive literature on the effect of measured local pollution on local outcomes.[8] Our study is related in particular to the work of Arceo *et al*. (2016), who use the meteorological phenomenon of thermal inversions to instrument for pollution level in Mexico. The focus there is the causal impact of local pollution on local outcomes (infant mortality) in Mexico City, where thermal inversions are used as an instrument for measured concentrations of particulate matter of 10 μm or less (PM_{10}) and carbon monoxide (CO). In our case, our primary interest is in the spillover effect of China's pollution on South Korea as mediated by a variety of pollutants (including those we cannot measure), rather than in the dose–response relationship for a particular pollutant. Thus, the reduced-form estimate of Asian dust–Chinese pollution interaction on South Korean mortality is our main interest.

In addition, our study is related to recent work by Schlenker and Walker (2016), which uses the day-to-day variation in airplane taxi time in California airports to induce exogenous variation *at the point source* of pollution, and links that to morbidity outcomes in local areas (within 10 km of each airport). We, however, are dealing with the issue of long-range spillover between countries, where the source country is very large with numerous point sources of pollution (and with the point-specific quantities of emission unknown to the researchers). Diffusion models that focus on specific point sources of pollution and relatively small local areas such as in Schlenker and Walker (2016) are not suitable in our context. We instead exploit variation *at the receiving end* of the pollution spillover, based on the incidence of Asian dust across district–time cells in South Korea. This approach thus addresses the major empirical challenge posed by correlated pollution cycles between two

[6] In contrast, for within-China domestic spillovers, there exist works such as Li *et al*. (2014) and Zheng *et al*. (2014). Also, in the context of within-U.S.A. domestic spillovers, where east coast states disproportionately bear the burden of midwestern coal burning, there is abundant evidence, which has played an important role in environmental policy design in the U.S.A. (e.g., NO_X Budget Trading Program). For a recent work on within-U.S.A. air pollution externality, see Holland *et al*. (2016).

[7] Hanna and Oliva (2015), for instance, show in the context of Mexico that lowered levels of SO_2 (due to the closure of a large refinery) lead to increased labour supply. In this respect, the mortality impact we focus on may be a small part of the larger cost of pollution spillover.

[8] See Zivin and Neidell (2013) for a survey of this line of research.

countries, where the source country is significantly larger than the affected country in area size.

Finally, this paper is also related to the public health literature on the health impacts—typically, daily mortality or hospital admissions—of Asian dust per se, where the incidence of Asian dust itself is viewed as a shock (see, e.g., Kwon *et al.*, 2002; Lee *et al.*, 2007; Chan and Ng, 2011; Kashima *et al.*, 2012; Lee *et al.*, 2013, 2014; Baek *et al.*, 2017). It is worthwhile to clarify that our focus is different from this line of research. We are interested in the effect of China's air pollution on South Korea rather than in that of Asian dust itself. Since Asian dust is a meteorological phenomenon (which is not caused by China), any direct effects found of Asian dust cannot be attributed to China. Hence, our approach focuses on the interaction between China's pollution and the Asian dust phenomenon and identifies the effects of China's pollution operating via Asian dust.

The data used and our identification strategy are described in Sections 1 and 2, respectively, after which Section 3 reports the main empirical results and robustness checks. Section 4 provides some concluding comments.

1. Background and Data

As background to our analysis, we first provide a brief description of the Asian dust phenomenon. Our primary data set consists of information on the incidence of Asian dust, the number of deaths by cause, and pollution levels in both South Korea and China. Our baseline analysis focuses on monthly variation across all 232 Korean districts between 2000 and 2011. An average South Korean district is 432 km^2 in size, with a population of about 210,000. Summary statistics of the variables discussed below are presented in Table 1.

1.1. *Asian Dust and Wind Patterns*

1.1.1. *Asian dust as a carrier of pollutants*

Scientific studies have documented that China's pollution can affect South Korea during Asian dust periods in two ways. First, the dust particles and the strong winds underlying the Asian dust phenomenon can directly affect pollution levels. For instance, Park *et al.* (2003) and Lee *et al.* (2007) document that in South Korea, the levels of major pollutants, such as PM_{10}, SO_2 and NO_2, are significantly elevated during the Asian dust periods. Besides these pollutants, which governments routinely monitor, increased levels of elements such as nickel (Ni), copper (Cu), zinc (Zn), cadmium (Cd) and lead (Pb) are also found in South Korea during the dust events. As Choi *et al.* (2001) explain, if dust particles do not pick up any man-made pollutants before reaching Korea, they should consist primarily of crustal elements such as sodium (Na), magnesium (Mg), aluminium (Al), calcium (Ca), iron (Fe) and manganese (Mn). Thus the observed increase in non-crustal elements (e.g., Ni, Cu, Zn, Cd and Pb) reveals that the Asian dust must have picked up pollutants from the industrialised regions of China. Second, in travelling long distances, dust particles can also react with (Chinese) pollutants and generate other compounds that may have adverse effects on health (Choi *et al.*, 2001; Li *et al.*, 2012). In particular, Nishikawa *et al.* (1991), Carmichael *et al.* (1996) and Mori *et al.* (2003), based on aerosol samples taken in Korea and Japan, respectively, show that during the long-range transport of the wind-blown dust particles, significant amounts of sulphates and nitrates are introduced through reaction with gaseous sulphur oxides (SO_X) and nitrogen oxides (NO_X).

Table 1. *Summary Statistics.*

Variable	Mean	SD	Obs.	Source
Dust (Korea)	0.79	1.72	32,248	1
Mean AQI (China)	73.7	12.3	32,248	2
Mortality rates (Korea, per 100K)				
Respiratory and cardiovascular (all)	12.23	8.27	29,464	3
Respiratory and cardiovascular (15–34)	0.43	1.92	29,464	3
Respiratory and cardiovascular (35–54)	2.75	4.26	29,464	3
Respiratory and cardiovascular (55–74)	18.91	12.06	29,464	3
Respiratory and cardiovascular (75+)	148.22	70.61	29,464	3
Cancers	16.30	9.32	29,464	3
Accidents	4.21	3.68	29,464	3
All internal causes for infants	37.94	92.01	29,464	3
All internal causes for children under 5	8.44	17.80	29,464	3
Pollutant concentration (Korea)				
PM_{10} ($\mu g/m^3$)	66.93	25.11	27,628	4
SO_2 (ppb)	11.29	6.97	27,759	4
NO_2 (ppb)	37.91	13.59	27,772	4
CO (ppm)	0.99	0.48	27,734	4
Ozone (ppb)	43.15	74.58	27,773	4
Local weather conditions (Korea)				
Rainfall (mm)/100	1.21	1.51	31,680	1
Mean temperature (C)	13.23	9.19	31,692	1
Max temperature (C)	24.73	8.01	31,692	1
Min temperature (C)	3.01	10.83	31,692	1
Mean wind speed (m/s)	2.17	0.81	31,692	1
Max wind speed (m/s)	9.02	2.86	31,692	1
Local production (Korea)				
ln export (to the world)	16.17	2.71	31,399	5
Energy production index	74.50	37.32	32,138	3
Westerly winds (China)				
No. days w. speed over the 85th percentile	3.44	5.22	27,840	6

Notes: This table presents summary statistics for the main variables using the following data sources: 1. Korea Meteorological Administration; 2. Ministry of Environmental Protection in China; 3. Statistics Korea; 4. National Institute of Environmental Research in South Korea; 5. South Korea Customs Service; 6. National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

By focusing on the interaction between China's pollution and the Asian dust phenomenon, we aim to isolate the effect of pollution spillover that operates via the two pathways discussed above. In our approach, Asian dust is viewed as a medium by which China's pollution can exercise influence on South Koreans, and our main objective is to identify the reduced-form effect of the Asian dust–China pollution interaction on cause-specific mortality in South Korea. While the identification of pollution spillover on every possible pollutant and toxic element is beyond the scope of this study, we examine the effect on the common pollutants such as SO_2 and NO_2 that governments routinely measure.

1.1.2. *Incidence of Asian dust*

The data on the incidence of Asian dust come from the Korean Meteorological Administration (KMA), which compiled incidence records for the 2000–11 period from 28 stations across South Korea (designated by stars in Figure 2(a)). To designate an Asian dust day, the KMA first verifies that dust storms occurred in the desert regions of Mongolia and China and then uses weather maps and satellite images to track their movements towards and across Korea. The KMA confirms the storms' presence through visual observation and issues a dust storm warning when necessary

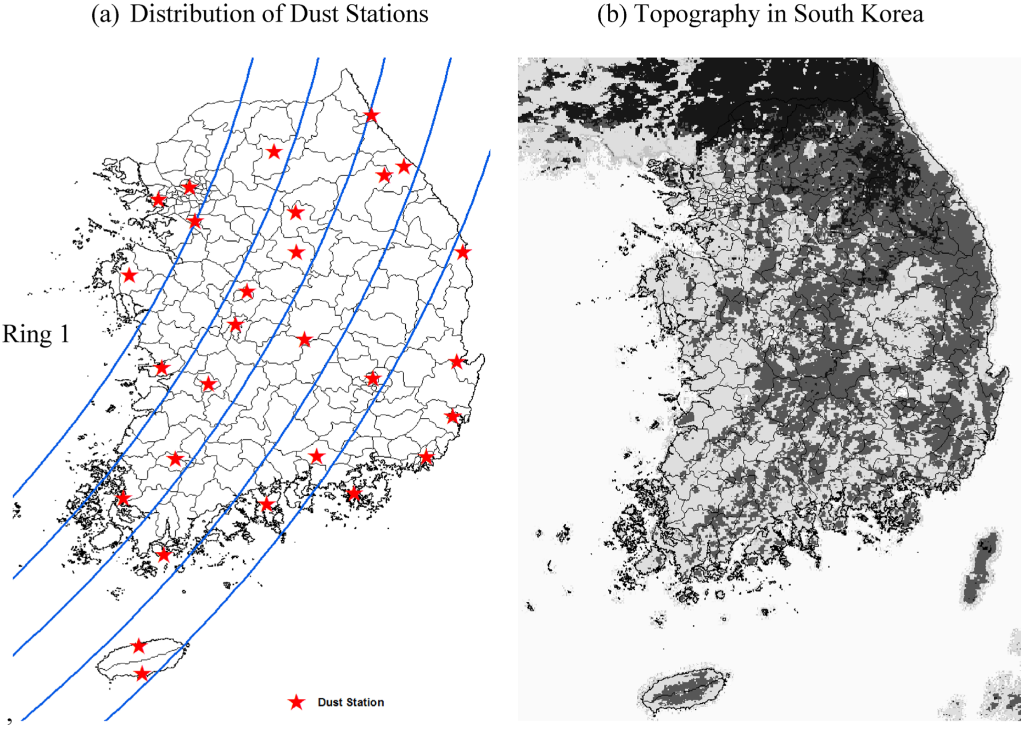


Fig. 2. *Topography and Asian Dust Stations in South Korea.*
Notes: Panel (a) maps the 28 stations where there is information on the daily incidence of Asian Dust. The arcs of concentric circles indicate different 'rings' that divide South Korean regions based on their distance from Beijing (1,000 km, 1,050 km . . . 1,200 km). Panel (b) shows that South Korea has a rich topography, which, together with idiosyncratic wind patterns, produces wide variations in the incidence of Asian dust.

(Lee *et al.*, 2013).[9] The main component of aerosols during the Asian dust events is dust particles, ranging in size from 1 to 10 μm, i.e., between the size of PM_1 and that of PM_{10} (Chun *et al.*, 2001). When Asian dust occurs, it is visible in the air. Our analysis covers 232 South Korean districts, each assigned Asian dust records from the nearest station, based on distance from the district centroid.

1.1.3. *Variation in Asian dust*

As Figure 2(b) illustrates, districts in South Korea vary greatly in topography. The wind patterns and topography of South Korea generate rich spatial and temporal variations in the incidence of Asian dust. As an example, Figure 3, which maps the incidence of Asian dust in March across three years, illustrates that the overall frequency of dust events varies significantly across years, even for the same month. Moreover, there are rich spatial variations within years. For instance, in March 2000, the western regions experienced more than five Asian dust days, whereas the eastern regions experienced around three. In March 2010, with stronger winds, the pattern was

[9] The KMA issues dust storm warnings based on PM_{10} concentrations: severe dust storms have over 400 μg/m^3 , and more-severe dust storms over 800 μg/m^3 for two continuous hours in a day. The warning can lead to some avoidance behaviour (Baek *et al.*, 2017). Our estimate should be thought of as the net effect on mortality after taking into account a possible reduction in mortality due to such avoidance behaviour.

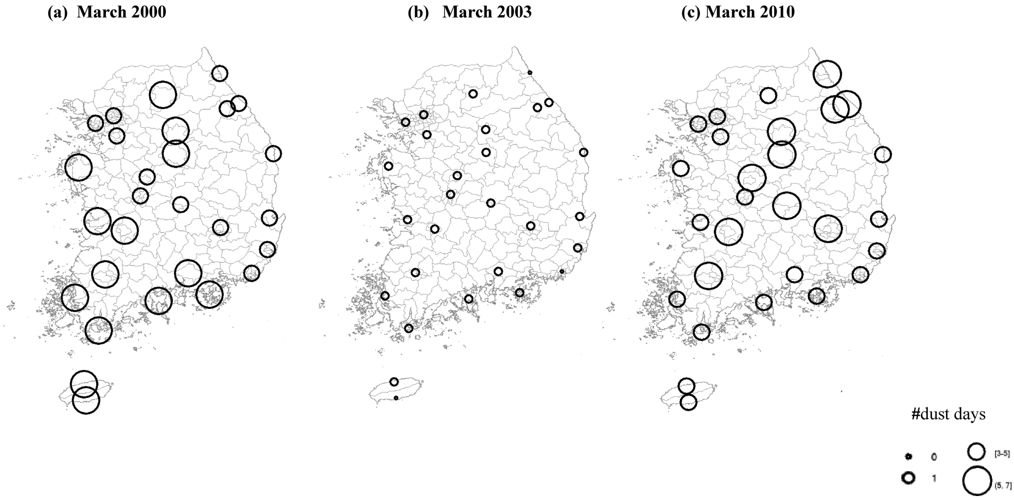


Fig. 3. *Examples of Asian Dust Variations in South Korea.*
Notes: This figure plots the distribution of dust days across dust stations in March 2000, March 2003 and March 2010. It illustrates that the incidence of Asian dust varies significantly across regions and years.

the opposite. In March 2003, all the regions were affected evenly, with an average region having one Asian dust day.

Asian dust storms also show strong (within-year) seasonality based on seasonal meteorological conditions. Figure 4(a) illustrates this seasonality by displaying the mean number of Asian dust days per month in our district-monthly data. Because of the humidity associated with the monsoon season, Asian dust never occurs in summer (June to August); thus, these months are omitted from the figure. Dust events are most frequent in spring (March to May), and the occurrence outside spring is less frequent.

1.1.4. *Asian dust and wind patterns*

To illustrate the relation between Asian dust and wind patterns, we draw on data from the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce, which include information on daily wind speed and direction collected by 499 stations located across China. Wind speed is reported in m/s, and wind direction in cardinal direction, where a wind blowing from the south (west), for example, is given as 180° (270°).

We aggregate these daily observations from the 499 stations up to a measure that can approximate the daily wind pattern over China as a whole. Specifically, to each station's daily-level observations, we assign a dummy variable of value one if the wind direction is between 180° and 360° (zero otherwise). We then treat the prevailing wind pattern over China on that day as being 'westerly' if the median of the station-daily dummies across all stations is one. In addition, we approximate the daily wind speed over China by taking the mean of station-daily data on wind speed.

We plot the distributions of daily wind speed and wind direction over China in the presence and absence of Asian dust in Figure 5. Panel (a) shows that wind speed is significantly higher on dust days than on non-dust days. The mean speed on dust days is 5.26 m/s, which is close to

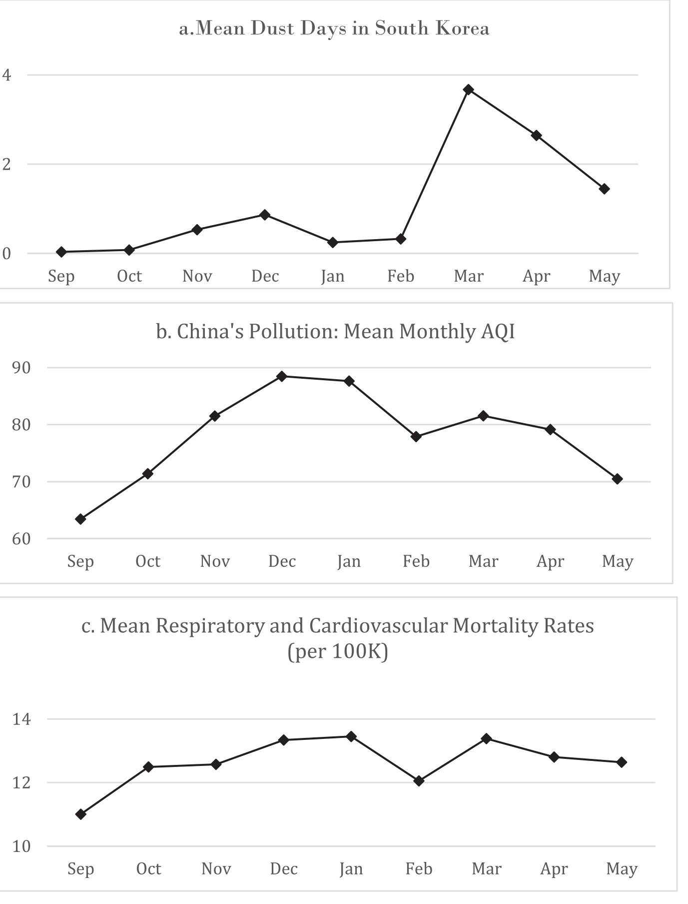


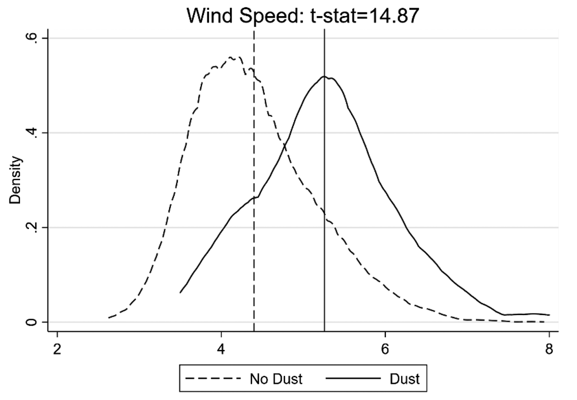
Fig. 4. *Monthly Variation in Asian Dust, Chinese Pollution and Mortality.*
Notes: This figure illustrates the monthly variation in different variables in the district-monthly data. It suggests that the seasonality of Asian dust and deaths do not coincide with each other.

the 85th percentile on the overall wind speed distribution. In panel (b) we observe that, even on non-dust days, winds over China are on average 'westerly', since the prevailing wind in these latitudes is westerly in the northern hemisphere. However, the winds are even more likely to be westerly on dust days and the difference is statistically significant. These patterns confirm that strong westerly winds are necessary (though not sufficient) for Asian dust.

1.2. *Mortality in South Korea*

The impacts of pollution on mortality are well documented, in particular regarding the sensitivity to air pollution of those with respiratory or cardiovascular diseases (see, e.g., Dockery *et al*., 1993; Samet *et al*., 2000; Zanobetti *et al*., 2003; and Dominici *et al*., 2006). Following the medical

(a) Wind speed and Asian Dust



(b) Wind direction and Asian Dust

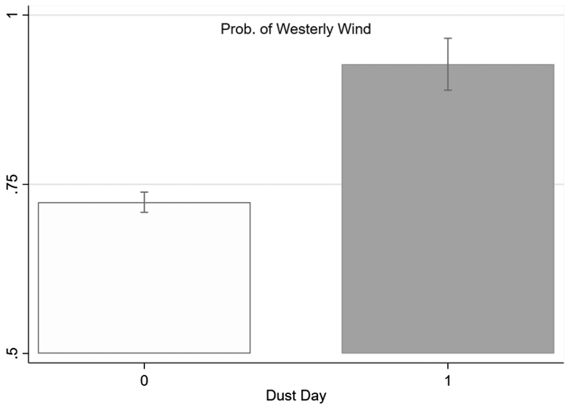


Fig. 5. *Wind Speed, Wind Direction and Asian Dust.*
Notes: Panel (a) shows that wind speed is higher on dust days. Panel (b) shows that the wind direction over China is more likely to be from west to east on dust days. The t-stats come from testing the difference in means between dust and non-dust days.

literature, our analysis focuses on respiratory and cardiovascular mortality as the key outcome of interest.

Our individual-level data on cause-specific mortality, compiled by Statistics Korea, show all deaths in South Korea on all days between 2000 and 2011. This information covers the date, place and cause of deaths, classified according to the World Health Organization's 10th revision of the International Classification of Diseases (ICD-10) as well as selective information on such characteristics as age and gender. Using these individual-level data, we construct a district-month-level data set on deaths by major causes, with a focus on respiratory (ICD-10 codes J00–J99) and cardiovascular (ICD-10 codes I00–I52) deaths. As a placebo test, we also investigate deaths from cancers (ICD-10 codes C00–C97) and accidents (ICD-10 codes V01–X59), which are unlikely to be affected in the short-run by China's pollution. In part of our analysis, we consider the differential impacts of Asian dust-induced Chinese pollution across subgroups of South Koreans by examining possible heterogeneity by age groups.

To obtain mortality rates, we denominate the count of deaths by the district-age-level population. The district-age-level population data come from South Korean censuses in 2000, 2005 and 2010. For population of intercensal years, we use linear interpolation. The mortality rate is expressed as deaths per 100,000 persons. As might be expected, deaths also exhibit seasonality, as illustrated by the monthly distributions of respiratory and cardiovascular mortality plotted in Figure 4(c). In our analysis, we always account for seasonality through the inclusion of month (of the year) fixed effects.

1.3. *Air Pollution in China*

For pollution values in China, we draw on daily information on air pollution in 120 cities across China (provided by the Ministry of Environmental Protection of China). The reported pollution information is based on the Air Quality Index (AQI), which runs from 0 to 500. The interpretation of the AQI is such that the higher the value, the greater the air pollution and concern for health.

As our baseline measure of China's influence, we use the monthly mean of the city-day-level observations of AQI. The mean and median of monthly AQI between June 2000 and December 2011 are 73.7 and 71.5, respectively, with a standard deviation of 12.3. Figure 4(b) plots our baseline measure of China's pollution across different months, illustrating that China is more polluting in winter and spring, consistent with increased wintertime pollution from coal heating (Chen *et al.*, 2013). For robustness, we also consider alternative ways of measuring China's influence: (*i*) weight AQI by distance to South Korea; (*ii*) use AQI from provincial capitals only; and *(iii*) count the share of 'polluted' cities with AQI above the sample mean. In addition, we also allow for possible non-linear effects of China's pollution on South Korea by including higher-order polynomials of China's pollution.

One possible concern is whether the AQI reported by the Chinese government is indeed informative about the true pollution condition in China. To understand whether the AQI captures meaningful variations in China's air quality, we examine the correlation between China's industrial production and our baseline pollution measure. The data on monthly production are very limited. We draw on the best available: figures from the Statistical Bureau of China on year-on-year growth of industrial value-added between 2000 and 2006. We then calculate the year-on-year change in our baseline measure of China's pollution and examine its correlation with the year-on-year growth in industrial production. As Appendix Figure A.2 shows, these two measures are significantly correlated (with a slope coefficient of 0.56 and standard error of 0.01), suggesting that our measure based on the AQI does capture meaningful variations in China's air quality.

1.4. *Local Pollution, Production and Weather in South Korea*

The data on observed (i.e., measured) pollution in South Korea—which is the combination of South Korea's locally generated pollution *and* possible pollution spillover from China—are available for 2001–11 from the National Institute of Environmental Research, which provides hourly information on the density of five major pollutants (PM_{10}, SO_2, NO_2, CO and ozone) for 147 monitoring sites. Similar to Arceo *et al.* (2016), we use the hourly measures of pollution to calculate the maximum daily 24-hour average for PM_{10} and average this over the month. For SO_2, NO_2, CO and ozone, we calculate the maximum daily 1-hour average and average that over the month. We assign the values from the nearest site to each district, based on the distance to the district centroid. The units of measurement are $\mu g/m$ for PM_{10}; ppb for SO_2, NO_2 and ozone; and ppm for CO. Using this month-level information, we examine how the interaction of Asian dust and China's pollution affects the concentration of different pollutants in a district-month.

We use two measures of local production in South Korea. First, we use data on the district-monthly export from South Korea to China and to the world for 2000 to 2011, which come from the South Korea Customs Service. Since export accounts for 30% to 55% of GDP in South Korea during this period, local export is a useful measure of local production. Second, we use the Statistics Korea data on local energy production, available at the province-month level in terms of an index, which measures the relative production level across months for each province (using the 12-month average from 2010 for that province as the benchmark = 1).

Finally, to control for the impact of local climate conditions, we use data provided by the Korean Meteorological Administration on monthly averages of daily measures of mean, maximum and minimum temperature; mean precipitation; and mean and maximum wind speed for 59 weather stations.[10] Districts are assigned the weather data from the nearest station, based on the distance from the district centroid.

2. Estimation Strategy

To identify the presence of pollution spillover from China to South Korea, we exploit the fact that the incidence of Asian dust varies within South Korea and over time for reasons unrelated to district-time-specific local activities. In particular, we examine how a given dust incidence in a district might differentially affect mortality depending on whether China happens to be more (or less) polluted at that time.

Our unit of analysis is district-month. One month is a sufficiently wide window for mortality to react. If the window of analysis is too narrow (e.g., a day), we may largely pick up 'harvesting effects' (Schwartz, 2000), namely the short-term forward shifting of the deaths of those who are on the verge of dying. On the other hand, if we make the window too wide (e.g., a year), not enough variation is left in Asian dust to exploit, and the variation in Asian dust will be difficult to isolate from other annual fluctuations.

Our main specification hence estimates the impact of Chinese pollution on district-level mortality that operates via Asian dust, *conditional on* the direct effects of Asian dust and Chinese pollution, respectively:

$$\begin{aligned} MR_{k,ym} = \gamma_0 + \gamma_1(D_{k,ym} \times CP_{ym}) + \gamma_2 D_{k,ym} + \gamma_3 CP_{ym} + \delta_1 \boldsymbol{X}_{k,ym} + \delta_2\left(D_{k,ym} \times \boldsymbol{X}_{k,ym}\right) \\ + \delta_3 \boldsymbol{W}_{k,ym} + \phi_{k,y} + \psi_{p(k),m} + u_{k,ym}, \end{aligned} \quad (1)$$

[10] Of these 59 weather stations, 28 are operated by the national government and the rest by regional governments. Asian dust data come from the 28 stations operated by the national government.

where $MR_{k,ym}$ is the cause-specific mortality rate (deaths per 100,000), and $D_{k,ym}$ the number of Asian dust days in South Korean district k in year y and month m. The variable CP_{ym} measures pollution in China in year y and month m. Our main coefficient of interest is γ_1, which measures the effect of Chinese pollution in year y and month m on mortality in South Korean district k that is exposed to Asian dust of frequency $D_{k,ym}$, conditional on the direct effects of $D_{k,ym}$ and CP_{ym}, respectively, along with the included controls described below. The parameter we estimate therefore measures the additional mortality in district k that is caused by Chinese pollution embodied in the Asian dust occurrence $D_{k,ym}$, over and above the direct effects of Asian dust and Chinese pollution, respectively.

To absorb variation in locally generated pollution and to account for other unobserved heterogeneity across districts and time, we include district-year fixed effects $\phi_{k,y}$ and province-specific month (of the year) fixed effects $\psi_{p(k),m}$ (where $p(k)$ indicates one of the 16 provinces to which district k belongs). The former accounts for district-year characteristics such as district GDP and year-average air quality as well as mortality, whereas the latter takes into consideration the seasonality of deaths and other season-specific shocks. As for the month fixed effects, rather than imposing common month effects on all districts, we allow province-specific month effects $\psi_{p(k),m}$ for districts inside province p. These effects capture the seasonality in economic activities as well as deaths that may vary across different regions.

In addition, we account for the effect of weather in a flexible functional form, as weather conditions are known to be important in determining mortality (see, e.g., Deschênes and Greenstone, 2011). In particular, we control for $\boldsymbol{W}_{k,ym}$ a vector that includes a cubic polynomial of local climatic conditions, including average, maximum and minimum temperatures; precipitation; and mean and maximum wind speeds. We also use fourth-order and fifth-order polynomials for robustness checks.

To absorb additional local variation over and beyond what is accounted for by the fixed effects and the included controls, we further control for $\boldsymbol{X}_{k,ym}$, a vector that includes district-year-month-level (log) exports to the world and a province-year-month-level energy production index.[11] Finally, to ensure that γ_1, our main coefficient of interest, captures the effect of Chinese pollution transported and distributed by Asian dust, without convolution with potential interaction effects of Asian dust and locally generated pollution, we also include the interaction of $\boldsymbol{X}_{k,ym}$ with Asian dust in our estimation.

Our strategy relies on the fact that Asian dust is a meteorological phenomenon that is exogenous to South Korea and affects different districts at different times depending on the underlying wind patterns. In Appendix Table A.1, we examine the correlation between Asian dust and local economic activities across district-time cells. As mentioned above, district-monthly economic variables are rare, but we obtained data on district-monthly exports to China and to the world, respectively. As shown in the table, the district-specific incidence of Asian dust is orthogonal to district-specific local activities (proxied by exports), in particular when we control for the climatic conditions, which is reassuring. In all regressions, we cluster standard errors at the district level.[12]

[11] District-specific (as opposed to South Korea overall) economic variables are typically available at the year level only, the effects of which are already accounted for by district-year fixed effects, $\phi_{k,y}$. The vector $\boldsymbol{X}_{k,ym}$ hence accounts for the additional effects of region-specific monthly economic activity over and beyond the effects of the fixed effects as well as the included controls.

[12] As reported in the Appendix, our results are robust to Conley (1999) standard errors.

3. Results

3.1. *Main Results*

In the tables below, we divide China's pollution measure by 12 (one standard deviation in the sample, see Table 1), so that the coefficient can be interpreted as the impact of a one standard deviation increase in China's pollution.

Table 2 reports the impacts on mortality rates from respiratory and cardiovascular diseases. According to column 1, in which Chinese pollution is not accounted for, Asian dust increases respiratory and cardiovascular mortality rates in South Korea, consistent with the findings in the public health literature focusing on the mortality effects of Asian dust per se (see, e.g., Kwon *et al*., 2002; Lee *et al*., 2007; Chan and Ng, 2011; Kashima *et al*., 2012; Lee *et al*., 2013, 2014). Columns 2 and 3 demonstrate a positive association between China's pollution and respiratory and cardiovascular mortality rates in South Korea. Interestingly, when conditioning on both Chinese pollution and Asian dust (column 3), the impact of Asian dust on mortality halves in magnitude and becomes insignificant. This is a first indication that the mortality effects of Asian dust depend on the extent of pollution in China.

Columns 4–7 present the results of our main specification, where, conditional on the direct effects of Asian dust and China's pollution, the interaction effect between Asian dust and China's pollution is estimated. The coefficient thus measures the effect of district-specific exposure to Chinese pollution induced by the unpredictable district-level occurrence of Asian dust (as the winds underlying Asian dust pass over mainland China and reach South Korea). The estimates in column 4, where we condition on district-year fixed effects and province-month fixed effects, show that the interaction of Asian dust and Chinese pollution increases the respiratory and cardiovascular mortality in affected South Korean districts. In the next columns, we add additional controls. Column 5 adds weather controls (a cubic polynomial of temperature, rainfall and wind speed measures), whereas column 6 adds controls for local production (energy and export). Column 7 allows for the effects of local production to vary with Asian dust. Overall, the estimates on the variable $D_{k,\ ym} \times CP_{ym}$ are stable across specifications, suggesting that these additional controls are only mildly correlated with the interaction between the district-specific occurrence of Asian dust and China's pollution.

As for the magnitude of the effect, consider for instance the estimate in column 7. It suggests that at the mean incidence of Asian dust in a month (about one day), if China's average AQI increases by 12 (one standard deviation in the sample), respiratory and cardiovascular mortality rates in that district increase by 0.040 per 100,000 in that month, which is about 0.33% of the mean (12.23 per 100,000, see Table 1). In absolute numbers, 0.040 more deaths per 100,000 individuals implies 20 more deaths per month, i.e., around 2,400 extra deaths over 10 years (based on a population of about 50 million in South Korea). Note that this is an estimate of China's impact on South Korea that operates via Asian dust, which itself is a rare event. Hence, it is likely a lower bound of the overall effect of China's pollution on South Korean mortality. We discuss the magnitude of our findings in comparison to other studies further below.

Since we are using a specification with interactions, interpreting the coefficient on $D_{k,\ ym}$ requires care. In column 4, for instance, the effect of dust appears significantly negative when China's AQI is set to zero. However, this information may be misleading, as China's mean AQI is never zero in reality (it ranges from 4.5 to 9.2 when normalised by the standard deviation of 12). At the minimum of China's pollution, the effect of Asian dust continues to be negative ($0.03 \times 84.5 - 0.251 = -0.08$), suggesting that when China is relatively clean, the diluting

Table 2. *The Impact of Dust×China's Pollution on Mortality Rates in South Korea.*

	(1)	(2)	(3)	(4) Baseline	(5)	(6)	(7)	(8) Placebo tests	(9)
Mean dependent var.	Mortality rates: Respiratory and cardiovascular 12.23							*Cancers 16.30*	*Accidents 4.21*
#Dust×China's mean AQI				0.038**	0.033*	0.043**	0.040**	−0.008	0.007
				(0.016)	(0.018)	(0.018)	(0.019)	(0.020)	(0.009)
#Dust	0.076***		0.039	−0.251*	−0.214	−0.313**	−0.293*	0.107	−0.041
	(0.025)		(0.032)	(0.131)	(0.142)	(0.149)	(0.154)	(0.164)	(0.071)
China's mean AQI		0.265***	0.193*	0.117	0.138	0.202*	0.200*	−0.080	0.005
		(0.081)	(0.104)	(0.105)	(0.107)	(0.110)	(0.111)	(0.121)	(0.060)
District FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province FE×Month FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather (cubic polynomial)	–	–	–	–	Yes	Yes	Yes	Yes	Yes
Local prod. (export, energy)	–	–	–	–	–	Yes	Yes	Yes	Yes
Local prod.×Dust	–	–	–	–	–	–	Yes	Yes	Yes
Observations	29,464	29,464	29,464	29,464	28,952	28,024	28,024	28,024	28,024
R-squared	0.695	0.695	0.695	0.696	0.703	0.717	0.717	0.718	0.473

Notes: This table shows that #Dust×China's mean AQI increases the mortality rates from respiratory and cardiovascular diseases but does not affect those from cancers or accidents. #Dust is the number of dust days in a district-month in Korea. China's mean AQI is divided by one standard deviation (12), so that the coefficient can be interpreted as the impact of an increase of 12 in China's AQI. Weather conditions include a cubic polynomial of the six weather variables listed in Table 1. Local production includes district-month export and province-month energy production. Standard errors are clustered at the district level. Significance levels: *** 1%, ** 5%, * 10%.

Table 3. *The Impact of Dust×China's Pollution on Mortality Rates in South Korea by Age Group.*

	(1)	(2)	(3)	(4)	(5)	(6)
Age groups	15–34	35–54	55–74	75+	Infant	Children under 5
	Respiratory and cardiovascular				All	All
Mean dependent var.	*0.43*	*2.75*	*18.91*	*148.22*	37.94	8.44
#Dust×China's mean AQI	0.005	0.012	0.104**	0.682***	0.414	0.109*
	(0.007)	(0.015)	(0.043)	(0.249)	(0.272)	(0.058)
#Dust	– 0.036	– 0.206	– 0.655	– 3.367	– 8.355**	– 1.784**
	(0.089)	(0.171)	(0.545)	(2.742)	(3.977)	(0.776)
China's mean AQI	– 0.025	0.055	0.572**	2.158	1.725	0.331
	(0.047)	(0.095)	(0.247)	(1.391)	(1.694)	(0.331)
District FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Province FE×Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather (cubic polynomial)	Yes	Yes	Yes	Yes	Yes	Yes
Local prod. (export, energy)	Yes	Yes	Yes	Yes	Yes	Yes
Local prod.×Dust	Yes	Yes	Yes	Yes	Yes	Yes
Observations	28,024	28,024	28,024	28,024	28,024	28,024
R-squared	0.118	0.180	0.324	0.351	0.119	0.114

Notes: This table shows that the elderly and very young children are particularly vulnerable to the pollution spillover. #Dust is the number of dust days in a district-month in Korea. China's mean AQI is divided by one standard deviation (12) so that the coefficient can be interpreted as the impact of an increase of 12 in China's AQI. Weather conditions include a cubic polynomial of the six weather variables listed in Table 1. Local production includes district-month export and province-month energy production. Standard errors are clustered at the district level. Significance levels: *** 1%, ** 5%, * 10%.

impact of dust (due to underlying winds) likely dominates the harmful effect (due to dust-induced Chinese pollution). In contrast, at the maximum of China's pollution, the marginal effect of Asian dust is positive ($0.03 \times 89.2 - 0.251 = 0.10$), with the coefficient more than twice as large as that in column 3. This illustrates that the effect of dust varies with the degree of pollution in China, which speaks directly to our identification strategy.

Columns 8–9 of Table 2 present two placebo tests. Specifically, we do not expect to see deaths from cancers or accidents respond to the short-run variation in pollution. As shown, mortality rates from cancers and accidents are not affected by the interaction between Asian dust and China's pollution.

3.2. *Impacts across Age Groups*

Next, we investigate the mortality impacts by different age groups, as some groups may be particularly vulnerable to pollution. We present our results in Table 3, where for the population aged 15 and above we focus on respiratory and cardiovascular mortality rates, as in the previous section. For infants and young children, we consider all internal causes of death together (as there are few deaths for each specific cause for this age group).

Columns 1–4 present the results on respiratory and cardiovascular mortality for different age groups: 15–34, 35–54, 55–74, and 75 and above. In all specifications, we condition on the full set of controls, corresponding to column 7 in Table 2. The estimates illustrate that our findings (in Table 2) on overall mortality are driven mainly by the elderly. The coefficient is the largest for those aged 75 and above, but the impact on those aged 55–74 is also sizeable. Evaluated at the mean mortality for the different age groups (see Table 1) and at the mean incidence of Asian dust (one day in a month), if China's average AQI increases by 12 (one standard deviation),

Table 4. *The Impact of Dust×China's Pollution on Pollutants in South Korea.*

	(1) SO_2	(2) SO_2	(3) NO_2	(4) NO_2	(5) CO	(6) CO	(7) Ozone	(8) Ozone
Mean dependent var.	11.29	11.29	37.91	37.91	0.99	0.99	43.15	43.15
#Dust×China's mean AQI		0.132***		0.136***		– 0.003***		– 0.060
		(0.015)		(0.027)		(0.001)		(0.045)
China's mean AQI		0.628***		1.441***		0.082***		3.077***
		(0.102)		(0.203)		(0.009)		(0.924)
#Dust	0.203***	– 0.966***	0.091**	– 2.313***	0.006**	0.013	– 1.230*	– 3.515
	(0.021)	(0.141)	(0.046)	(0.345)	(0.001)	(0.012)	(0.694)	(2.436)
District FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province FE×Month FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather (cubic polynomial)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Local prod. (export, energy)	–	Yes	–	Yes	–	Yes	–	Yes
Local prod.×Dust	–	Yes	–	Yes	–	Yes	–	Yes
Observations	27,759	27,759	27,772	27,772	27,734	27,734	27,773	27,773
R-squared	0.741	0.744	0.732	0.734	0.737	0.739	0.148	0.148

Notes: This table shows that #Dust×China's Mean AQI increases SO_2 and NO_2 in South Korea. #Dust is the number of dust days in a district-month in Korea. China's Mean AQI is divided by one standard deviation (12) so that the coefficient can be interpreted as the impact of an increase of 12 in China's AQI. Weather conditions include a cubic polynomial of the six weather variables listed in Table 1. Local production includes district-month export and province-month energy production. Standard errors are clustered at the district level. Significance levels: *** 1%, ** 5%, * 10%.

the respiratory and cardiovascular mortality rates in South Korea increase by 0.104 and 0.682 per 100,000 for those aged 55–74 and aged 75+, respectively, around 0.55% of the mean levels in both cases. In contrast, we do not find a significant effect on those aged between 15 and 54 (columns 1–2).

Column 5 of Table 3 presents the impact on infant mortality. Although it is not precisely estimated, the magnitude is large. Conditional on a dust day in a month, if China's average AQI increases by one standard deviation, infant mortality in South Korea increases by 0.414 per 100,000, around 1.09% of the mean level. Column 6 presents the impact on the under-five mortality. The impact is 0.109 per 100,000, around 1.29% of the mean level. These results suggest that very young children are particularly vulnerable to pollution, consistent with prior research focusing on infant mortality in developing countries; see, for example, Jayachandran (2009), Tanaka (2015) and Arceo *et al*. (2016).

3.3. *The Impact on Pollutants*

To explore the possible channels through which dust-induced Chinese pollution affects South Korean mortality, we now examine the effect of $D_{k,\ ym} \times CP_{ym}$ on the concentration of different pollutants. Although numerous minerals and toxic elements could be responsible (see the discussion in Subsection 1.1), we are limited to examining the effects through common pollutants such as SO_2, NO_2, CO and ozone, whose level of concentration is routinely monitored by governments. The density of PM_{10} is a criterion in the definition of an Asian dust day (see footnote 9) and is by definition highly correlated with the dust incidence.[13]

We display in Table 4 the impact of Asian dust, China's pollution, and the interaction between the two, on district-level SO_2, NO_2, CO and ozone concentrations. The specifications we

[13] The sample mean of PM_{10} concentration is 66.93. In a regression of PM_{10} on Asian dust with the same set of controls as column 1 of Table 4, the estimated coefficient on Asian dust is 5.69 with a standard error of 0.09. This says that one extra day of Asian dust in a month elevates the concentration of PM_{10} by 8.5 (5.74/66.93)% of the mean.

estimate are similar to equation (1), where we replace the mortality with pollution concentration. In columns 1, 3, 5 and 7 we condition on Asian dust only, while in columns 2, 4, 6 and 8 we condition on Asian dust, China's pollution, and their interaction (and the interaction of Asian dust with energy production and export).

Estimates in column 1 of Table 4 show that Asian dust occurrence is highly correlated with the level of SO_2. The estimate indicates that one extra day of Asian dust in a month increases the concentration of SO_2 by 0.203, about 1.80% of the mean level. As emphasised by Choi *et al.* (2001), Asian dust should be free of such pollutants, unless it has been exposed to man-made pollution on its way to South Korea. In column 2, we attempt to isolate the influence of Chinese pollution that operates via Asian dust, conditioning on the direct effects of Chinese pollution and Asian dust, respectively. The estimates suggest that SO_2 is increased by $D_{k,ym} \times CP_{ym}$, conditional on $D_{k,ym}$ and CP_{ym} as well as an extensive list of local controls. Specifically, conditional on a dust day, if China's average AQI increases by 12 (one standard deviation), SO_2 concentration in South Korea increases by 0.132, around 1.17% of the mean level. Interestingly, the effect of Asian dust alone on SO_2 now turns negative. This may be related to the fact that, if China is not polluted, the presence of the strong winds that underlie the Asian dust may dissipate any local pollution by SO_2, thus letting its level drop below the average. Columns 3–4 show a similar pattern with respect to NO_2: conditional on a dust day, if China's average AQI increases by 12, NO_2 in South Korea also increases by 0.136, around 0.36% of the mean level.

We do not find that the levels of CO or ozone are elevated by $D_{k,ym} \times CP_{ym}$ (columns 5–8). This is consistent with the existing scientific literature (see Nishikawa *et al.*, 1991; Carmichael *et al.*, 1996; Mori *et al.*, 2003; Park *et al.*, 2003; Lee *et al.*, 2007) that emphasises SO_X and NO_X as the major pollutants transported by Asian dust.

In Subsection 3.1, our baseline analysis on mortality showed that at the mean incidence of Asian dust (roughly one day per month), if China's average AQI increases by 12 (one standard deviation), respiratory and cardiovascular mortality among the general population in South Korea increases by 0.040, around 0.33% of the mean. The corresponding impact on infant mortality (see Subsection 3.2) is around 1.09% of the mean (0.414/37.94 in Table 3). Since Asian dust is capable of bringing a variety of toxic materials at the same time (including those we cannot measure, see Subsection 1.1), we cannot isolate the dose–response relationship for a single pollutant. Therefore, any figure on the relationship between an Asian dust-induced pollutant and mortality will not be the isolated impact of that pollutant (as in some other works), but the combined impact of that pollutant and all other correlated pollutants (observed and unobserved) that are brought to a district by Asian dust. With this caveat in mind, we can make a rough calculation to compare the pollutant–mortality relationship with those found in other studies.

According to the estimates in Tables 2–4, the implied elasticity of respiratory and cardiovascular mortality with respect to SO_2 and NO_2 is 0.28 (0.33/1.17) and 0.92 (0.33/0.36), respectively. In the context of the U.S.A., Anderson (2015) estimates the elasticity with respect to NO_2 to be about 0.10–0.18 for the elderly (75+). Furthermore, in the context of Germany, Luechinger (2014) estimates the elasticity of infant mortality with respect to SO_2 to be between 0.07 and 0.13, compared with our implied elasticity of 0.93 (1.09/1.17). A major difference of our study is that Asian dust carries multiple pollutants. In addition, the elasticity we identify is the effect of extra pollution brought by Asian dust, over and above Korea's local pollution (which we account for through fixed effects and other controls). As discussed in Arceo *et al.* (2016), if there is a non-linear dose–response relationship between pollution and mortality, marginal changes in pollution may be more damaging at higher levels of air pollution. Therefore, in our context, the elasticity we identify based on China's pollution (over and above Korea's local pollution) may be larger than what may be the case at lower levels of baseline pollution.

3.4. *Additional Results and Robustness Checks*

3.4.1. *The lagged impacts of pollution spillover*

Our baseline focuses on the concurrent effect of pollution spillover. It is possible that the lagged pollution spillover also affects mortality, where the link between lagged pollution spillover and current mortality rates can be positive or negative. On the one hand, there could be some persistent effect of pollution spillover, which is positive. On the other hand, if our finding is driven mainly by a harvesting effect (death displacement), we expect to see a negative correlation (i.e., a significant decrease in deaths after an initial surge). To see which effect is more important, we estimate the same regressions as in Table 2, but now include lagged Asian dust and lagged Chinese pollution and their interaction. The time period is one month, and we add lags up to three months before the current month.

In Table 5, we present specifications with different sets of controls. The concurrent effect of Asian dust-induced Chinese pollution is only slightly smaller than our estimates in Table 2. In addition, the one-month lag $D_{k,\ ym-1} \times CP_{ym-1}$ has likewise a positive impact on respiratory and cardiovascular deaths in period ym (second row), and the magnitude is similar to that using concurrent impact (as displayed in Table 2), while further lags beyond the second month are smaller and insignificant throughout.[14] Overall, the results in Table 5 suggest that a harvesting effect, if present, is likely dominated by the persistent effect of pollution beyond the first month. This in turn implies that the contemporaneous effects we estimate in Table 2 are likely a conservative estimate of the total effect.

3.4.2. *An event-study approach*

Next, we zoom in closer to the actual days of Asian dust occurrence and examine mortality effects for periods before, during and after dust episodes. We consider all the dust episodes—i.e., district-days on which Asian dust occurred—in the data and a six-week period surrounding each dust episode. The 'Post' period refers to the week of dust (0–7 days after dust), and the second and the third weeks after dust; the 'Pre' period refers to the three weeks before dust.[15] We compare the mortality patterns week-by-week when Chinese pollution is above versus below the median (AQI = 76.97) in this sample, while conditioning on the district fixed effects throughout.

We present the regression results for respiratory and cardiovascular diseases in columns 1 and 2 of Appendix Table A.2, using three weeks before dust as the reference group. Figure 6 displays the coefficients in column 1, along with the 95% confidence intervals. As shown, there is a significant increase in respiratory and cardiovascular mortality following dust episodes, whereas there are no significant pre-trends. Moreover, following a dust event, the difference between high and low Chinese pollution situations is significant only for mortality from respiratory and cardiovascular

[14] The p-values for the joint significance of the coefficients on $D_{k,ym} \times CP_{ym}$ and $D_{k,ym-1} \times CP_{ym-1}$ are 0.04, 0.06, 0.07 and 0.07 in columns 1–4 of Table 5, respectively.

[15] To ensure that these periods are mutually exclusive, the 'Pre' period only includes the district-days on which Asian dust did not occur and no dust episodes had occurred during the previous three weeks.

Table 5. *The Impacts of Lagged Spillover on Mortality.*

	(1)	(2)	(3)	(4)
Mortality rates		Respiratory and cardiovascular		
#Dust×China's mean AQI	0.035**	0.029	0.035*	0.034*
	(0.017)	(0.019)	(0.019)	(0.020)
L.#Dust×L.China's mean AQI	0.027	0.033**	0.027*	0.028*
	(0.017)	(0.017)	(0.016)	(0.016)
L2.#Dust×L2.China's mean AQ	−0.017	−0.018	−0.019	−0.019
	(0.017)	(0.018)	(0.018)	(0.018)
L3.#Dust×L3.China's mean AQ	0.004	−0.002	−0.005	−0.005
	(0.017)	(0.018)	(0.018)	(0.018)
China's mean AQI	0.093	0.110	0.177	0.184
	(0.109)	(0.109)	(0.113)	(0.114)
#Dust	−0.237*	−0.191	−0.264*	0.087
	(0.137)	(0.150)	(0.155)	(0.245)
L.China's mean AQI	−0.042	0.062	0.164	0.171
	(0.120)	(0.131)	(0.119)	(0.120)
L.#Dust	−0.173	−0.250*	−0.221*	−0.231*
	(0.135)	(0.130)	(0.128)	(0.129)
L2.China's mean AQI	−0.073	−0.087	−0.121	−0.126
	(0.107)	(0.111)	(0.112)	(0.112)
L2.#Dust	0.132	0.153	0.164	0.166
	(0.136)	(0.140)	(0.141)	(0.141)
L3.China's mean AQI	0.055	−0.003	0.024	0.029
	(0.110)	(0.113)	(0.114)	(0.114)
L3.#Dust	−0.050	0.034	0.051	0.051
	(0.144)	(0.146)	(0.140)	(0.140)
District FE×Year FE	Yes	Yes	Yes	Yes
Province FE×Month FE	Yes	Yes	Yes	Yes
Weather (cubic polynomial)	–	Yes	Yes	Yes
Local prod. (export, energy)	–	–	Yes	Yes
Local prod.×Dust	–	–	–	Yes
Observations	28,768	28,268	27,370	27,370
R-squared	0.695	0.703	0.717	0.717

Notes: This table shows that the interaction of China's pollution and dust in the previous month also matters for respiratory and cardiovascular mortality rates. #Dust is the number of dust days in a district-month in Korea. China's mean AQI is divided by one standard deviation (12) so that the coefficient can be interpreted as the impact of an increase of 12 in China's AQI. Weather conditions include a cubic polynomial of the six weather variables listed in Table 1. Local production includes district-month export and province-month energy production. Standard errors are clustered at the district level. Significance levels: *** 1%, **5%, * 10%.

diseases and not for cancer- or accident-related mortality (columns 3–6 in Appendix Table A.2), which is also consistent with our baseline analysis.

3.4.3. *Examining spillovers within South Korea*

Although we have interpreted the coefficient on $D_{k,ym} \times CP_{ym}$ as the effect of exposure to China's pollution via Asian dust, if the latter also facilitates pollution spillover within Korea, we might be overstating the impact of China. For instance, Asian dust storms (which blow from west to east) may potentially transport not only China's pollution but also pollution from the northwest part of South Korea to other South Korean districts. We conduct two checks to examine the importance of this concern.

First, we check whether pollution spillover *within* South Korea matters for our finding. We focus on the pollution-generating activities of the South Korean regions closest to China (Ring 1 in Figure 2), which include Seoul (South Korea's capital) and Incheon (a major port), as well as

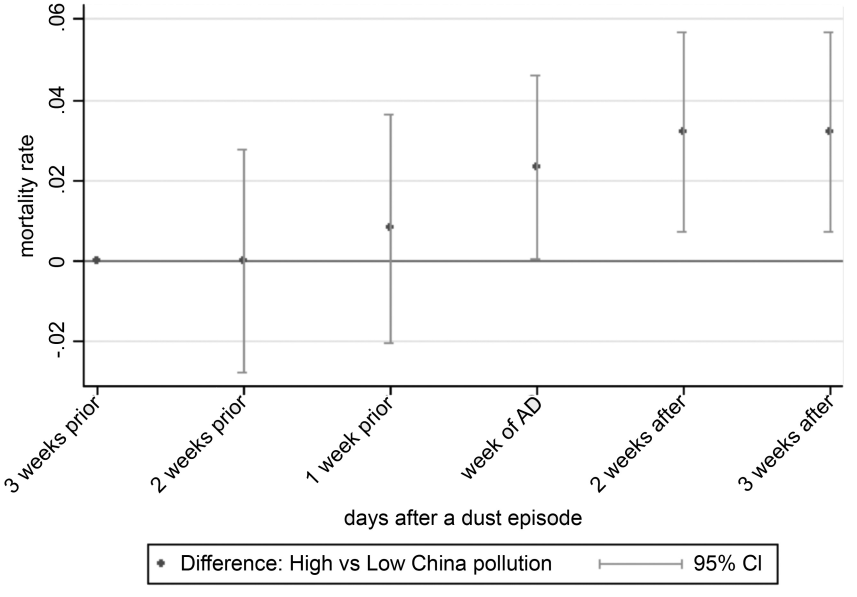


Fig. 6. *Results Using an Event-Study Approach.*

Notes: This figure plots the coefficients in column 1 of Appendix Table A.2. It compares the difference in respiratory and cardiovascular mortality rates when Chinese pollution is above vs. below the median (AQI = 76.97) in the sample for a six-week period surrounding each dust episode. It shows no significant pre-trends.

the industrial complexes surrounding these cities. We restrict our sample to all districts *outside* Ring 1 and investigate how industrial activity in Ring 1 affects mortality in all other districts that have been affected by Asian dust. In other words, we estimate regressions similar to those in (1), where now—instead of China's pollution—we use energy production in South Korea's Ring 1 as a regressor.

In column 1 of Table 6, we first re-estimate our main specification (the same specification as in column 7 of Table 2) in this subsample. The coefficient on the interaction of Asian dust and Chinese pollution is 0.055, which serves as our benchmark. Next, in column 2, we estimate a variant of equation (1) that includes the mean energy production index among districts in Ring 1 and its interaction with Asian dust. It shows that the coefficient on Ring 1's pollution is positive, suggesting that local pollution spills over irrespective of Asian dust.[16] However, the interaction effect between Ring 1's pollution and Asian dust is indistinguishable from zero, which is in contrast to the positive and significant interaction effect between Chinese pollution and Asian dust. There could be several reasons for this. First, as discussed above, Ring 1's pollution could

[16] The key sources of energy production in South Korea as of 2011 are coal (40%), nuclear (31%), natural gas (20%), oil (5%), hydropower (2%) and renewables and other sources (2%). The large share of coal in the fuel mix renders energy production one of the main contributors to South Korea's emission of sulphur oxides (SO_x) and nitrogen oxides (NO_x).

Table 6. *Checking the Role of Pollution Spillover within South Korea on Respiratory and Cardiovascular Deaths.*

	(1)	(2)	(3)	(4)
	Spillover within Korea			Korea as one region
#Dust×China's mean AQI	0.055*		0.065**	0.081*
	(0.028)		(0.029)	(0.047)
China's mean AQI	0.239*		0.312**	0.080
	(0.144)		(0.148)	(0.174)
#Dust×Korea Ring 1's energy production		0.001	0.000	
		(0.002)	(0.002)	
Korea Ring 1's energy production		0.047***	0.051***	
		(0.009)	(0.009)	
#Dust	– 0.089	0.426**	– 0.263	– 6.014
	(0.332)	(0.196)	(0.334)	(6.566)
District FE×Year FE	Yes	Yes	Yes	Yes
Province FE×Month FE	Yes	Yes	Yes	Yes
Weather (cubic polynomial)	Yes	Yes	Yes	Yes
Local prod. (export, energy)	Yes	Yes	Yes	Yes
Local prod.×Dust	Yes	Yes	Yes	Yes
Observations	20,999	20,999	20,999	127
R-squared	0.673	0.674	0.674	0.842

Notes: This table shows that our main finding is unlikely to be driven by spillover within Korea. Korea Ring 1's energy production indicates the energy production in the first ring in the west of Figure 2(a). #Dust is the number of dust days in a district-month in Korea. China's mean AQI is divided by one standard deviation (12) so that the coefficient can be interpreted as the impact of an increase of 12 in China's AQI. Weather conditions include a cubic polynomial of the six weather variables listed in Table 1. Local production includes district-month export and province-month energy production. Standard errors in columns 1–3 are clustered at the district level. Significance levels: *** 1%, **5%, * 10%.

affect other regions irrespective of Asian dust. Therefore, its potential additional effects via Asian dust may not be detectable. Second, Asian dust does not necessarily pass through Ring 1 (as illustrated in Figure 3), whereas it definitely passes through China before reaching anywhere in South Korea.[17] In column 3, we include both $D_{k,ym} \times CP_{ym}$ and the interaction effect of Ring 1's energy production and Asian dust. The coefficient on $D_{k,ym} \times CP_{ym}$ is 0.065, which is, if anything, slightly larger than in column 1. This shows that our main estimate of $D_{k,ym} \times CP_{ym}$ is indeed picking up the effect of Chinese pollution transported via Asian dust, rather than the effect of South Korea's own pollution potentially redistributed by Asian dust.

Second, to internalize any possible redistribution of pollution within South Korea—irrespective of China's impact—we estimate a specification in which the whole of South Korea is treated as a single region. Obviously, as we now pool all districts, we lose a lot of variation. As shown in column 4 of Table 6, the effect size for South Korea as a single region is comparable to the estimates from the district-month-level analysis in Table 2, although estimates are less precise. The fact that we continue to find a positive and significant interaction effect of Chinese pollution and Asian dust in this aggregate data suggests that our baseline findings from district-month-level analysis are unlikely to be due to the redistribution of South Korea's own local pollution via Asian dust.

[17] This has to do with the facts that South Korea lies to the east of both China and other source regions of Asian dust and that China is vast in area size (relative to South Korea).

3.4.4. *Possible influence of other neighbours*

So far, we have focused on the effects of China's pollution carried via Asian dust. However, Asian dust may potentially carry pollutants from other source countries such as Mongolia and Kazakhstan as well as Russia (although at the aggregate level the emission from China is far larger than that from these other countries; see the yearly emissions data in Appendix Figure A.3).[18]

To address this issue, we collect monthly pollutant data for Kazakhstan, Mongolia and Russia and examine their interaction effects with Asian dust, in a similar specification to our main analysis. The best data available (at the monthly level) are the satellite NO_2 data provided by NASA.[19] For each country, we define a dummy indicating whether its monthly NO_2 level is in the fourth quartile on the distribution (i.e., the country is relatively more polluting) and examine the effects of Higher NO_2 (by Country) $\times$ Asian Dust on mortality rates from respiratory and heart diseases in South Korea. The results are presented in Appendix Table A.3. As shown, Higher NO_2 in China $\times$ Asian Dust is associated with higher mortality rates in South Korea (column 1), consistent with our main analysis in the paper. In contrast, there is no similar pattern when using NO_2 data from the other countries (columns 2–4). Column 5 further shows that the interaction effect of China's pollution and Asian dust holds when we control for the possible effects from other countries. Therefore, our main finding is unlikely to be driven by the influence of other neighbouring countries.

3.4.5. *Measures of China's pollution and specification tests*

As our baseline measure of China's pollution condition, we use the monthly mean of city-daily observations of AQI in China. To check the robustness of our findings, we use three alternative ways to aggregate the AQI. The first is the monthly mean of AQI weighted by distance to South Korea. Specifically, for each of the 120 Chinese cities with AQI information, we calculate their nearest distance to South Korea and weight the AQI by the inverse distance. The second is the monthly mean of AQI among provincial capitals only. The data for the provincial capitals are consistently available throughout the sample period, whereas the data for other smaller cities are available only for the later periods in the sample. Therefore, focusing on the capital cities allows us to verify that our findings are not driven by the variation in information availability within China. Lastly, instead of taking the arithmetic mean of AQI, we count the monthly share of 'polluted' cities in China, i.e., the share of city-daily AQIs that are above the sample mean. This allows us to classify the data into relatively clean versus relatively polluted periods within our sample, which does not rely on the absolute 'level' of AQI.

The results are reported in Appendix Table A.4. In all columns except for column 4 (where the 'share' measure is used), the Chinese pollution measure is divided by its standard deviation so that the coefficient can be interpreted as a response to a one standard deviation increase in the relevant measure. Column 1 repeats our baseline estimates (column 7 in Table 2). The results using weighted AQI and information from provincial capitals are similar to our baseline estimates (columns 2–3). Column 4 shows the estimate based on the 'share' of city-daily AQI above the sample mean. To compare with other columns, note that a one standard deviation increase in the mean-based measure translates into a roughly 0.34 percentage point increase in the share-based

[18] Depending on pollutants, the emission level in China is 1.6 to 2.9 times as high as that in Russia, 7 to 17 times that in Kazakhstan, and 78 to 373 times that in Mongolia. Moreover, the pollution cycles of these countries are not systematically correlated with that of China.

[19] The data since 2004 are available at https://neo.sci.gsfc.nasa.gov/view.php?datasetId=AURA_NO2_M&year=2004.

measure.[20] Multiplying the coefficient 0.124 in column 4 by 0.34, we obtain 0.042, which is comparable to the effect size in columns 1–3, and our estimates in Table 2. Overall, our results are robust to different ways of aggregating China's pollution.

In addition, we conduct several specification tests. In particular, we check whether our interaction effect, $D_{k,ym} \times CP_{ym}$, might capture the non-linear effects of China's pollution on South Korea. Columns 5 and 6 present the results after controlling for a higher-order polynomial of China's pollution (3rd and 5th). If anything, the effect size becomes larger, which further indicates that our baseline estimates (Table 2) are not overstating China's impact on South Korean mortality and provide a lower bound on China's impact on South Korea.

3.4.6. *Measurement of mortality*

We use mortality rates (deaths per 100,000) in our baseline analysis. As the district-level population data are available only for the census years, we interpolate the population data. To check whether the interpolation matters, we report results from a specification where we employ log deaths as the dependent variable (Appendix Table A.5). In column 1, we directly control for log (interpolated) population on the right hand side (RHS). In column 2, we flexibly account for district-yearly population (and other) effects by including district-by-year fixed effects as additional regressors. As shown, our main coefficient of interest (Asian dust $\times$ China's pollution) remains stable in either specification, suggesting that our baseline results are unlikely to be driven by the interpolation of population.[21]

3.4.7. *Additional checks*

In our analysis so far, all the standard errors are clustered at the district level. As a robustness check, we employ Conley (1999) standard errors to allow for spatial dependence beyond individual districts. We follow the codes of Hsiang (2010) and report results based on a distance cut-off of 60 km (as implied by the distance to the first nearest neighbours in our data), 120 km and 180 km, respectively. As shown in columns 1–3 of Table A.6, standard errors are slightly larger than the estimates in Table 2, but the coefficients remain statistically significant. Our findings are also robust to excluding the three summer months where there is no Asian dust (column 4). Furthermore, they are robust to including the fourth-order and fifth-order polynomials of weather conditions instead of a cubic polynomial (columns 5–6).

3.4.8. *Results using winds*

Based on Asian dust, we focus on establishing a causal link from Chinese pollution to South Korean mortality. The key advantage of using Asian dust (interacted with pollution condition in China) is that it gives us quasi-random variation in district-specific exposure to Chinese pollution (and its by-products). Asian dust, however, is a rare natural phenomenon, occurring only on about one day a month. Therefore, while conducive to establishing a causal effect of Chinese pollution on South Korea—which is the main objective of this paper—estimates based on (district-time

[20] In the normal distribution, a probability mass of 0.68 is within one standard deviation on either side of the mean. If we increase the AQI for every city-day in that month by one standard deviation, 0.34 share will cross over to the right side of the mean, leading to an increase by 0.34 in our 'share' measure.

[21] The magnitude is comparable to our baseline: at the mean incidence of Asian dust (about one day per month), if China's average AQI increases by one standard deviation in the sample, respiratory and cardiovascular mortality in South Korea increases by about 0.3% (= exp(0.003) − 1) of the monthly mean, which is not far from what we obtain in our main analysis (0.33%).

Table 7. *Results Using Winds as a Carrier of China's Pollution.*

	(1) Mortality rates (respir. & cardio.)	(2) SO_2	(3) NO_2	(4) Mortality rates (respir. & cardio.)	(5) SO_2	(6) NO_2
#Strong west winds × China's mean AQI	0.025***	0.074***	0.051***			
	(0.009)	(0.008)	(0.015)			
#Strong east winds × China's mean AQI				− 0.023	0.013	− 0.020
				(0.031)	(0.026)	(0.051)
#Strong west winds	− 0.072	− 0.531***	− 0.731***			
	(0.091)	(0.072)	(0.164)			
#Strong east winds				0.170	0.160	1.133**
				(0.277)	(0.243)	(0.458)
China's mean AQI	0.100	0.286**	0.989***	0.391***	0.962***	0.958***
	(0.114)	(0.110)	(0.226)	(0.093)	(0.098)	(0.194)
District FE × Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Province FE × Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather (cubic polynomial)	Yes	Yes	Yes	Yes	Yes	Yes
Local prod. (export, energy)	Yes	Yes	Yes	Yes	Yes	Yes
Local prod. × Winds	Yes	Yes	Yes	Yes	Yes	Yes
Observations	26,506	25,130	25,143	26,506	25,130	25,143
R-squared	0.713	0.745	0.727	0.712	0.744	0.727

Notes: This table reports the results using winds as a carrier of China's pollution, where 'strong west (east) winds' indicates whether the mean wind speed across China on that day is at the 85th percentile or above on the distribution of wind speed in the sample, with a median wind direction being westerly (easterly). China's mean AQI is divided by one standard deviation (12) so that the coefficient can be interpreted as the impact of an increase of 12 in China's AQI. Weather conditions include a cubic polynomial of the six weather variables listed in Table 1. Local production includes district-month export and province-month energy production. Standard errors are clustered at the district level. Significance levels: *** 1%, **5%, **** 10%.

variation in) Asian dust are likely to be far lower than the overall impact of Chinese pollution on South Korea.

An alternative would be to consider strong westerly winds blowing over China, which could potentially transport Chinese pollution to South Korea. Note that unlike Asian dust, which gives us both spatial and temporal variation within South Korea, winds blowing over China provide time-series variation only. Nevertheless, to benchmark our findings, we compare the effect of Asian dust as a carrier with that of strong westerly winds blowing over China towards the Korean peninsula.[22] We define 'strong west (east) winds' as a dummy indicating whether the mean wind speed across China on that day is at the 85th percentile on the distribution of wind speed in the sample or above, with a median wind direction being westerly (easterly).[23] We then count for each month the number of days with strong west (east) winds and examine the impact of their interaction with China's pollution.

The results are reported in Table 7. Column 1 shows that at the mean occurrence of strong westerly winds (3.44 days per month), if China's average AQI increases by 12 (one standard deviation), respiratory and cardiovascular mortality rates in South Korea increase by 0.086

[22] From the perspective of South Korea, time-series variation in winds (blowing over China) is much 'cruder' than the within-Korea variation in the incidence of Asian dust. Nonetheless, the time-series variation we obtain from the wind data is likely informative in this context because the surface area of China is much larger than that of South Korea. If, on the contrary, China and South Korea were of equal sizes or if South Korea were larger than China, it may be that crude wind patterns over China alone would be insufficient in determining China's influence on the air quality in South Korea.

[23] We use the 85th percentile as the threshold because the mean wind speed on a dust day is around the 85th percentile on the wind speed distribution.

(0.025×3.44), about 0.69% of the mean or about two to three times the effect we find using Asian dust. Similar to the findings on pollutants in Table 4, we find that SO_2 and NO_2 are also elevated by strong westerly winds (columns 2–3 of Table 7). These estimates, which should be assessed with care because they rely on a far less rigorous identification design and on coarse time-series variations only, are about two to three times larger than the spillover effect operating via Asian dust. This suggests that the total effect of Chinese pollution on South Korean mortality is likely greater than the effect we isolate here based on the specific variation in Asian dust.

As a placebo test, we use the number of days with 'strong east winds' and do not find a pattern comparable to that based on 'strong west winds' (presented in columns 4–6 of Table 7), which provides further support for our hypothesis. For instance, the interaction of strong east winds and China's pollution is insignificantly correlated with respiratory and cardiovascular deaths, SO_2 and NO_2.

3.4.9. *Discussion on the magnitudes of effects*

Although (arguably) causally identified, it is not immediately obvious whether the effects we isolate via Asian dust—a rare event—are economically significant. Hence, we conduct two sets of rough calculations.

First, we monetise the mortality effects we identify via Asian dust. To monetise the health costs of pollution, the value of statistical life (VSL) is often used in the literature (e.g., Miller, 2000; Chay and Greenstone, 2003; Aldy and Viscusi, 2007). Following this approach, the mortality cost for South Korea of a one standard deviation increase in Chinese pollution is around U.S.$206 million a year, which is sizeable.[24]

Second, we try to gauge the *overall* effect of China's pollution on South Korea operating via strong westerly winds (with or without Asian dust). As shown in Table 7, 'strong westerly winds'—which mimic wind patterns of Asian dust times—are capable of transporting Chinese pollution to South Korea, thereby increasing respiratory and cardiovascular mortality. Based on 'strong westerly winds' as a carrier, we obtain a spillover effect (presented in Table 7) two to three times that identified by Asian dust alone as a carrier.

The first calculation shows that the effect of China's pollution we isolate via Asian dust is not negligible when looked at in monetary terms, even though Asian dust is a rare phenomenon. The second calculation illustrates that the overall effect of China's pollution on South Korea is likely larger than what we isolate via Asian dust alone.

4. Conclusions

In this paper, we exploit within-South Korea and over-time variation in Asian dust, a meteorological phenomenon exogenous to South Korea, to establish a causal link between China's air pollution and South Korean mortality. In particular, we examine how a given dust incidence in a

[24] The steps to get this number are as follows. A typical value of VSL is about 120 times GDP per capita (Miller, 2000). The GDP per capita in South Korea in 2000 is around U.S.$12,000, which gives us an estimate of U.S.$1.44 million (about one-third that for the U.S.A.). A literature study on VSL argues that one needs to discount this value for senior citizens and suggests a discount rate of 0.6 (Aldy and Viscusi, 2007). Since the deaths of the elderly is a major part of our findings, we consider a VSL of U.S.$0.86 million for them. This gives us an estimated VSL of U.S.$206 million due to 240 extra deaths a year associated with a one standard deviation increase in China's pollution at the mean incidence of Asian dust. Of course, this is only for the mortality effects, without considering the additional effects of pollution on such outcomes as health, productivity, labour supply, etc.

district might differentially affect mortality depending on whether China happens to be more (or less) polluted at that time.

Our findings, based on combined data sources from China, South Korea and the U.S.A., suggest that, conditional on Asian dust, China's pollution significantly increases South Korean deaths from respiratory and cardiovascular diseases—the diseases most sensitive to air pollution—but not deaths from cancers or accidents. In particular, we find that the mortality effects are largely concentrated in children under five and the elderly. Our conservative estimates show that at the mean incidence of Asian dust, if China's average AQI increases by 12 (one standard deviation in the sample), respiratory and cardiovascular mortality rates in South Korea increase by 0.040 per 100,000, or 0.33% of the mean. We conduct an extensive set of robustness checks, and, across all cases, China's pollution matters for South Korean mortality. The significance and magnitude of our findings thus shed some light on the ongoing political debate between China and South Korea.

Asian dust itself is a natural phenomenon that has been present for centuries in this region. Thus, our analysis did not use the no-Asian dust scenario as the counterfactual. Rather, our analysis focused on using variation in China's pollution while allowing for the direct effect of Asian dust occurrence on South Korea. Therefore, the spillover effect presented in this study has clear policy implications, since China's pollution is something the government of China can directly influence through its economic policies and regulations. One way to interpret the significance of our findings is to consider policy changes in China that affect China's air quality. China has been using energy-saving policies to reduce pollution during the period. Zheng *et al*. (2015) show that this policy reduces mean AQI by about 5. Had China continued to pollute as much as before those regulations, the impact of Chinese pollution on South Korean mortality *that operates via Asian dust* would have been around 1,200 extra deaths from respiratory and cardiovascular diseases during the period of 2000–11. Given that mortality we focused on here is just one of the many possible consequences of pollution, this comparison suggests that an environmental policy change in China can have impacts that reach beyond China owing to cross-border spillovers.

Appendix A

Figures A1–A3.
Tables A1–A6.

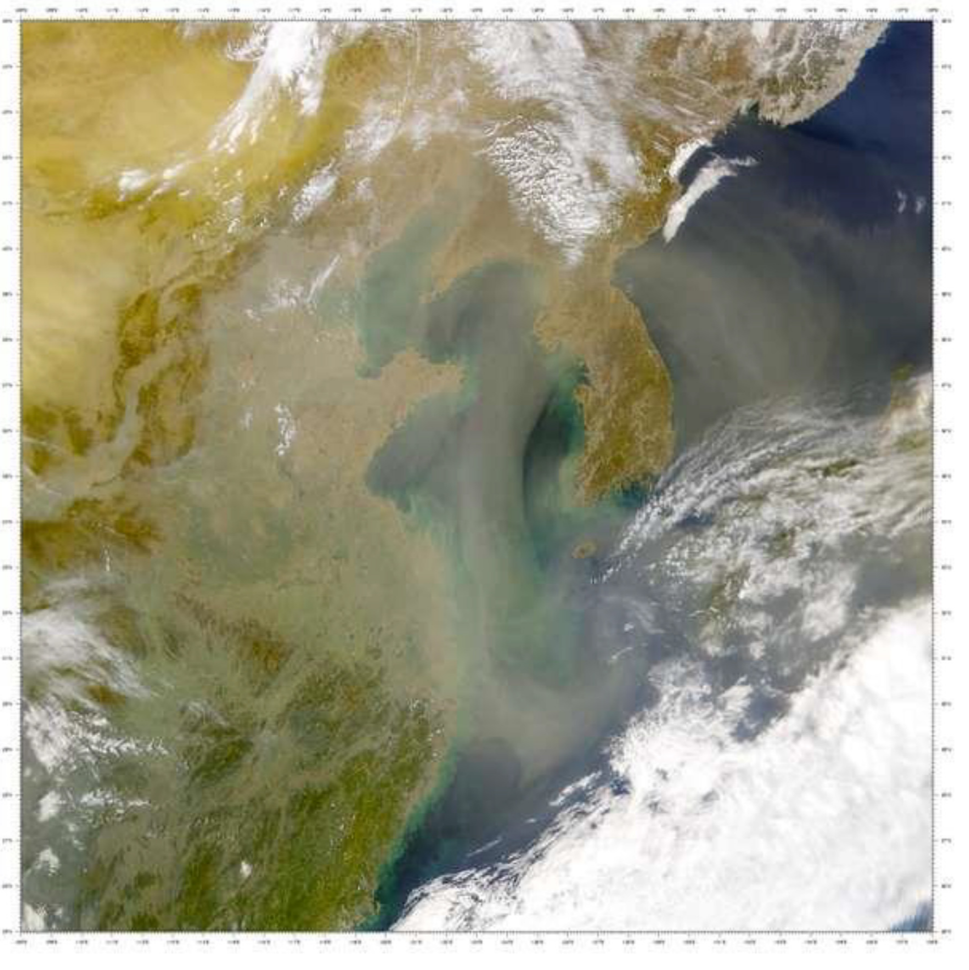


Fig. A1. *Dust Clouds Leaving China and Travelling towards Korea and Japan on March 21, 2001.*
Source. The SeaWiFS Project, NASA/Goddard Space Flight Centre, and ORBIMAGE (http://visibleearth.nasa.gov/view_rec.php?id=1707).

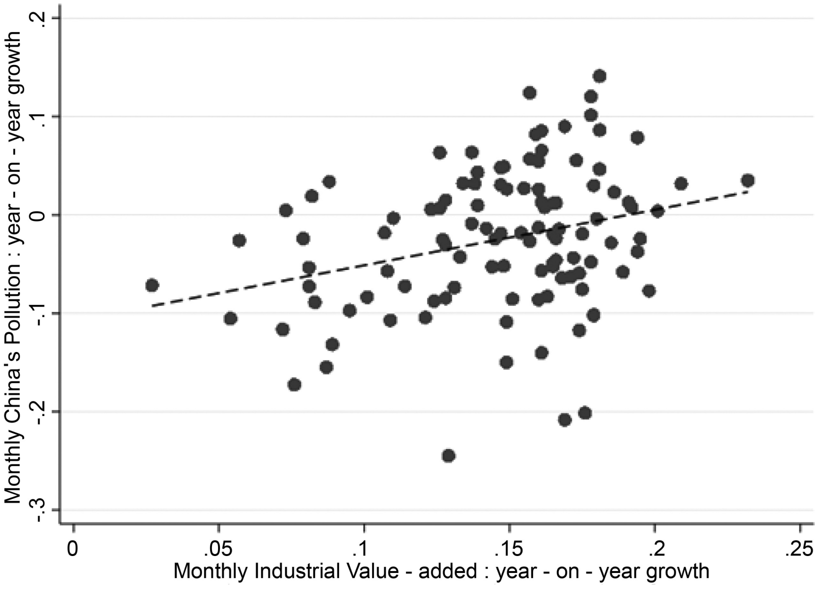


Fig. A2. *Checking Pollution Data in China.*

Notes: This figure plots the year-on-year growth of our measure of China's pollution vs. the year-on-year growth of industrial valued-added from the China Statistical Bureau. The positive correlation (with a coefficient of 0.56 and standard error of 0.01) suggests that our pollution measure captures part of the industrial production in China.

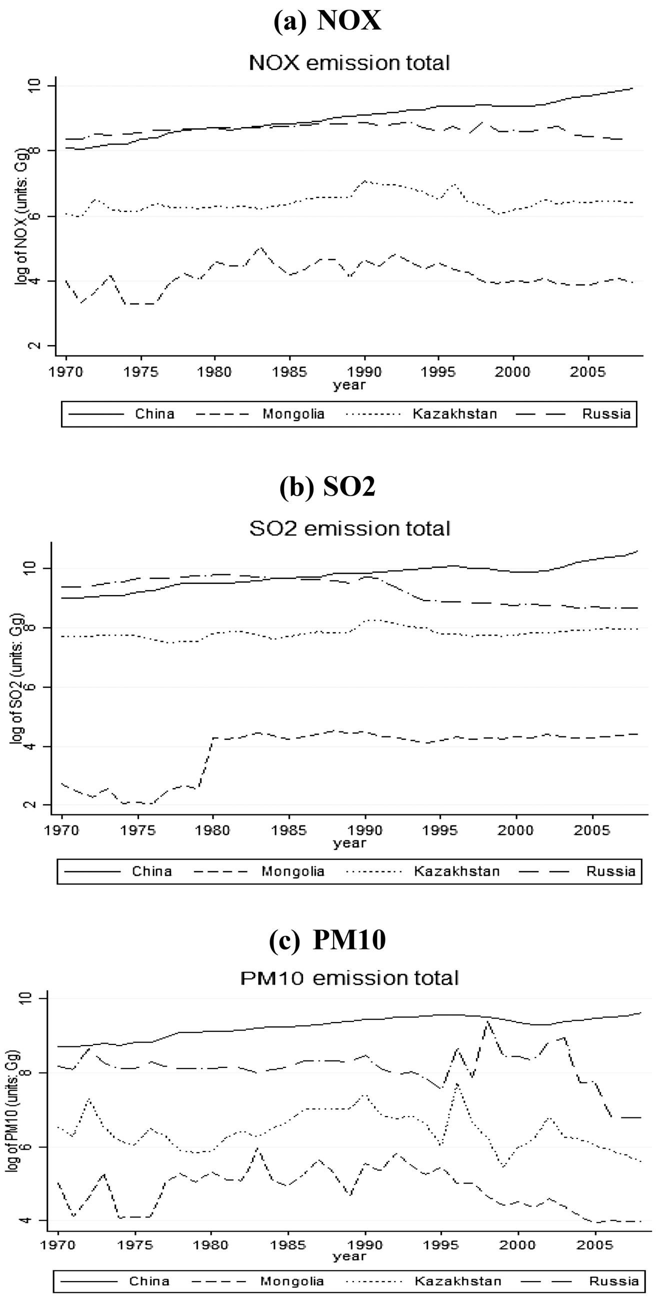


Fig. A3. *NO_X, SO_2, and PM10 Emissions by Countries.*
Source. Authors' calculations based on the European Commission, Joint Research Centre/PBL Netherlands Environmental Assessment Agency. Emission Database for Global Atmospheric Research (EDGAR), release version 4.3.2. http://edgar.jrc.ec.europe.eu.

Table A1. *Correlation between Asian Dust and Local Production.*

	(1)	(2)	(3)	(4)
	ln(Export to China)		ln(Export to world)	
#Dust×100	0.206	0.019	0.375**	0.214
	(0.281)	(0.297)	(0.188)	(0.186)
District FE×Year FE	Yes	Yes	Yes	Yes
Province FE×Month FE	Yes	Yes	Yes	Yes
Weather (cubic polynomial)	–	Yes	–	Yes
Observations	27,528	27,528	30,826	30,826
R-squared	0.947	0.948	0.970	0.970

Notes: This table shows that district-monthly Asian dust incidence is not significantly correlated with local production (proxied by exports). Weather conditions include a cubic polynomial of the six weather variables listed in Table 1. Standard errors are clustered at the district level. Significance levels: *** 1%, ** 5%, **** 10%.

Table A2. *Results from an Event-Study Approach.*

	(1)	(2)	(3)	(4)	(5)	(6)
	Mortality rates					
	Resp. & Cardio.		*Cancers*		*Accidents*	
2 weeks before AD×CPH	0.000		0.008		− 0.006	
	(0.014)		(0.016)		(0.008)	
1 week before AD×CPH	0.008		− 0.007		0.011	
	(0.014)		(0.015)		(0.007)	
Week of AD×CPH	0.023**		0.000		− 0.005	
	(0.012)		(0.013)		(0.006)	
2 weeks after AD×CPH	0.032**		0.011		0.007	
	(0.013)		(0.013)		(0.007)	
3 weeks after AD×CPH	0.032**		0.020		0.001	
	(0.013)		(0.014)		(0.007)	
Post×CPH		0.025***		0.008		− 0.002
		(0.006)		(0.007)		(0.004)
Week FE, CPH FE	Yes	Yes	Yes	Yes	Yes	Yes
District FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	313,428	313,428	313,428	313,428	313,428	313,428
R-squared	0.067	0.067	0.064	0.064	0.021	0.021

Notes: The sample includes all district-days on which Asian dust (AD) occurred and a six-week period surrounding each dust episode. Three weeks before AD is left as the reference group. CPH indicates whether Chinese pollution is above the median (AQI = 76.97) in the sample. Standard errors are clustered at the district level. Significance levels: *** 1%, ** 5%, * 10%.

Table A3. *The Importance of Other Countries.*

	(1)	(2)	(3)	(4)	(5)
Higher NO_2 (China)×#Dust	0.454***				0.469***
	(0.094)				(0.094)
Higher NO_2 (China)	0.135				0.138
	(0.150)				(0.159)
Higher NO_2 (Kazak)×#Dust		– 0.155			– 0.051
		(0.202)			(0.209)
Higher NO_2 (Kazak)		0.082			0.184
		(0.201)			(0.202)
Higher NO_2 (Russia)×#Dust			0.104		0.121
			(0.078)		(0.078)
Higher NO_2 (Russia)			0.530***		0.526***
			(0.177)		(0.176)
Higher NO_2 (Mongolia)				– 1.417	– 0.440
				(1.446)	(1.508)
#Dust	0.004	0.027	– 0.027	0.023	– 0.058
	(0.040)	(0.041)	(0.057)	(0.040)	(0.057)
District FE×Year FE, Province FE×Month FE	Yes	Yes	Yes	Yes	Yes
Weather (cubic polynomial)	Yes	Yes	Yes	Yes	Yes
Local production (export, energy)	Yes	Yes	Yes	Yes	Yes
Local prod.×Dust	Yes	Yes	Yes	Yes	Yes
Observations	16,693	16,693	16,693	16,693	16,693
R-squared	0.716	0.716	0.716	0.716	0.717

Notes: This table presents the results on the influence of pollution in other countries. Higher NO_2 ×#Dust is always 0 for Mongolia as Mongolia is less dirty in the dust season. Standard errors are clustered at the district level. Significance levels: *** 1%, ** 5%, * 10%.

Table A4. *Alternative Measures of China's Pollution.*

	(1)	(2)	(3)	(4)	(5)	(6)
Measure of China's pollution	Mean AQI	Weighted AQI	Prov. capital AQI	Share above mean	Mean AQI	Mean AQI
#Dust×China's pollution	0.040**	0.033*	0.041**	0.124***	0.095**	0.073**
	(0.019)	(0.019)	(0.020)	(0.032)	(0.030)	(0.032)
China's pollution	0.200*	0.116	0.374***	0.005		
	(0.111)	(0.106)	(0.113)	(0.093)		
District FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Prov FE×Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather (cubic polynomial)	Yes	Yes	Yes	Yes	Yes	Yes
Local prod. (export, energy)	Yes	Yes	Yes	Yes	Yes	Yes
Local prod.×Dust	Yes	Yes	Yes	Yes	Yes	Yes
Higher-order polynomial of China's Pollution	–	–	–	–	3rd	5th
Observations	28,024	28,024	28,024	28,024	28,024	28,024
R-squared	0.717	0.717	0.717	0.717	0.717	0.717

Notes: This table reports the results using variants of China's pollution measure. China's pollution is divided by the standard deviation in all columns except for column (4) (which uses the monthly share of city-daily AQI above the sample mean). Columns 5 and 6 show that the results are robust to allowing non-linear effects of China's pollution. Weather conditions include a cubic polynomial of the six weather variables listed in Table 1. Local production includes district-month export and province-month energy production. Standard errors are clustered at the district level. Significance levels: *** 1%, **5%, * 10%.

Table A5. *Using Log Deaths as the Dependent Variable.*

	(1)	(2)	(3)	(4)	(5)	(6)
#Dust×China's mean AQI	0.003***	0.003***	0.003**	0.003**	0.003**	0.003**
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
#Dust	– 0.020**	– 0.020**	– 0.022**	– 0.020**	– 0.022**	– 0.022**
	(0.009)	(0.009)	(0.009)	(0.010)	(0.010)	(0.010)
China's Mean AQI	0.012*	0.010	0.013*	0.011	0.016**	0.015**
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
Log population	0.364***		0.366***		0.373***	
	(0.088)		(0.087)		(0.088)	
District FE×Year FE	–	Yes	–	Yes	–	Yes
District FE, Year FE	Yes	–	Yes	–	Yes	–
Prov FE×Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather (cubic polynomial)	–	–	Yes	Yes	Yes	Yes
Local prod. (export, energy)	–	–	–	–	Yes	Yes
Local prod.×Dust	–	–	–	–	Yes	Yes
Observations	27,972	27,972	27,972	27,972	27,972	27,972
R-squared	0.777	0.805	0.777	0.805	0.777	0.805

Notes: Dependent variable uses log of deaths from respiratory and cardiovascular diseases. This table reports the results using log deaths instead of mortality rates as the dependent variable. Columns 1, 3 and 5 include log Population on the RHS, whereas columns 2, 4 and 6 use district-by-year FE to account for population (and other) effects. Standard errors are clustered at the district level. Significance levels: *** 1%, ** 5%, * 10%.

Table A6. *Results with Conley Standard Errors, Excluding Summer and Higher-Order Polynomials of Weather Conditions.*

	(1)	(2)	(3)	(4)	(5)	(6)
	Conley standard errors			Excluding		
	60km	120km	180km	summer	Higher order of weather	
#Dust×China's mean AQI	0.040**	0.040*	0.040*	0.041**	0.040**	0.039**
	(0.018)	(0.021)	(0.021)	(0.019)	(0.019)	(0.019)
District FE×Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Province FE×Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather (cubic polynomial)	Yes	Yes	Yes	Yes		
Local prod. (export, energy)	Yes	Yes	Yes	Yes	Yes	Yes
Local prod.×Dust	Yes	Yes	Yes	Yes	Yes	Yes
4th-order polynomial of weather	–	–	–	–	Yes	–
5th-order polynomial of weather	–	–	–	–	–	Yes
Observations	28,024	28,024	28,024	20,743	28,024	28,024
R-squared	0.717	0.717	0.717	0.730	0.717	0.717

Notes: Dependent variable is respiratory and cardiovascular mortality rates. This table shows that our baseline results in Table 2 are robust to using Conley (1999) standard errors (columns 1–3), excluding summer months (column 4), and including higher-order polynomials of local weather conditions in South Korea (columns 5–6). #Dust is the number of dust days in a district-month in Korea. China's mean AQI is divided by one standard deviation (12) so that the coefficient can be interpreted as the impact of an increase of 12 in China's AQI. Weather conditions include a cubic polynomial of the six weather variables listed in Table 1. Local production includes district-month export and province-month energy production. Standard errors in columns 4–6 are clustered at the district level. Significance levels: *** 1%, ** 5%, * 10%.

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