Air Pollution and Infant Mortality:
A Natural Experiment from Power Plant Desulfurization

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Abstract

The paper estimates the effect of SO_2 pollution on infant mortality in Germany, 1985-2003. To avoid simultaneity problems, I exploit the natural experiment created by the mandated desulfurization at power plants, with wind directions dividing counties into treatment and control groups. Instrumental variable estimates are larger than conventional estimates and translate into an elasticity of 0.08-0.14. The observed reduction in pollution implies an annual gain of 850-1600 infant lives. Estimates are robust to controls for economic activity, climate, reunification effects, rural/urban trends and TSP pollution and are comparable across subsamples. Excess mortality mainly accrues in the first month after birth. (100 words)

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Introduction

Extreme pollution events like the smog episode in the Meuse Valley, Belgium, in 1930, in Donora, Pennsylvania, in 1948, and in London in 1952 and 1956 caused a severalfold increase in mortality and, thereby, raised awareness of the detrimental health effects of pollution. Negative effects on human health are beyond doubt a major source of the overall welfare loss associated with pollution. Consequently, safety and health concerns are a primary rationale for air quality regulations such as the Clean Air Act in the U.S. and the Federal Immission Control Act in Germany. For example, the latter act has the stated purpose "to protect human beings […] against harmful effects […] and to take precautions against the emergence of any such harmful effects […]."

These regulations brought about considerable improvements in air quality. As an example, Figure 1 depicts the sulfur dioxide (SO_2) concentration in Germany in 1985-2003. Other developed countries experienced a similar decline in SO_2 concentrations. Of course, general trends mask considerable heterogeneity and people living, for instance, in the vicinity of coal-fired power plants can still be exposed to high and increasing pollution levels. Moreover, the pollution situation in developing countries looks less bright and is often getting worse. Therefore, it is natural to ask if the improvements in air quality were accompanied by improvements in health and, more generally, to assess the health effects of air pollution.

Mortality is arguably the most important health outcome. With regard to the health effects of air pollution, *adult* mortality it is also the longest and most widely studied health outcome (Anderson 2009). Epidemiologists typically rely either on time-series analyses, cross-section analyses or cohort analyses, i.e. longitudinal analyses of populations with different levels of long term exposure to air pollution. For example, analyzing daily data for London in the years 1958-1972, Schwartz and Marcus (1990) find highly significant relationships between mortality and SO_2 both over the whole period and in individual years. Similarly, Mendelsohn and Orcutt (1979) observe a positive and significant association between mortality and SO_2 in a cross-section of groups of U.S. counties in 1970. Or, in a large cohort of nonsmoking Californians followed over the period 1977-1992, SO_2 showed a strong relationship with lung cancer mortality (Abbey et al. 1999).

Even though it has already been observed in the London smog episodes that the death toll was relatively greatest among infants (e.g., Logan 1956), epidemiological studies concentrate largely on adult mortality. This is all the more surprising because studies on adult mortality suffer from conceptual and methodological problems that studies on infant mortality obviate (Chay and Greenstone 2003b). First, the excess deaths attributable to air pollution may occur primarily among the old and infirm, who may not have lived long anyway. Of course, this "harvesting" is also important for studies on infant mortality that identify effects on the basis of short term variation in mortality and pollution. But if decreases in air pollution are found to reduce infant mortality rates overall, the number of life-years gained is large. Second, there is considerable uncertainty regarding the life-time exposure of adults. As Chay and Greenstone (2003b) argue, this uncertainty is greatly reduced by the low migration rates of pregnant women and infants. These advantages sparked a recent interest in the effects of air pollution, not only among epidemiologists but also among economists (see references below).

Concerns regarding "harvesting" and life-time exposure are specific to studies on mortality. But in addition, studies on mortality are also affected by omitted variable and simultaneity problems common in all non-experimental, correlational studies. For instance, local air pollution is correlated with local economic activity, demographic patterns and other unobserved factors that have independent effects on mortality. Intervention analyses go some way in addressing these concerns. The finding of a reduction in SO_2 pollution and mortality in the aftermath of an overnight introduction of low sulfur fuel in 1990 in Hong Kong provides certainly more convincing evidence than classical time-series studies (Hedley et al. 2002). Yet, without an adequate control group, it is difficult to rule out alternative explanations.

In two pioneering studies, Chay and Greenstone (2003b; a) use natural experiments to assess the effect of total suspended particulate (TSP) pollution on infant mortality. The natural experiments are provided by the comparatively harsh regulation imposed on U.S. counties that did not meet the Clean Air Act standards in the early 1070s (Chay and Greenstone 2003a) and by the large variation across U.S. counties in changes in TSP pollution caused by the 1980s regression (Chay and Greenstone 2003b). In both studies, the estimates based on regulation- or recession-induced changes in TSP concentration are stronger and more robust than either conventional cross-section or panel estimates; the estimated elasticity is 0.5 in the 1970s and 0.35 in the 1980s. Currie and Neidell (2005) address omitted variable and simultaneity problems by using the within zip-code month variation to identify the effect of air pollution on infant mortality. This identifications strategy may make the results susceptible to concerns about "harvesting" and does not allow the authors to capture cumulative effects. However, the strategy is particularly well suited for their purpose since they are interested in the effect of pollutants with potentially important short-term effects, notably carbon monoxide (CO) and ozone (O_3). Moreover, direct tests for "harvesting" reject related concerns. The results of Currie and Neidell (2005) imply an elasticity of 2.05 for CO; no effects are found for particulate matter (PM) and O_3. Currie and Schmieder (2009) investigate the effect of emissions of a wider range of toxic chemicals in the U.S. The implied elasticities range from 1.82 for heavy metals to 6.11 for volatile organic compounds and 6.49 for chemicals known to affect child development. Foster et al. (2009) use a measure based on satellite imagery that is correlated with PM pollution to study the effects on respiratory mortality in infants in Mexico. They find evidence that improvements in air quality, largely attributable to a voluntary pollution reduction program, reduced infant mortality with an elasticity of 4.4.

This paper contributes to this literature in three respects. First, as in Chay and Greenstone (2003a), the paper uses regulation-induced changes in air pollution to identify the effects on infant mortality. At the same time, it recognizes that the consequences may extend far beyond the immediate vicinity of regulated sources because of the typically large transport distances of gaseous pollutants. Specifically, air pollution is instrumented with the estimated improvement in air quality caused by the mandated installation of scrubbers at power plants. The instrument is a difference-in-difference term with the retrofitting of power plants as treatment and the prevailing wind direction dividing counties into treatment and control groups.

Second, the paper analyzes the effect of SO_2 pollution. SO_2 pollution has been largely neglected by the epidemiological literature on infant mortality (in contrast to TSP pollution; for a review, see Glinianaia et al. 2004), especially by the recent economic literature on infant mortality. Cross-sectional analyses across U.S. counties in 1970 (Mendelsohn and Orcutt 1979) and in 1990 (Lipfert et al. 2000) as well as across Czech districts in 1989-1991 (Bobak and Leon 1999) yield insignificant and inconsistent results. An exception are Bobak and Leon (1992) who find a weakly significant association between SO_2 and postneonatal respiratory mortality in a sample of Czech districts in 1986-1988. Given the facts that SO_2 pollution is the focus of many air quality regulations, that there is considerable evidence for effects on adult mortality (see references above) and that the strongest and most consistent effects on pregnancy outcomes are found for SO_2 and not for other pollutants (for a review, see Šram et al. 2005), this neglect is surprising.

Third, the paper uses data from Germany in 1985-2003. The recent literature mainly concentrates on the U.S. and, to a lesser extent, on developing countries. Therefore, evidence from another highly developed country validates findings from the U.S. At the same time, developed countries share many similarities, so that the results for Germany can be used to evaluate policies in other countries such as, for example, the SO_2 emission trading program in the U.S.

[Figure 1 about here]

The most important finding is that SO_2 pollution increases infant mortality. The co-movement of SO_2 pollution and infant mortality shown in Figure 1 anticipates this result. The analysis in later sections of the paper suggests that this relationship is causal and quantifies the effect. In the whole sample, the IV estimates are around 1.9 times larger compared to the conventional estimates. According to the conventional estimates, 0.028 infant lives (per 1000 live births) are saved if SO_2 concentration falls by 1 $\mu g/m^3$; according to the conventional estimates, the same reduction in SO_2 concentration saves 0.051 infant lives (per 1000 live births). This translates into elasticities of 0.08 and 0.14, respectively. For most subsamples considered, the absolute and relative magnitudes are very similar. Further, the estimates are robust to controls for local economic and demographic development, climate, reunification effects and rural/urban trends as well as TSP pollution. Further, estimates suggests that between 50 and 80 percent of the excess mortality accrues in the first month after birth and around one third within the first day.

The remainder of the paper is organized as follows. Section 2 introduces the pollution data and the strategy to instrument SO_2 concentrations. Section 3 presents the mortality data and control variables, the baseline regressions along with various robustness tests and the estimates for mortality within different time bands. Section 4 concludes.

2. Pollution: data, evolution and instrument

The data on SO_2 concentration come from the German federal environmental agency (*Umweltbundesamt*; hereafter UBA for short). The UBA provides data on the annual mean SO_2 concentration measured at the monitors belonging to the monitoring networks of the 16 state environmental agencies and the UBA for the years 1985 to 2003. Data are available for 553 monitors or, in individual years, between 196 monitors in 1985 and 416 monitors in 1994. In order to estimate the SO_2 concentration at all other locations, I interpolate the monitor readings on a grid with cell size of 1 km^2 covering the whole area of Germany. The data are interpolated with the method of inverse distance weighting. The value of cell *i* of the grid is estimated as the weighted average over the readings at the 9 nearest monitors *j* using the inverse cubed distance (D_{ij}^{-3}) as weights:

$$grid\ value_i = \sum_{j=1}^{9} monitor\ reading_j \cdot D_{ij}^{-3} \Bigg/ \sum_{j=1}^{9} D_{ij}^{-3} . \qquad (1)$$

The parameters have been suggested by the UBA and have been determined by the UBA on the basis of empirical studies. However, both interpolated values and regressions results are very similar for slightly different parameters.

In order to match the pollution data with the survey data, I aggregate the interpolated values on the level of German counties and estimate annual mean SO_2 concentrations.[1] The mean SO_2 concentration per county for the years 1985, 1990, 1995 and 2000 is depicted in Figure 2.

[Figure 2 about here]

The pattern and evolution of SO_2 pollution reveals two striking features. First, in the mid-1980s, pollution was highly concentrated at three hotspots: the Ruhr area in the west, Northern Hesse in the centre and the area around Leipzig in the east, by then all important industrial centres and coal mining areas. Second, air quality improved dramatically between 1985 and 1990 in West Germany and after 1990 in East Germany. In large part, these improvements reflect the effect of an amendment to the large combustion plant ordinance enacted in 1983 (the ordinance is based on the German Federal Immission Control Act cited in the introduction). The ordinance required fossil fuel fired power plants to be retrofitted with flue gas desulfurization. Time limits were in the range between three and nine years from 1986 on. It is important to note that time limits were statutorily fixed and depended on the capacity of a power plant and its actual emissions but that they were not in the discretion

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[1] In 1994, population per county was between 31,800 in Klingenthal and 2,170,000 in West Berlin with a median of 131,400. The number of counties fell from 543 in 1993 to 439 in 2001 as several counties in the East Germany merged. The analysis in this paper is based on the 439 counties at the end of the merging process.

of the operating companies or regulatory bodies. The unification treaty of 1990 subjected power plants in East Germany to the same regulations. East German power plants had to install scrubbers from 1993 on. As in West Germany, the ordinance specified different time limits for different categories of power plants.

However, the pattern and evolution of SO_2 pollution also points at the potential simultaneity of local economic activity and pollution. Since 1980, the Ruhrgebiet undergoes structural change. New jobs in the service sector compensate only partially for job losses in the industrial sector. Similarly, the area around Leipzig is still recovering from the collapse of industrial production after reunifications. To address this potential source of bias, I instrument air pollution by exploiting the mandated retrofitting of power plants, coupled with information on the geography of power plants and wind directions.

I use the changes in SO_2 concentration caused by the large combustion plant ordinance and consequent retrofitting of power plants as an instrument for SO_2 pollution. My instrument in later stages of the analysis is the difference-in-difference term with desulfurization at power plants as the treatment and with counties assigned to control and treatment groups according to prevailing wind directions at power plants. In a standard difference-in-difference setting, this term would simply be the interaction of a dummy variable with value one if power plant j has installed a scrubber at time t, $1(scrubber)_{jt}$, and a dummy variable and with value one if county c lies downwind of power plant j, $1(downwind)_{cj}$. Hence, one would explain the SO_2 concentration in county c at time t, P_{ct}, as follows:

$$P_{ct} = \alpha_0 + \alpha_2 1(scrubber)_{jt} \cdot 1(downwind)_{cj} + \chi_c + \tau_t + \varepsilon_{ct}, \tag{2}$$

where χ_c and τ_t are county and time specific effects respectively.

I depart from this idealized setting in three respects. First, treatment and control group status is a matter of degree rather than one of kind. Although there is everywhere a predominant wind direction distinguishing counties into up- and downwind counties, wind directions can change. Therefore, the treatment group variable, $f(R_{cj})$, is the frequency that county c lies downwind of power plant j and the difference-in-difference term becomes $1(scrubber)_{jt} \cdot f(R_{cj})$.

Second, since I consider simultaneously all power plants j and all counties c, the treatment variable is a weighted sum of desulfurization at all power plants. The weights are the uncleaned, pre-desulfurization, emissions of the plants, E_j, and a distance decay function, $g(D_{cj})$. The new difference-in-difference term thus is $\sum_j E_j \cdot 1(scrubber)_{jt} \cdot g(D_{cj}) \cdot f(R_{cj})$. The distance decay is modelled as an exponential curve with an implied characteristic decay distance of 480 km, $g(D_{cj}) = \exp(-2.1\text{E-}6 \cdot D_{cj})$, as suggested by field studies (Schwartz 1989; Summers and Fricke 1989). The decrease in concentration with distance captures both removal of material by deposition and dilution or dispersion caused by lateral or vertical mixing of air.

Third, some power plants shut down, others are newly built. Therefore, it is necessary to control for changes in the power plant population by introducing an additional term in equation 2 for the weighted sum of uncleaned emissions, $\sum_j E_j \cdot 1(active)_{jt} \cdot g(D_{cj}) \cdot f(R_{cj})$, where $1(active)_{jt}$ is a dummy variable indicating whether power plant j is active at time t. Taking all three departures into account, the difference-in-difference setting thus becomes:

$$\begin{aligned} P_{ct} = \alpha_0 &+ \alpha_1 \sum_j 1(active)_{jt} \cdot E_j \cdot g(D_{cj}) \cdot f(R_{cj}) \\ &- \alpha_1 \alpha_2 \sum_j 1(active)_{jt} \cdot E_j \cdot 1(scrubber)_{jt} \cdot g(D_{cj}) \cdot f(R_{cj}) + \chi_c + \tau_t + \varepsilon_{ct}. \end{aligned} \tag{3}$$

In equation 3, the second term on the right hand side denotes the weighted sum of uncleaned SO_2 emissions, the third term denotes the weighted sum of retained SO_2 emissions. In later stages of the analysis, the weighted sum of retained SO_2 emissions – conditional on the weighted sum of uncleaned SO_2 emissions, county and time specific effects as well as on all the control variables introduced in section 3 – will be my instrument for air pollution. The identifying assumption is that there exists no systematic difference in the effect of retrofitting of power plants on infant mortality between up- and downwind counties except through the effect on pollution.[2]

As can be seen from equation 3, I require information on the pre-desulfurization SO_2 emissions of the power plants, information on when plants installed scrubbers, wind directions at the plants as well as direction and distance vectors between counties and plants.

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[2] It is worth noting that the costs of the regulation such as increased electricity prices and secondary benefits such as jobs created in the environmental industry are equally spatially distributed (or at least orthogonal to wind directions). Further, the statutory provisions were enacted before the period considered. Therefore, the actual installation of scrubbers does not reflect other changes such as a shift in political power from upwind to downwind regions.

For 303 fossil fuel fired generating units, i.e. all units active between 1985 and 2003 with an electricity capacity of 100 MW and more, I have information on the launching year, year of desulfurization, the year the unit was shut down, capacity, fuel and fuel efficiency. The data are from the UBA, information published by the operating companies and the technical literature, a survey mailed to operating companies and statutory provisions (the reader is referred to the appendix A.1 for details). I georeference power plants using a route planer. The locations of the power plants are depicted in panel A of Figure 3. With emission factors published in the literature and the plants characteristics, annual SO_2 emissions can be estimated. Frequencies of wind directions in 12 30-degree sectors measured at 43 wind stations describe the wind situation at the power plants. From an originally larger sample of wind stations, I use for each plant the closest wind station. The stations are shown in panel B of Figure 3. The predominant wind direction is west-southwest. In order to relate the data at the plant level with the pollution data at the county level, I calculate the Euclidean distance and direction between every power plant and every county.

[Figure 3 about here]

The reason for instrumenting SO_2 concentration is its potential correlation with local economic activity, demographic patterns and other unobserved factors that have independent effects on mortality. In order to assess the importance of this issue and in order to provide support for my instrumenting strategy, Table 1 presents the results from 'pseudo first stage' regressions, i.e. from regressions of important economic (and demographic) variables on SO_2 concentration and on my instrument as well as on the full set of control variables introduced in section 3. The economic outcomes on the left hand side are GDP per capita, employment and population at the county level.

[Table 1 about here]

Although the ultimate source of concern is a correlation between air pollution and *unobserved* economic and demographic outcomes, Table 1 confirms the conjecture that pollution and local economic and demographic activity are correlated and supports the instrumenting approach: While SO_2 concentration is correlated with GDP per capita and population, the instrument is not. Employment is neither correlated with SO_2 concentration nor with the instrument.

One might worry that counties lying downwind of a retrofitted power plant experienced improvements in air quality and infant mortality before the plant installed the scrubber. In this case, the difference-in-difference term in equation 3 that is used as an instrument would partly capture these pre-existing trends. In order to assess this issue, Figure 4, panels A. and C., plots for each county the differences in SO_2 concentration and infant mortality between the first year of the desulfurization process and the last year before the process against the estimated effect of desulfurization averaged over the whole sample period. The pre-desulfurization differences relate to the years 1986-1985 for West Germany and the years 1993-1992 for East Germany. Figure 4, panels B. and D., also plots the differences in SO_2 concentration and infant mortality between the third and the first year of desulfurization process against averaged values of the estimated effect of desulfurization. The post-desulfurization differences relate to the years 1989-1986 for West Germany and the years 1996-1993 for East Germany. These years mark the time frame during which the most polluting power plants were required to install scrubbers. Figure 4 both plots both actual values and Kernel-weighted local polynomial regression-smoothed values.

[Figure 4 about here]

As we can see from Figure 4, panels A. and C., in the years before the desulfurization process, average values of the estimated effect of desulfurization are not related to changes in SO_2 concentration. For the actual values, the correlation (ρ) is -0.06 (p = 0.352). In contrast, average values of the estimated effect of desulfurization are strongly related to changes in SO_2 concentration after the desulfurization process started ($\rho = -0.48$; $p < 0.0001$). The same pattern holds for infant mortality rates even though it may be less visible to the naked eye. The correlation pre-desulfurization is -0.02 (p = 0.798), post-desulfurization it is -0.17 (p = 0.024).[3]

Having described the pollution data and the strategy to address omitted variable and simultaneity problems, we can now turn to the analysis on the effects of SO_2 pollution on infant mortality.

3. Effect of SO_2 pollution on infant mortality

3.1 Data and empirical strategy

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[3] It is important to note that the actual development stacks the deck against finding the instrument to be valid. Even though power plants were not statutorily required to install scrubbers before 1986 and 1993 in West and East Germany, respectively, individual power plants (< 6 percent) were retrofitted before these dates to test desulfurization technologies or in connection with regular overhauls.

The data on infant mortality originally come from the 15 state statistical agencies (Hamburg and Schleswig-Holstein share one agency). The state agencies are required by federal laws to collect data on births and deaths in a standardized way. Aggregated values at the county level are then either published in state reports or available on request. The German Youth Institute, an independent research institute on children and families, compiled and courteously provided the data for the years 1986-2003. The data for the year 1985 come directly from the statistical agencies. Infant mortality is reported as the number of deaths per 1000 live births. As can be seen from the summary statistics reported in Table 2, 5.78 infants per 1000 live births died on average in the sample period. Until 1999, disaggregated data on the number of deaths within 1 day and 28 days are available. Due to changes in federal laws, states no longer reported detailed information on early infant deaths in later years.

[Table 2 about here]

The explanatory variable of interest is the annual mean concentration of SO_2 introduced in the Section 2. The mean concentration in the sample is 15.78 $\mu g/m^3$.

A first set of control variables includes basic economic and demographic variables, namely GDP per capita, employment and population. The data are from Cambridge Econometrics. A second set of control variable includes climate or weather variables. Pollution and mortality are both likely to be correlated with climate or weather conditions. In particular, extreme conditions can be expected to be important drivers of increased infant mortality (Deschênes and Greenstone 2007). Therefore, some specification will control for the mean temperature in the coldest month, the mean temperature in the hottest month, the mean precipitation in the driest month and the mean precipitation in the wettest month. The variables are constructed on the basis of daily data from the German meteorological office (*Deutscher Wetterdienst*) and the European Climate Assessment and Data. I choose for each county the nearest of 35 weather stations with continuous readings to describe the weather situation.

On the basis of this data set, I estimate different variants of the following empirical model:

$$IMR_{ct} = \beta_0 + \beta_1 P_{ct} + \beta_2 Z_{ct} + \chi_c + \tau_t + \varepsilon_{ct}, \tag{4}$$

where IMR_{ct} is the infant mortality rate in county c in year t, P_{ct} the SO_2 concentration in this county and year, Z_{ct} a vector of control variables, χ_c and τ_t county and year effects and ε_{ct} an error term. I estimate all variants of equation 4 with ordinary least squares and two stage least squares.

The functional form of the relationship between SO_2 concentration and infant mortality cannot be determined on an a priori basis. There is a widely held belief that the relationship between pollution and mortality may be non-linear. However, in the present case, F-tests clearly reject models with second or third order polynomials. Hence, the relationship is modelled linearly.

Throughout, a robust estimator of variance is used that allows for an unspecified form of correlation between observations from the same analytical region defined by the federal Office for Building and Regional Planning. In this way, serial and spatial correlations are accounted for. Each of the 92 analytical regions in Germany includes an economic centre with its hinterland. The regions are defined on the basis of commuted flows and often correspond to the planning regions of the states. Thus, counties within these regions are likely to be exposed to common shocks.

3.2 Basic results

Table 3 presents the basic results for the whole sample. It presents the result from three specifications for both the conventional and the instrumental variable panel estimates. Columns (1) and (4) present the results from the most parsimonious model that only controls for county and year effects. Columns (2) and (5) additionally include the economic variables. Columns (3) and (6) contain the richest models with controls for climate conditions.

[Table 3 about here]

The most important finding reported in Table 3 is that SO_2 concentration has a positive and highly statistically significant effect on infant mortality. According to the conventional estimates, 0.028 infant lives are lost per 1000 live births for every 1 $\mu g/m^3$ increase in SO_2 concentration (weighted average of coefficients with the inverse of the robust standard errors as weights). The corresponding figure for the instrumental variable estimates is 0.051 infant lives. Hence, the instrumental variable estimates are around 1.9 times higher. This is consistent with the notion that conventional estimates are biased by omitted variables (and by measurement errors). The ratio of 1.9 is comparable to the corresponding ratio in Chay and Greenstone (2003b) for the years 1980-1982 amounting to 1.5.

The estimates are robust to changes in the specification. The conventional estimates are not more sensitive than the instrumental variable estimates, contrary to what might be expected and contrary to previous findings (Chay and Greenstone 2003b; a). However, this is not very surprising in light of the small and insignificant effects of most of the control variables. Only mean precipitation in driest month has a significant positive effect. The positive effect supports the conjecture that extreme climate conditions are detrimental. The positive effect for the mean temperature in the coldest month points in the same direction but the estimate is small and imprecise. An increase in employment seems to reduce infant mortality but, again, the effect is not statistically significant. All other variables have inconsistent effects.

Turing to the first stage regressions, we can see that the instrument has the expected effect on SO_2 pollution. Further, the effect is strong and highly statistically significant. The F-test and the partial R^2 suggest that the instrument is relevant and that it has reasonable explanatory power.

There are several ways to put the results into perspective. First, the marginal effects of 0.028 and 0.051 translate into an elasticity of 0.08-0.14. This elasticity can be compared to the elasticity from previous studies. However, even though elasticity is independent from measurement units and averaging times, vast differences between pollutants, locations, time periods and study designs imply that the comparison needs to be taken with a grain of salt. From a comparison with the elasticities reported in the introduction, it can be seen that my estimates are lower than the lowest estimate found in previous studies.

Second, one can calculate the number of infant lives saved in each year by the very large reduction in SO_2 pollution over the sample period. The average decrease in SO_2 concentration in counties between the first and the last year that they are in the sample is around 42 $\mu g/m^3$. With around 746,000 live births each in year in Germany, the number of lives saved amounts to around 850 for the conventional estimates and to around 1600 for the instrumental variable estimates.

Third, if we are prepared to monetize these gains in live years, we can compare the benefits in infant health to the costs of regulation. Chay and Greenstone (2003b; a) use a value of a statistical life (VSL) estimate of $1.6 million (1997 US$) based on a study by Ashenfelter and Greenstone (2004); Currie and Neidell (2005) use EPA’s estimate of $4.8 million (1999 US$); the median VSL estimate for prime aged workers in the U.S. in the meta-analysis of Viscusi and Aldy (2003) is $6.7 million. Hence, the estimates differ by an order of magnitude and so will the estimates of infant health benefits. The lowest annual benefit estimate for each of the around 27,793,000 households in the year 1989 based on the ordinary least square regressions and the VSL estimate from Ashenfelter and Greenstone (2004) is around $50

(1997 US$), the highest estimate based on the two stage least square regressions and the VSL estimate of Viscusi and Aldy (2003) amounts to US$390 (2000 US$).

These estimates can be compared to rough estimates of the private compliance costs (not social costs; see Hazilla and Kopp 1990) for West Germany in the range of between $33 and $165 per year and household (2000 US$).[4] The comparison thus suggests that reduced infant mortality alone justifies the regulatory costs. Of course, not the entire improvement in air quality can be attributed to the large combustion plant ordinance. But the reduction in infant mortality is likely to be indicative of much larger health benefits in reduced morbidity and mortality. Adding aesthetic benefits and reduced material damages yields even larger overall benefits. Using the life satisfaction approach to the valuation of public goods, Luechinger (2009) finds that the overall social benefits of improved air quality exceed the health benefits presented here.

3.3 Robustness tests and extensions

Table 4 reports the results from a battery of robustness tests. On the one hand, I replicate the baseline regressions for several subsamples, namely for West Germany, for East Germany, for the 1985-1990 period and for the 1990-2003 period.[5] On the other hand, I control for additional confounding variables.

The models presented in columns (4), (9), (14), (19) and (24) contain year specific distance-to-city polynomials and year specific close to the East-West German border effects as additional control variables. The year specific distance-to-city polynomials are intended to capture urban/rural trends. The year specific close to the East-West German border effects should capture reunification related effects. Closeness is defined as 75 kilometers, i.e. by a dummy variable with value one for all counties within 75 kilometers of the East-West German border. Redding and Sturm (2008) show that West German cities within this distance of the East-West German border experienced a substantial decline in population growth

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[4] Schaerer and Haug (1990) put the cost of installation of scrubbers at West German power plants at DM 14.2 billion (1988 DM). Doubling this value to account for operation costs, assuming a real long-term interest rate of 5 percent and dividing by 27,793,000 households (living in Germany in 1989), gives an estimate of $33 (2000 US$) per household and year. Another estimate of desulfurization at power plants provided by Schaerer and Haug (1990) is DM 0.0075 per kWh of electricity produced. In 1989, West German power plants produced 452.39 billion kWh of electricity. The costs per household and year are therefore $80 (2000 US$). Finally, Schulz' (1985) most pessimistic cost estimate is DM 9 per person and month (1984 DM assumed) or $165 (2000 US$) per household and year.

[5] Two reasons explain the uneven partition of the time periods. First, this partition roughly separates the main period of desulfurization in the West from the main period of desulfurization is the East. This is only rough. Desulfurization continues after 1990 in the West and the West is also affected by desulfurization in the East. Second, starting from 1991, individual level data on deaths and births are available. Therefore, the subsample for the period 1991-2003 allows us to anticipate what results we may expect from an analysis of the individual level data.

relative to other West German cities as a consequence of the German division after the Second World War. Similarly, in the aftermath of the German reunification these cities experienced a relative increase in the population growth, although this latter effect is smaller.

The models in columns (5), (10), (15), (20) and (25) control for the TSP concentration. SO_2 and TSP concentrations are often correlated. Hence, without controlling for the TSP concentration, the SO_2 concentration may reflect air pollution more generally. In Bobak and Leon (1999), the effect of SO_2 concentration falls below conventional level if both measures of air pollution are jointly included. It is important to note that some of the correlation between SO_2 concentration and TSP concentration is causal since SO_2 provides a reservoir from which sulfates and sulfuric acid, both components of TSP, derive. To the extent that the correlation is causally linked in this way, a decrease in the effect of the effect of SO_2 does not render SO_2 pollution irrelevant.

[Table 4 about here]

Generally, the estimates are robust across subsamples. An exception is the East German subsample in which no effect can be found with ordinary least squares. The two stage least square estimates are insignificant and sensitive to changes in the specification in the East German subsample, but the average effect across specifications is comparable to the results from other subsamples. For the conventional estimates, the average effects across specifications range from -0.003 in the East German subsample to 0.028 in the sample for the 1991-2003 period. The median is 0.027. For the instrumental variable estimates, the average effects range from 0.043 for the 1991-2003 period to 0.055 for the 1986-1990 period. The median is 0.050. The instrumental variable estimates are more robust than the conventional estimates across subsamples: While the smallest average effect is around 80 percent of the largest average effect in the case of the instrumental variable estimates, even the second smallest average effect is only around 75 percent of the largest average effect in the case of the conventional estimates.

Within subsamples, the two stage least square estimates are slightly less robust than the conventional estimates. The only change in specification that has any real consequences is the inclusion of the controls for urban/rural trends and reunification related effects. The effect of SO_2 increases if these additional controls are included in three out of five samples with the effect being more pronounced for the two stage least square estimates.

Adding a variable for the TSP concentration has virtually no effect on the SO_2 coefficient. Conditional on the SO_2 concentration, only very small, statistically insignificant and across subsamples inconsistent effects are found the TSP concentration.[6] While the robustness of the SO_2 effect is noteworthy, not too much should be made of the non-result for TSP concentration: Conventional estimates for TSP pollution suffer from the same omitted variable and simultaneity problems that motivated the instrumental variable approach in this paper. Consequently, conventional estimates for TSP pollution have been found to be very small and sensitive before (Chay and Greenstone 2003b; a).

Table 5 presents the estimated effects of SO_2 concentration on infant mortality within 1 day (columns (1), (2) and (3)) and within the first 28 days (columns (4), (5) and (6)) after birth. Since disaggregated data are only available until 1999, Table 5 also reports the estimated effect for infant mortality within 1 year for this period. As can be seen from Table 5, between around 50 percent (conventional estimates) and 80 percent (instrumental variable estimates) of the excess mortality caused by SO_2 pollution can be attributed to an increase in excess mortality in the neonatal period (i.e. the first month after birth). Further, around 30 percent of the excess mortality caused by SO_2 pollution is due to increased infant deaths within the 1 day. In the sample, around 30 percent of all infants dying in the first year dye within the first day and around 60 percent within the first month. Thus, the instrumental variable estimate suggests that SO_2 has a disproportionate effect on mortality within the first month. As Chay and Greenstone (2003b; a) argue this finding may be interpreted as evidence that SO_2 affects infant mortality through fetal exposure in pregnancy and poor fetal development. However, since the other estimates for early infant deaths in Table 5 show no disproportionate effect, this interpretation remains tentative.

4. Conclusion

The most important finding of this paper is that SO_2 pollution increases infant mortality. Previous studies convincingly documented the detrimental effects on infant health of pollutants such as TSP, CO and various toxic chemicals. Other studies showed that SO_2 pollution can increase adult mortality and that SO_2 is one of the major pollutants leading to adverse pregnancy outcomes. However, evidence on the effects of SO2 concentration on infant mortality is sparse and inconclusive. This paper contributes to filling this gap.

The estimated elasticity is smaller than the elasticities found for other pollutants. Yet, the very large reductions in SO_2 concentration experienced in many developed countries imply

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[6] The results are not reported but are available on request.

that the cumulative effects are large. The reduction in SO_2 concentration in Germany over the sample period results in a reduction of 850-1600 infant deaths each year.

This finding has immediate implications for the retrospective evaluation of air quality regulations such as the German large combustion plant ordinance or the U.S. SO_2 emission trading program. Further, the finding suggests that air quality regulations are likely to entail large welfare gains in developing countries with annual mean SO_2 concentrations in urban areas often exceeding 100 μg/m^3. Two further considerations strengthen this conclusion. First, reduced infant mortality is only one benefit of clean air. The estimates presented in this paper are likely to be indicative for much broader benefits in terms of reduced morbidity and mortality. Further, improvements in air quality have aesthetic effects and lower material damages. Thus, the overall social benefits of clean air may far exceed the health benefits presented here (Luechinger 2009). Second, SO_2 is mainly emitted by large and stationary sources. This facilitates market-based approaches to air quality regulation.

Given the sparse evidence on the effect of SO_2 pollution on infant mortality, similar findings for other countries and periods would validate the results presented here. Further, there are some caveats to the present study that could usefully be addressed in future research. Most importantly, this is study is based on aggregate data and, thus, cannot control for child and parent characteristics. Therefore, it would be worthwhile to replicate the study with individual level data for those years that these data are available.

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Appendix

A.1 *Power plants and wind directions: data and data sources*

This appendix provides a detailed description of the data on German power plants and wind directions used to estimate the causal effect of flue gas desulphurisation on annual mean SO_2 concentrations at county level.

Power plants

The data for fossil fuel fired generating units with an electricity capacity of 100 MW and more are from the UBA, information published by the operating companies and the technical literature, a survey mailed to operating companies and statutory provisions. To a list of 396 generating units provided by the UBA, I add 56 units and then reduce the number of units to 390 by combining all units with identical location and characteristics. Of theses 390 units, 7 units have a capacity of less than 100 MW, 351 were active in the period 1985 to 2003 and 303 units were active and are neither nuclear or hydroelectric power plants. The UBA list contains information on the plant name, operator and/or owner, zip code of contact address (which does not necessarily correspond to the plant's location), the launching year, the year the plant was shut down, capacity and fuel. I complement the data with the location, the year of desulphurisation, fuel efficiency and estimates of annual SO_2 emissions.

Location: If possible, I establish the exact address using information published by the operating companies, the technical literature or a route planner. Otherwise, the centroid of the zip code is assumed as a plant's location. I georeference the addresses with a route planner.

Year of refit: Published information and responses to my survey of operating companies allows me to determine the year scrubbers were installed for 224 units (61 percent). For the other units the year can be approximated on the basis of statutory provisions, the launching year, the year the plant was shut down and the capacity.

Fuel efficiency (η_j): Published information and survey responses provide information on the fuel efficiency of 196 units (54 percent). For the other units fuel efficiency is predicted based on the following regression (t-values in parentheses):

$$\eta_j = \underset{(3.76)}{9.6E\text{-}4\cdot \mathit{start\ year}_j} + \underset{(6.98)}{9.9E\text{-}5\cdot \mathit{capacity}_j} \underset{(-1.25)}{-0.035\cdot 1(\mathit{lignite})_j} + \underset{(0.27)}{0.008\cdot 1(\mathit{sub\text{-}bituminous\ coal})_j} +$$

$$\underset{(1.98)}{0.054\cdot 1(\mathit{natural\ gas})_j} \underset{(-1.56)}{-0.042\cdot 1(\mathit{HEL})_j} \underset{(2.32)}{+0.079\cdot 1(\mathit{HS})_j} \underset{(-2.73)}{-0.103\cdot 1(\mathit{uranium})_j} \underset{(4.03)}{+0.185\cdot 1(\mathit{hydro})_j} -$$

$$\underset{(-1.72)}{-0.053\cdot 1(\mathit{mixed\ fuel})_j} \underset{(-3.37)}{-0.027\cdot 1(\mathit{desox})_j} \underset{(5.39)}{+0.056\cdot 1(\mathit{denox})_j} \underset{(-3.13)}{-1.589}$$

$R^2 = 0.727$, Prob > F = 0.000

Emissions: In order to estimate annual SO_2 emissions, I use emission factors, *EF*, from a time shortly before scrubbers were installed (Bakkum et al. 1987). Emission factors are defined as the industry wide average ratio between the emission rate and the actual load differentiated according to fuel and capacity. Assuming full utilization of capacities, the annual emission at plant j, E_j, can be estimated as

$$E_j = EF(\mathit{fuel}, \mathit{capacity})\cdot \mathit{capacity}_j\cdot \eta_j^{-1}\cdot \mathit{time\ period}\ (31{,}536{,}000\ \text{seconds}).$$

This calculation overstates emissions because the assumption of constant full utilization is not plausible but I lack data on utilization rates. Moreover, the procedure allows me to capture the important differences in emissions between fuels and plant sizes.

Wind stations

Frequencies of wind directions in 12 30-degree sectors measured wind stations are published in Traup and Kruse (1996). The wind atlas contains data on 107 wind stations of which 12 are not representative for a larger area. For each power plant the wind station closest to the plant is used to describe the wind situation at the plant, restricting the number of wind stations to 43. The frequency distributions are based on measurement series of at least 5 years, in most cases 15 years and in some cases more than 15 years in the period between 1976 and 1995.

Table 1. Partial correlation between economic variables and SO_2 and predicted ΔSO_2

Dependent variable	GDP p. c.	Employment	Population
Main explanatory variable			
SO_2	-0.033 **	-0.006	0.095 **
	(0.006)	(0.011)	(0.016)
R^2 within	0.57	0.59	0.67
Number of observations	7371	7371	7371
Number of counties	439	439	439
Number of clusters	92	92	92
Main explanatory variable			
Predicted ΔSO_2	0.140	-0.133	-0.357
	(0.093)	(0.197)	(0.331)
R^2 within	0.56	0.59	0.66
Number of observations	7371	7371	7371
Number of counties	439	439	439
Number of clusters	92	92	92
Control variables			
Economic variables	Yes	Yes	Yes
Climate variables	Yes	Yes	Yes
County effects	Yes	Yes	Yes
Year effects	Yes	Yes	Yes

Notes: (1) OLS fixed-effects regressions; predicted ΔSO_2 is the estimated effect of desulfurization at power plants. (2) Cluster robust standard errors in parentheses. (3) ** is significant at the 99 percent level.

Table 2. Summary statistics

	Obs.	Mean	Median	Std. Dev.	Min	Max
Infant mortality rate (deaths per 1000 live births)	7371	5.78	5.40	2.87	0.00	23.30
SO_2 ($\mu g/m^3$)	7371	15.78	10.36	16.05	1.54	174.07
GDP per capita (in 1000 1995 euros)	7371	21.55	19.54	9.13	4.88	83.91
Employment (in 1000)	7371	87.92	59.00	114.37	17.00	1649.00
Population (in 1000)	7371	187.97	135.00	207.77	33.00	3474.00
Mean temperature in coldest month (in °C)	7371	-0.51	-0.35	2.60	-8.90	5.51
Mean temperature in hottest month (in °C)	7371	19.18	19.15	1.80	14.84	24.33
Mean precipitation in driest month (in mm)	7371	0.59	0.55	0.34	0.00	1.83
Mean precipitation in wettest month (in mm)	7371	4.09	3.97	1.21	1.67	11.64

Table 3. Basic results: Effect of SO2 pollution on infant mortality

A. Second stage regression

Dependent variable	Conventional Estimate			IV Estimate		
Infant mortality rate	(1)	(2)	(3)	(4)	(5)	(6)
Pollution						
SO_2	0.028 **	0.027 **	0.027 **	0.051 **	0.051 **	0.052 **
	(0.005)	(0.005)	(0.005)	(0.010)	(0.010)	(0.010)
Economic variables						
GDP per capita		-0.013	-0.011		0.008	0.010
		(0.022)	(0.022)		(0.024)	(0.023)
Employment		-0.006	-0.007		-0.005	-0.006
		(0.006)	(0.006)		(0.006)	(0.006)
Population		0.002	0.002		-0.002	-0.002
		(0.005)	(0.005)		(0.005)	(0.005)
Climate variables						
Mean temp. coldest month			0.002			0.003
			(0.042)			(0.042)
Mean temp. hottest month			-0.007			0.009
			(0.066)			(0.064)
Mean precip. driest month			0.273 *			0.257 *
			(0.132)			(0.129)
Mean precip. wettest month			0.007			0.006
			(0.032)			(0.033)
Pred. pre-duslf. SO_2	-	-	-	Yes	Yes	Yes
County effects	Yes	Yes	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes	Yes	Yes
Prob > F	0.000	0.000	0.000	0.000	0.000	0.000
R^2 within	0.26	0.26	0.26	0.26	0.26	0.26

B. First stage regression

Dependent variable						
SO_2						
Excluded instrument						
Predicted ΔSO_2				-5.692 **	-5.460 **	-5.529 **
				(0.549)	(0.493)	(0.513)
Pred. pre-duslf. SO_2						
Pred. pre-duslf. SO_2				13.572 **	12.587 **	12.633 **
				(1.997)	(1.705)	(1.728)
Included instruments				Yes	Yes	Yes
Number of observations	7371	7371	7371	7371	7371	7371
Number of counties	439	439	439	439	439	439
Number of clusters	92	92	92	92	92	92
Partial R^2 for SO_2	-	-	-	0.17	0.17	0.17
F-test of excluded instruments	-	-	-	107.41	122.72	116.14
Prob > F	-	-	-	0.000	0.000	0.000

Notes: (1) OLS fixed-effects and IV fixed-effects regressions. SO_2 is instrumented with the estimated effect of desulfurization at power plants. (2) Cluster robust standard errors in parentheses. (3) ** is significant at the 99 percent level and * at the 95 percent level.

Table 4. Robustness tests

Dependent variable	Germany					West Germany				
Infant mortality rate	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Conventional estimates										
SO_2	0.028 **	0.027 **	0.027 **	0.029 **	0.027 **	0.020 *	0.020 *	0.021 *	0.026 **	0.020 *
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.008)	(0.008)	(0.008)	(0.009)	(0.009)
R^2 within	0.26	0.26	0.26	0.27	0.26	0.30	0.30	0.30	0.30	0.30
Number of observations	7371	7371	7371	7371	7371	5979	5979	5979	5979	5979
Number of counties	439	439	439	439	439	327	327	327	327	327
Number of clusters	92	92	92	92	92	72	72	72	72	72
IV estimates										
SO_2	0.051 **	0.051 **	0.052 **	0.064 **	0.054 **	0.044 **	0.045 **	0.047 **	0.066 **	0.047 **
	(0.010)	(0.010)	(0.010)	(0.011)	(0.010)	(0.012)	(0.012)	(0.013)	(0.015)	(0.013)
R^2 within	0.26	0.26	0.26	0.26	0.26	0.30	0.30	0.30	0.30	0.30
Number of observations	7371	7371	7371	7371	7371	5979	5979	5979	5979	5979
Number of counties	439	439	439	439	439	327	327	327	327	327
Number of clusters	92	92	92	92	92	72	72	72	72	72
Control variables										
Economic variables	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
Climate variables	No	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes
Year spec. distance to city	No	No	No	Yes	Yes	No	No	No	Yes	Yes
Year spec. close to E-W border	No	No	No	Yes	No	No	No	No	Yes	No
TSP concentration	No	No	No	No	Yes	No	No	No	No	Yes
County effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

To be continued.

Table 4, part 2

Dependent variable	East Germany					1986-1990				
Infant mortality rate	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
Conventional estimates										
SO_2	-0.004	-0.005	-0.005	-0.004	-0.003	0.026 *	0.026 *	0.025 *	0.032 **	0.024 *
	(0.012)	(0.012)	(0.012)	(0.015)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)
R^2 within	0.22	0.22	0.22	0.23	0.22	0.09	0.09	0.09	0.10	0.09
Number of observations	1392	1392	1392	1392	1392	1806	1806	1806	1806	1806
Number of counties	112	112	112	112	112	326	326	326	326	326
Number of clusters	21	21	21	21	21	71	71	71	71	71
IV estimates										
SO_2	0.081	0.085	0.064	0.016	0.043	0.050 **	0.052 **	0.054 **	0.068 **	0.055 **
	(0.111)	(0.129)	(0.098)	(0.055)	(0.075)	(0.015)	(0.016)	(0.017)	(0.018)	(0.018)
R^2 within	0.13	0.13	0.17	0.24	0.20	0.09	0.09	0.09	0.09	0.09
Number of observations	1392	1392	1392	1392	1392	1806	1806	1806	1806	1806
Number of counties	112	112	112	112	112	326	326	326	326	326
Number of clusters	21	21	21	21	21	71	71	71	71	71
Control variables										
Economic variables	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
Climate variables	No	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes
Year spec. distance to city	No	No	No	Yes	Yes	No	No	No	Yes	Yes
Year spec. close to E-W border	No	No	No	Yes	No	No	No	No	Yes	No
TSP concentration	No	No	No	No	Yes	No	No	No	No	Yes
County effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

To be continued.

Table 4, part 3

Dependent variable	1991-2003				
Infant mortality rate	(21)	(22)	(23)	(24)	(25)
Conventional estimates					
SO_2	0.031 **	0.028 **	0.027 **	0.029 **	0.028 **
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)
R^2 within	0.11	0.11	0.12	0.12	0.12
Number of observations	5488	5488	5488	5488	5488
Number of counties	439	439	439	439	439
Number of clusters	92	92	92	92	92
IV estimates					
SO_2	0.042 **	0.043 **	0.043 **	0.045 **	0.043 **
	(0.013)	(0.015)	(0.015)	(0.017)	(0.015)
R^2 within	0.11	0.11	0.11	0.12	0.11
Number of observations	5488	5488	5488	5488	5488
Number of counties	439	439	439	439	439
Number of clusters	92	92	92	92	92
Control variables					
Economic variables	No	Yes	Yes	Yes	Yes
Climate variables	No	No	Yes	Yes	Yes
Year spec. distance to city	No	No	No	Yes	Yes
Year spec. close to E-W border	No	No	No	Yes	No
TSP concentration	No	No	No	No	Yes
County effects	Yes	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes	Yes

Notes: (1) OLS fixed-effects and IV fixed-effects regressions. SO_2 is instrumented with the estimated effect of desulfurization at power plants. (2) Cluster robust standard errors in parentheses. (3) ** is significant at the 99 percent level and * at the 95 percent level.

Table 5. SO_2 pollution and infant mortality within 1 day, 28 days and 1 year

Dependent variable	Deaths within 1 day			Deaths within 28 days			Deaths within 1year		
Infant mortality rate	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Conventional estimates									
SO_2	0.007 *	0.008 **	0.008 **	0.013 **	0.013 **	0.013 **	0.027 **	0.028 **	0.028 **
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)	(0.005)	(0.005)
R^2 within	0.05	0.05	0.05	0.11	0.11	0.11	0.26	0.26	0.27
Number of observations	4380	4380	4380	4380	4380	4380	4380	4380	4380
Number of counties	433	433	433	433	433	433	433	433	433
Number of clusters	92	92	92	92	92	92	92	92	92
IV estimates									
SO_2	0.013 **	0.014 **	0.015 **	0.031 **	0.032 **	0.033 **	0.038 **	0.039 **	0.041 **
	(0.005)	(0.005)	(0.005)	(0.008)	(0.008)	(0.008)	(0.010)	(0.011)	(0.011)
R^2 within	0.05	0.05	0.05	0.11	0.11	0.11	0.26	0.26	0.26
Number of observations	4380	4380	4380	4380	4380	4380	4380	4380	4380
Number of counties	433	433	433	433	433	433	433	433	433
Number of clusters	92	92	92	92	92	92	92	92	92
Control variables									
Economic variables	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Climate variables	No	No	Yes	No	No	Yes	No	No	Yes
County effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: (1) OLS fixed-effects and IV fixed-effects regressions. SO_2 is instrumented with the estimated effect of desulfurization at power plants. (2) Cluster robust standard errors in parentheses. (3) ** is significant at the 99 percent level and * at the 95 percent level.

Figure 1. SO$_2$ concentration and infant mortality in East and West Germany, 1985 - 2003

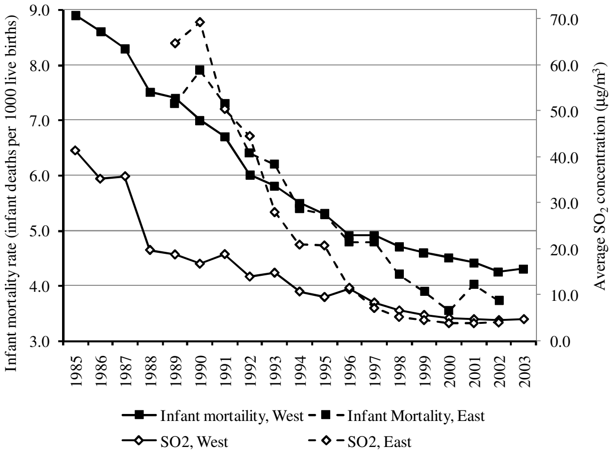
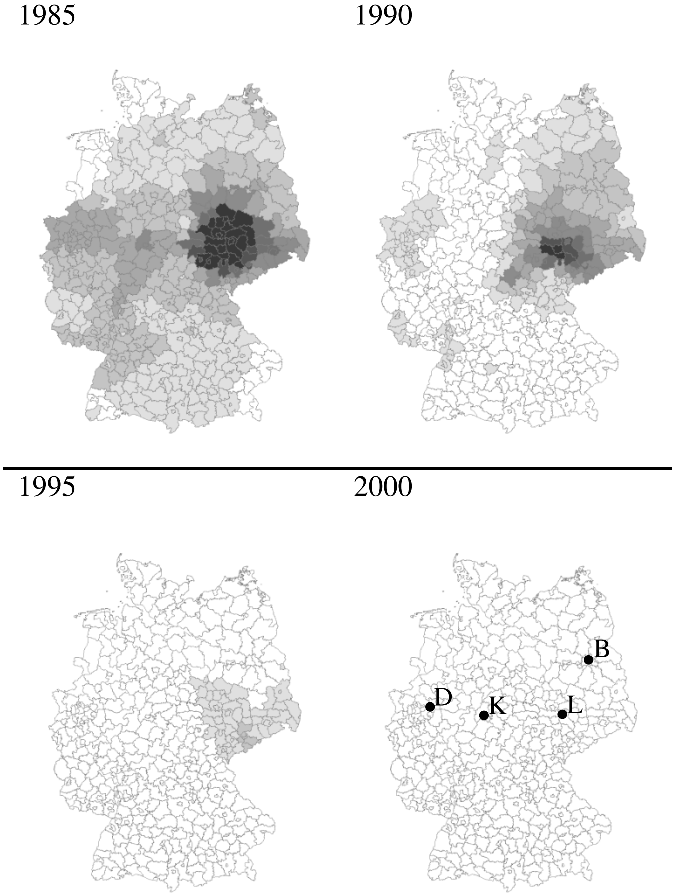
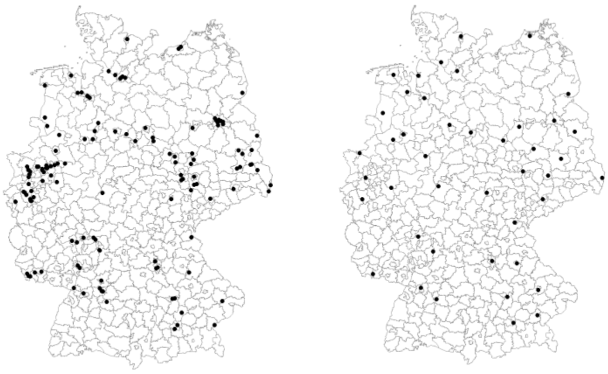


Figure 2. SO_2 concentration in German counties; 1985,1990, 1995 and 2000



Legend: □ ≤ 20 $\mu g/m^3$, □ 20 - 40 $\mu g/m^3$, □ 40 - 60 $\mu g/m^3$, □ 60 - 80 $\mu g/m^3$, □ 80 - 100 $\mu g/m^3$, ■ 100 - 125 $\mu g/m^3$, ■ 125 - 150 $\mu g/m^3$ and ■ > 150 $\mu g/m^3$; cities: D Dortmund in the Ruhr area, K Kassel in Northern Hesse, L Leipzig and B Berlin.

Figure 3. Locations of fossil fuel fired power plants and wind stations

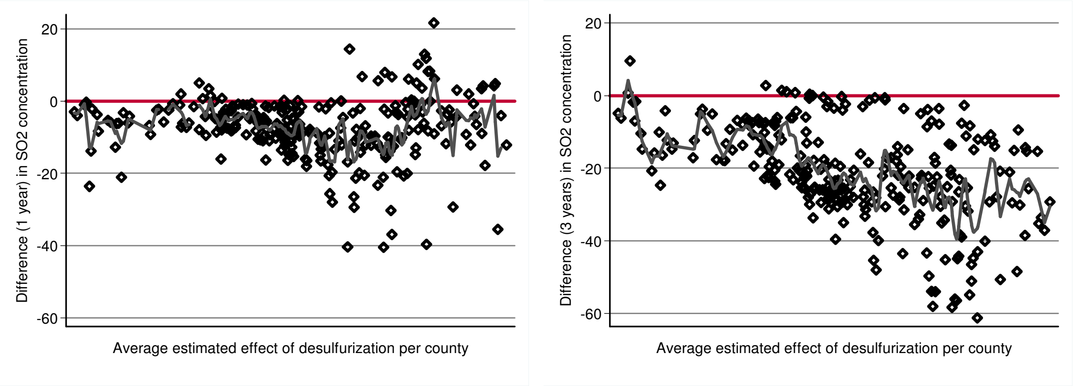


A. Power plants

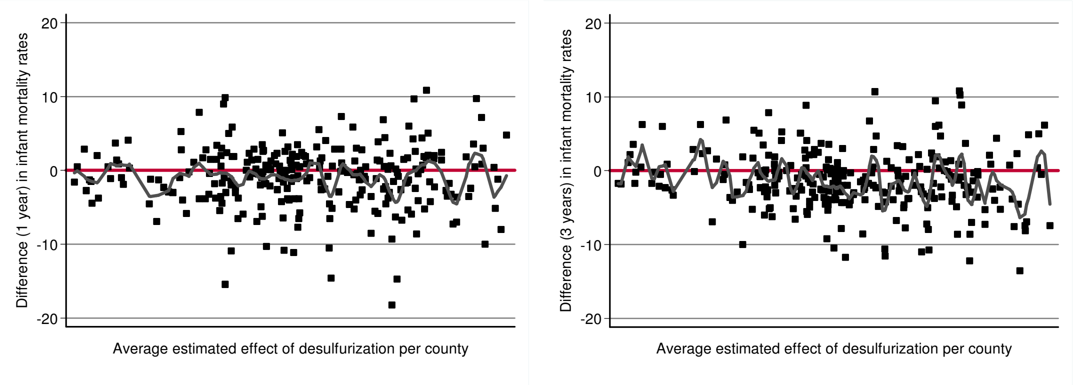
B. Wind stations

Figure 4. Pre- and post-desulfurization pollution and infant mortality differences and average estimated effect of desulfurization per county

A. Pre-desulfurization pollution differences B. Post-desulfurization pollution differences



C. Pre-desulfurization mortality differences D. Post-desulfurization mortality differences



Notes: (1) Pre-desulfurization differences relate to the years 1986-1985 for West Germany and the years 1993-1992 for East Germany, post-desulfurization differences to the years 1989-1986 for West Germany and 1996-1993 for East Germany. (2) The panels show the actual and Kernel-weighted local polynomial regression-smoothed values. Stata's default options are used for Kernel smoothing, i.e. an Epanechnikov kernel function, zero degree polynomial and rule-of-thumb bandwidth.