Coal, Smoke, and Death:

Bituminous Coal and American Home Heating, 1920-1959

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Air pollution was severe in many parts of the United States in the first half of the twentieth century. Much of the air pollution was attributable to bituminous coal. This paper uses newly digitized state-month mortality data to estimate the effects of bituminous coal consumption for heating on mortality rates in the U.S. between 1920 and 1959. The use of coal for heating was high until the mid-1940s, and then declined sharply. The switch to cleaner fuels was driven by plausibly exogenous changes in the availability of natural gas, the end of war-related supply restrictions, and a series of coal strikes from 1946-1950. The identification strategy leverages the fact that coal consumption for heating increases during cold weather. Specifically, the mortality effects are identified from differences in the temperature-mortality response functions in state-years with greater coal consumption. Cold weather spells in high coal state-years saw greater increases in the mortality rates than cold weather spells in low coal state-years. Our estimates suggest that reductions in the use of bituminous coal for heating between 1945 and 1959 decreased average annual mortality by 2.2-3.5 percent, January mortality by 3.2-5.1 percent, average annual infant mortality by 1.6-2.8 percent, and January infant mortality by 3.1-4.6 percent. Our estimates are likely to be a lower-bound, since they only capture short-run relationships between coal and mortality.

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1. Introduction

Humans have used fuels for heating for millennia. These fuels caused indoor and outdoor air pollution. The outdoor component was particularly significant in cities, where widespread burning of fuels led to large concentrations in particulates. As wood began scarce, many societies began to burn coal. In developing countries today, the use of coal for heating is causing severe air pollution in cities (Almond et al 2009, Cohen et al 2004). The United States experienced similar issues in large cities in the 1930s and 1940s (Eisenbud 1978, Tarr 1996, Tarr and Clay 2012). London experienced killing 'fogs' or smogs from the 1850s on, and its most famous fog in 1952 (Clay and Troesken 2010).

This paper uses newly digitized mortality data from the United States at the state-month level to quantify the effects of changing coal use on overall mortality and on infant mortality. The use of bituminous coal for heating was high from 1920 through the mid-1940s and then began to decline sharply for arguably exogenous reasons. At its peak, more than 50 percent of United States households used coal for home heating, and the vast majority, 66-86 percent of these households used bituminous coal. The decline in the use of coal, which began in the mid-1940s, was driven by coal strikes of the second half of the 1940s, the end of war-related supply restrictions on oil and natural gas, increased supply via new long-distance pipelines, and the availability of low-cost conversion units for furnaces.

Coal use for heating is likely to have had two countervailing effects on mortality. Greater consumption of coal for heat is likely to have some "protective effect", since indoor heating reducing the physiological stress associated with cold temperatures. At the same time, the use of coal for heating has a significant "air pollution effect", which is increasing in population density. Many residential coal users were located in dense urban areas, burned the coal at relatively low temperatures, and had low chimneys, all of which increased population exposure to pollution. In contrast to residential users, companies involved in manufacturing and electricity generation tended to be located away from the most densely populated areas, burned coal at high temperatures, and had higher smokestacks that allowed for dispersion of smoke across a much wider area. An increase in coal consumption has a theoretically ambiguous effect on mortality, when the protective effects and polluting effects are both relevant. However, the rapid adoption of cleaner fuels in the 1940s is hypothesized to yield improvements in air quality and health without sacrificing indoor heat.

Our identification strategy leverages variation in the interaction between weather and bituminous coal consumption within states over time. As we explain in the background section, the variation in coal consumption *across states* is most likely due to proximity to deposits across states, and the variation in coal consumption *over time* is related to a series of shocks that occurred in the mid-1940s that lead to rapid declines in the use of coal for home heating. These historical facts bolster the causal interpretation of our estimates. The key variable in our regression model is the estimated consumption of bituminous coal per capita interacted with heating degree-days with a base of 65. In simple terms, the identifying variation comes from the differences in the mortality response from the unusually cold winters in high- versus low-coal-consumption states (or state-years). The controls include main effects for the coal consumption and heating degree days, as well as state by month fixed effects, (national) year by month fixed effects, and state-specific time trends. The coal consumption measures were interpolated from 5-year estimates from the *Historic Emissions of Sulfur and Nitrogen Oxides in the United States from 1900 to 1980*. Heating degree-day variables were constructed from daily weather station-day temperature readings from the United States Historical Climatology Network.

Reductions in the use of bituminous coal for heating between 1945 and 1959 decreased annual average mortality 2.2-3.5 percent, January mortality by 3.2-5.1 percent, annual average infant mortality by 1.6-2.8 percent, and January infant mortality by 3.2-4.6 percent. Our results are robust to a variety of specification checks, including using a heating degree day base of 50F; using a two month moving average of heating degree days; and controlling for income, other uses of bituminous coal, and these variables interacted with heating degree days. Also, we find that states with higher consumption in 1920 experienced greater declines in temperature-mortality response function after 1945 than states with lower coal consumption, which is consistent with our estimates being driven by arguably exogenous post-1945 decline in coal consumption. Our estimates are likely to be a lower-bound, since they only capture short-run relationships between coal and mortality.

Our paper complements pollution-mortality studies that rely on contemporary data. Chay and Greenstone (2003a, 2003b), Currie and Neidell (2005), Currie, Neidell, and Schmieder (2009), Currie and Walker (2011), Knittel, Miller, and Sanders (2012) have examined the effect of pollution on infant mortality in the U.S. in the late 20th century. Arceo-Gomez, Hanna, Oliva (2012) present results from Mexico, where particulate levels are roughly twice the levels in the U.S. There is also a closely related epidemiology literature (Pope et al 2002 and Laden 2006). Our paper examines infant and overall mortality in a period where winter urban particulate levels are roughly eight times the levels in the U.S. in the late 20th century and four times the levels in Mexico. The levels experienced in the historical U.S. were more comparable to those experienced in developing countries today (Almond et al., 2009, Cohen et al 2004).[1]

[1] This paper also contributes to the small but expanding historical literature on fuel use and fuel transitions (Wright 1964, Herbert 1992, Castaneda 1999).

2. Coal

Figure 1 shows energy consumption by source in the U.S. economy as a whole. Until the 1880s, the primary source of fuel in the economy was wood. Wood was surpassed by coal in the 1880s and coal remained the dominant fuel source through the 1940s, when it was surpassed by petroleum. Initially, anthracite coal from eastern Pennsylvania was dominant. As deposits west of the Alleghenies were developed and transportation facilities improved, bituminous coal became dominant.

Over this period, bituminous coal was used for many purposes. Figure 2 illustrates the trends in consumption for four primary uses– heating, industrial production, electricity generation and rail transportation. Consumption differs over time across the four uses. Bituminous coal consumption for electricity rises fairly steadily. Bituminous consumption for heating rises fairly steadily and then falls after 1945. Bituminous consumption for industrial purposes is fairly volatile, peaking in the 1920s and again in the 1940s. Consumption by railroads peaks in 1920, falls to 1935, increases in 1940 and 1945 and the resumes its decline. Our identification strategy leverages the variation in coal consumption over time within states.

Bituminous coal, particularly bituminous coal for heating, was also considered a major contributor to winter particulate pollution. In 1930 the U.S. Public Health Service received an appropriation of $25,000 to study air pollution. As the introduction to the study noted, "In recent years the pollution of the atmosphere by smoke and other impurities, especially in the larger cities, has been the subject of much discussion. … There has been much discussion as to the injurious effects of smoke upon health."[2] Given their limited resources, the goal of the 1930 study was solely to collect data on air quality in large American cities. Owens automatic air

[2] Ives et al (1936), p. 1.

filters were run continuously in fourteen large U. S. cities beginning in July 1931. Total suspended particulates (TSP) were also sampled, although with lower frequency, because of the higher cost of data analysis. Analysis showed that TSP levels were highly correlated with the shade of the Owens automatic air filter. Figure 4 shows that winter air quality was nearly twice as bad as summer air quality. Average TSP in the winter months in these cities was 510. The study explored heating's contribution to pollution by examining pollution by time of day and by comparing Sundays, when most businesses were shut, to weekdays. Both analyses suggested that heating with coal was a major cause of pollution. Based on this analysis, the study concluded "the nonindustrial pollution in the winter, resulting from the heating of residences, apartment houses, hotels, and other buildings, appears to be a greater factor than the year-round industrial pollution."[3] We return to this issue in a later section.

Figure 3 provides further evidence on the seasonality of consumption of retail coal, which was used for heating and for hot water, and the seasonality of other coal uses, including electricity generation, industrial production, and transportation. The *Minerals Yearbook* only began reporting consumption by use by month in 1951.[4] January consumption for retail coal was more than three times the consumption in the lowest month, which typically falls in the May-July window. In comparison, non-retail use was only slightly seasonal. Analysis of other years indicates that the seasonality of coal consumption was fairly stable across the 1950s. This suggests that consumption of retail coal followed similar patterns in the earlier period. Our identification strategy also leverages the variation in coal consumption for heating across months within states.

[3] Ives et al (1936), p. 47.
[4] Other years of data have similar seasonal relationships.

Table 1 presents selected estimates of particulate pollution in the United States and developing countries. Particulates were not routinely measured in the United States until the late 1960s. While particulate pollution in the United States is currently low and has been relatively low level for a number of decades, it was high in the 1930s. Additional evidence on levels of sootfall from New York and Pittsburgh suggest that levels remained high into the mid-1940s.[5] Notably, pollution levels in American cities in the 1930s were similar to pollution levels in developing countries in the late twentieth century.

Household Fuel Choices

Households can be thought of as choosing a heating fuel from the available choices based on price per BTU and then choosing an amount of fuel to consume based on weather and income.[6] Heating was a likely to have been a normal good for most households, so it is not surprising that the consumption of heat tracked income. Figure 5 shows real income and BTUs per capita for the period 1935-1960 from Strout (1961). Over this period consumption of BTUs increased by more than 50 percent, with most of this increase occurring in the 1935-1944 time period, along with real income growth.

From 1910 through the mid-1940s, households predominantly chose coal for heating. Figure 6 shows the evolution of per capita consumption of bituminous and anthracite coal over time. Anthracite consumption fell as bituminous became widely available at lower prices.[7] Figure 7 presents the shares of household heating fuels in 1940, 1950, and 1960. 1940 was the first year that the decennial census asked households about heating fuels and was quite close to

[5] See Davidson and Davis (2005) for Pittsburgh and Eisenbud (1978) for New York.
[6] As we discuss in section 3, the external health effects of coal consumption were not well understood until the 1990s. And – to the extent that households considered it – they were likely to undervalue these effects.
[7] Retail sales of anthracite coal are not available until the 1950s. At that point, they were 20 percent of retail coal sales on a tonnage basis (*Minerals Yearbook*). Estimates in the mid 1920s suggested that 65 percent of anthracite was being used for heating. Department of Commerce (1929), p. 6. The series in Figure 6 uses this 65 percent estimate.

the peak year of retail coal consumption.[8] In 1940, coal was the dominant heating fuel, followed by wood. Natural gas and fuel oil were each around 10 percent. Between 1940 and 1960, the use of coal and wood fell sharply and was matched by sharp increases in the use of natural gas and fuel oil.

Although 55 percent of U.S. households in 1940 used coal for home heating, usage varied widely by population density and by region. The fraction of households using coal was high in urban (64 percent) and rural-nonfarm (54 percent) areas. Rural farm households still largely used wood (67 percent), although a modest fraction of households used coal (28 percent). In the North, which was populous, cold, and close to coal deposits, the fraction of households using coal in rural nonfarm (72 percent), rural farm (49 percent), and urban (79 percent) areas were much higher than the national average. The fraction of households using coal in urban areas in the South was much smaller (44 percent). In the West, households in urban areas were predominantly using natural gas (49 percent), as opposed to coal (24 percent). The energy mix in the West region reflected their proximity to natural gas fields in the Southwest.

Proximity to coal fields was a strong predictor of the use of coal for home heating. Figure 8 shows the location of coal deposits in 1920. All of the deposits except the small black ones in eastern Pennsylvania were bituminous. Figure 9 illustrates that being close to a bituminous coal field, like in the Midwest or West, was strongly correlated with bituminous coal consumption in 1920. One exception, despite its proximity to bituminous deposits, was Pennsylvania. Pennsylvania was in the lowest quartile, because anthracite was widely used for heating.

The Switch to Other Fuels

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[8] Unfortunately, the census did not ask whether households were consuming anthracite or bituminous coal.

In the second half of the 1940s, cleaner fuels – natural gas and heating oil – quickly began to supersede coal for use in heating. Understanding why consumers were switching heating fuels is crucial for interpreting our estimates. Based on the available evidence, the most important factors appear to have been the price and availability of coal relative to alternative heating sources. Figure 10 presents city-level fuel prices per million BTU (in 2010$) for 1941-1954. Natural gas prices were falling rapidly, for reasons which will be discussed shortly. The December prices of bituminous and anthracite were rising.

The *Greensburgh (PA) Daily Tribune* reported the results of a recent survey of residents' fuel choices in March 1946: "The survey disclosed that most local people are converting to natural gas because of the higher prices of coal, and because of the elimination of firing the furnace, removing ashes, and cleaning up basement dust by the use of gas. Gas furnaces are still somewhat more expensive to operate than coal furnaces, but the difference in most instances is not much considering the added conveniences."[9]

Coal strikes throughout the 1940s raised the specter that a large strike could cause prices to increase and shortages to emerge. Strikes had occurred in the pre-war period, notably in 1939 and 1941. The strikes in 1946 and 1949-1950 sharply restricted production, adversely affected coal stocks, and raised prices. In both cases, daily production fell from 2 million tons per day to well below 1 million tons per day.[10] These strikes idled manufacturing, prompted restrictions in electricity production (dimouts), and caused restrictions in freight shipments and travel. In response to the second strike in November 1946, the *New York Times* reported, "Further reductions in travel, heating, lighting and even cuts in the dispatch of mail were officially

[9] *Greensburg (PA) Daily Tribune*, March 22, 1946, p. 1.
[10] Bituminous Coal section*, Mineral Resources*, 1939-1952. See also, *Statistical Abstract of the United States*, 1951, Table 825: Work stoppages in Anthracite and Bituminous Coal Mining Industries by Major Issues Involved, 1938 to 1950.

foreseen in the event of a prolonged strike."[11] The Public Buildings Administration ordered "reduce[d] heating temperatures to the wartime maximum of 68 degrees if they use coal." [12]A coal supplier in the New York area quoted in the *Wall Street Journal* in 1946 explicitly linked the strikes to switches in fuels "Every time John Lewis stages a coal strike I lose several score customers to oil."[13]

One major constraint on switching was the availability of alternative fuels. Fuel oil was shipped via tanker or train and was available in many large cities by the 1940s. Gas was widely used for cooking in cities by the 1940s, because of its superior properties to coal. Data from the 1940 Census indicates that coal was only used by 12 percent of households for cooking nationally and 8 percent of households in urban areas. The gas for cooking was, however, manufactured gas, which was extracted from coal. Manufactured gas was generally too costly to be used for heating. The widespread use of gas for cooking meant that the switch to coal for heating was relatively straightforward. Gas pipelines had already been built to carry manufactured gas to homes and buildings. Connections still had to be made between furnaces basements and the incoming pipe, and pressures had to be adjusted. Compared to having to build gas infrastructure from scratch, however, but this was a relatively straightforward task.

Two problems had to be solved before natural gas from the Southwest could be used for heating.[14] Pipelines had to be built to move the gas from the Southwest to the Midwest and the East, and storage capacity had to be developed to store gas near the destination. The issue was that winter demands for gas were much higher than summer demands, so gas had to be to moved during the summer and fall and stored near population centers for use in the winter. Figures 9a

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[11] *New York Times*, November 22, 1946, p. 2.
[12] *New York Times*, November 22, 1946, p. 2.
[13] *Wall Street Journal*, September 26, 1946, p. 1.
[14] Hebert (1992) and Castaneda (1993).

and 9b show Natural Gas Pipelines in 1940 and 1949. By 1940, some pipelines had been built. The distances that they moved gas and their capacity were still fairly limited. By 1949, major expansion of natural gas pipelines had taken place.

The sale and conversion of the Big Inch and Little Big Inch pipelines dramatically expanded the nation's capacity to move natural gas. Early in World War II German submarines were routinely sinking ships carrying oil. Proposed in 1940, the pipelines were built in 1942-1943 to move oil from Texas to the East Coast. In 1947, the pipelines were sold to the Texas East Transmission Company and were converted to natural gas.

The development of high-volume long-distance pipelines spurred the development of underground storage, which rose from 250 billion cubic feet in 1947 to 1,859 billion cubic feet in 1954.[15] Storage was primarily located in former gas, oil, or mixed oil and gas fields in Pennsylvania, Michigan, Ohio, and West Virginia.

The share of residential gas customers using gas for heating rose from 36 percent in 1949 to 53 percent in 1954. Figure 11 demonstrates that the gas industry experienced sharp upticks in the sale of gas furnaces and in conversion burners. Conversion burners allowed homeowners to switch from using coal to natural gas without replacing the entire furnace.

The end of World War II also led to a boom in the use of heating oil. Supply was becoming an issue even before the United States entered the war as shipping capacity became scarce. Rationing of fuel oil beginning in October 1942 limited the ability of coal users to switch to fuel oil. It reportedly also incentivized some fuel oil users to switch back to coal, which was not rationed. In New York in the fall of 1945, the removal of rationing on oil and the strengthening of rationing of anthracite coal prompted a rush to convert to oil. The *New York*

[15] American Gas Association (1956).

Times reported "The present wave of conversions to oil is not confined to systems that burned oil before the wartime shortage caused a shift to coal. Many systems that were originally installed for coal are being converted to oil or replaced with oil equipment."[16] The *Times* also noted that the original oil to coal conversion cost about $50 and the reconversion cost about $50 if the oil burner and controls were still in working order. By 1946, oil was even more popular and the main constraint was the availability of oil-burning furnaces. A September 1946 Wall Street Journal article on heating oil reported, "Such production [375,000 units] will merely dent the market which currently shows a six to eight-month backlog of unfilled orders."[17]

We leverage many of these historical events, including the strikes, the war, and the postwar expansion of natural pipelines, to identify the causal effects of coal on mortality.

3. Coal-Related Emissions and Mortality

Emissions

Most of the discussion that follows will focus on particulates, since most of the early measurement of air pollution involved particulates and most of the epidemiological work has been done on particulates. Particulates are highly correlated with other coal-related emissions such as carbon monoxide and sulfur dioxide. Some recent studies find mortality effects from these emissions as well. This section should be read as being about coal-related emissions broadly construed.

[16] *New York Times*, September 12, 1945, p. 22 (continued from page 1).
[17] *Wall Street Journal*, September 26, 1946, p. 1.

When burned for heating purposes, different fuels have different particulate burdens.[18] The challenge is to understand the particulate emissions from historical stoves, fireplaces, and furnaces. Butcher and Ellenbecker (1982) examined particulates from wood, bituminous coal, and anthracite coal when burned in a residential heater. They found that "Particulate emission factors for wood ranged from 1.6 to 6.4 g/kg (fuel) and were found to depend on the fuel load and the firing rate ... The average particulate emission factors for bituminous and anthracite coal are 10.4 and 0.50 g/kg."[19] The relative ordering for particulate emissions was likely to be bituminous coal, wood, and anthracite coal.

Human exposures to particulates will depend on properties of the fuel and the conditions under which is burned. At the beginning of the twentieth century, exposure occurred both indoors and outdoors, as households burned fuel in open stoves or fireplaces in homes. Ryhl-Svendsen et al (2010) reconstructed indoor exposure to particulate matter from wood burning in historical homes in Denmark. They find "a woman living in this type of house during the 17–19th century would be exposed to daily averages of 1.1 ppm CO and 196 μg m^{-3} $PM_{2.5}$, which exceeds WHO guideline for $PM_{2.5}$, and is comparable to what is today observed for women in rural areas of developing countries."[20] In comparison, current EPA limits are 65 μg m^{-3} $PM_{2.5.}$ By the 1930s as households moved to closed stoves and furnaces and to gas for cooking, the burden from indoor combustion declined. Indoor air quality could still be low, however, due to poor outdoor air quality.

[18] A related channel may be through CO emissions, which are highly correlated with particulate matter. Most of the epidemiology literature has focused on particulates. Some recent work finds effects of CO, although separately identifying the effects of CO and particulate matter remains difficult.
[19] Butcher and Ellenbecker (1982), p. 380.
[20] Ryhl-Svendsen et al (2010), p. 735.

Historically coal for heating appears to have been a major contributor to outdoor particulate pollution. Although only scattered evidence exists on air quality for our sample period (1920-1959), they are consistent with reductions in household use of coal having had a significant impact on air quality. The Public Health Service study in the 1930s, which was discussed previously, suggested that coal was a major contributor. An analysis of hours of winter solar radiation – an indirect measure of air pollution in the United States – by Husar and Patterson (1980) shows gains in the 1950s. The gains were particularly large for the North-Central region which had high numbers of heating degree days and intensive use of coal. This is consistent with the evidence in Table 1, which indicates that pollution declined substantially between the early 1930s and the mid-1950s.

Contemporary evidence also supports the importance of residential coal burning as a contributor to outdoor pollution. In Dublin, following the ban on the sale of coal for heating in September 1990, mean winter black smoke concentrations fell by 64 percent and overall concentrations fell 36 percent.[21] Evidence from Poland, where coal is still widely used for home heating, confirms the importance of this source for pollution. A major E.U. study used trace elements to decompose the source of PM during the winter of 2005 in Krakow. It concluded that "residential sources were also found to create the lion's share – beyond any single industrial source – of airborne PM measured near the ground."[22] While some features of Krakow, notably its hilly topography, may have contributed to this effect, one commentator noted that "even low

[21] Clancy et al (2002). Black smoke is a measure of light absorption of PM and is highly correlated with measures of PM10 and PM2.5
[22] Powell (2009), p. 8474, discussing Junninen et al (2009).

emission sources can elevate the concentration level if emission sources are located close to the ground."[23]

Mortality

From the 19th century, public health officials and interested observers had suspected that air pollution was linked to mortality. The 1930s Public Health Service study notes: "No definite relation between smoke and health has, up to the present time, been shown to exist, and no attempt was made in the present study to investigate this phase of the subject, on account of the complexity of the problem and the limited amount of time and money available."[24] Researchers continued to investigate the link. The main constraints were having sufficient high quality particulate data and mortality data and having computers and statistical techniques that could process the data.

Despite the efforts of earlier researchers, it was not until the 1990s that the epidemiological literature convincingly documented the link between airborne particulates and mortality.[25] The studies use different measures of particulates – total suspended particulates (TSP), which are typically less than 25-45 microns, particulates less than 10 microns (PM_{10}), and particulates less than 2.5 microns ($PM_{2.5}$) – and different samples. In the United States, the main samples have been the Harvard Six Cities Sample (Laden et al 2006) and the American Cancer Society Cancer Prevention II study (Pope et al 2002). The studies began in the late 1970s and early 1980s, respectively. Their findings are based on tracking of sample participants, all of whom were adults when they entered the studies. The main outcome measure is overall

[23] Powell (2009), p. 8474, discussing Junninen et al (2009).
[24] Ives et al (1936), p. 1.
[25] The studies examine mortality from particulate exposure at different frequencies, daily, monthly, and annually. One concern with the high frequency studies is that pollution is merely shifting the timing of mortality, but not affecting overall mortality. While shifts in the timing, known as 'harvesting', are occurring for some individuals, the studies find that exposure to particulates also increases overall mortality (Schwartz 2000, Pope et al 2009).

mortality, although the studies also track cause of death data. The reason the studies focus on overall mortality is that cause of death is often subjective and attributions of cause of death may change over time.

More recent studies using quasi-natural experiments also find strong links between particulates and mortality. Chay and Greenstone (2003a, 2003b), Currie and Neidell (2005), and Currie and Walker (2011) exploit permanent declines in pollution to measure the effects on infant mortality in the U.S. in the late 20th century. Epidemiological studies use quasi-natural experiments created by the shutdown of power plants and policy changes regarding the burning of coal.[26] Other papers utilize temporal or seasonal variation in pollution that are not permanent. Currie, Neidell, and Schmeider (2009) have very detailed data on pollution exposure, which varies over time and space, and some mothers with multiple births at different pollution exposures. Knittel, Miller, and Sanders (2012) examine the effect of temporal changes in pollution caused by traffic shocks. Arceo-Gomez, Hanna, Oliva (2012) use a similar strategy to examine the link in Mexico. Clay and Troesken (2010) link variation in weather-related smogs to overall mortality in London.

Research by Pope et al (2004) and DelFino et al (2005) suggest that particulates cause mortality in the adult population through three main mechanisms. The first is that particulates cause pulmonary and systemic inflammation and accelerated atherosclerosis. The second is that particulates adversely affect cardiac autonomic function, causing heart arrhythmias. The third, but less important, mechanism is through pneumonia.[27]

For infants, particulates cause mortality population through two main mechanisms. The first is prenatal. Curry and Walker (2011) use a natural experiment caused by the replacement of

[26] See Pope et al (1992), Clancy et al (2002), Hedley et al (2002), and Pope et al (2007).
[27] For a thorough discussion of the mechanisms for adults and children, see Lockwood (2012).

manual tolling with EZ Pass, which greatly reduced idling and local pollution. Their results show that particulates adversely affect the likelihood of premature delivery and birth weight. Prenatal impacts are likely to be particularly important for much of our sample period, because successful interventions to help premature or low birth weight babies were extremely limited before 1959. The second mechanism is postnatal effects on respiratory and cardiovascular outcomes. Woodruff et al (2008) used U.S. infant birth and death records covering 1999-2002, demographic characteristics, and pollution data. They find a link between particulates and respiratory-related infant mortality. Recent work Arceo-Gomez et al (2012) using data from Mexico supports the link between pollution and infant mortality from respiratory or cardio-vascular causes.

4. Data

Data on overall and infant mortality at the state-month level are taken from the annual *Vital Statistics* volumes. Mortality statistics are reported for "registration states", or states that met specified reporting criteria of the National Center for Health Statistics. Although mortality reporting at the annual level began in 1900, reporting of overall mortality at the state-month level began in 1910 and reporting of infant mortality by state-month began in 1939. There were 19 registration states (including the District of Columbia) in 1910, 34 registration states in 1920, and 49 registration states in 1933. This paper uses data beginning in 1920, at which point 70 percent of states had entered.

Mortality rates were constructed using historical population estimates from the Decennial Censuses. These population estimates were linearly interpolated to construct state-year population estimates. Mortality counts were then divided by the population estimate in 100,000s to get the mortality rate.

Infant mortality rates were constructed using annual state-level birth data from 1940-1959. Birth data were collected from Vital Statistics by Amy Finkelstein and Heidi Williams. To get estimates that were comparable to conventionally reported (annual) estimates, annual live births were divided by 12 to construct monthly mortality rates. Mortality rates are reported per 100,000 live births.

Heating degree days and other climatic data are from the United States Historical Climatology Network (USHCN) Daily Dataset. The USHCN data covers the period from the late 19th century to the present. The data set is comprised of approximately 1,200 weather stations, which were selected by the Department of Energy and the NCDC based on "length of record, percent of missing data, number of station moves and other station changes that may affect data homogeneity." Available weather variables include daily maximum temperature, daily minimum temperatures, and total daily rainfall. Daily mean temperatures are the simple average of the minimum and maximum temperatures.[28]

The temperatures are used to construct "degree day" variables. A temperature of T would have heating degree days (HDD) with a base of H of H minus T for all values of T *less than* H and zero otherwise. We follow the convention and use heating degree days with a base of 65 degrees Fahrenheit, but a 50 degree base is also evaluated. Conversely, a temperature of T would results in a cooling degree days (CDD) with a base of C of T minus C for all values of T *greater than* C and zero otherwise.

The daily weather-station data is aggregated to the state-month level using population-distance weights. This procedure involves three steps. The distance between each weather

[28] Humidity is not available for this period. Humidity is likely to be an important determinant of mortality (Barreca 2012). However, humidity and temperature are strongly correlated in nature. So long as humidity's independent effect on mortality is uncorrelated with state-year coal consumption then our results will be unbiased. That is, the temperature main effect includes humidity's impact.

station and each county centroid is calculated for those weather stations that are within 50 miles of the county centroid. The variables are aggregated to the county-month level using inverse-distance weights. The county-month weather variables are aggregated to the state-month level using the county population as weights.[29]

Fuel consumption data by use is from the *Historic Emissions of Sulfur and Nitrogen Oxides in the United States from 1900 to 1980.*[30] Gschwandtner et al (1983) constructed state-level estimates of coal use by type for 1900-1980 for the purpose of constructing estimates historic emissions of sulfur and nitrogen oxides. Data for 1900-1945, estimates of state-level consumption were created by assigning state shares by use, which were available in 1889, 1917, 1927, and 1957, to national annual estimates by use from *Resources of the United States* and later *Mineral Yearbooks* to get state estimates by use at 5 year intervals.[31] For the period 1950-1960, additional data was available that allowed improvement of the 1950, 1955, and 1960 estimates. To create annual measures, we linearly interpolate between the years ending in 5 and 0. Some specifications use state monthly coal consumption. Data on national monthly coal consumption is available for the 1950s. These data were used to construct monthly shares of coal consumption. Monthly coal consumption was constructed by multiplying monthly shares by state annual consumption.

State per capita income is from the U.S. Bureau of Economic Analysis. The series begins in 1929 and runs to the present. The BEA produces estimates of both nominal and real per capita income. The analysis uses real per capita income in 2010 dollars. It is worth noting that in cross

[29] The county population data are from the decennial censuses and are linearly interpolated between census years.
[30] For more detail, see Chapter 2 of Gschwandtner et al (1983).
[31] The 1889 data is from Census of Manufacturing (1889). The 1917 data is from Lesher (1917). The 1927 data is from Tryon and Rogers (1927). The 1957 data is from U.S. Bureau of Mines (1957). For railroads, the data are from 1889, 1917, 1937 and 1947. The 1889 data is from the Census of Manufacturing. The 1917 data is from the U.S. Bureau of Railways (1917). The 1937 and 1947 for railroads are from *Minerals Yearbook*.

section, in the pooled sample, and in time series, income is weakly correlated with consumption of bituminous coal.[32] This is because some wealthy states were far from bituminous coal deposits and, therefore, consumed anthracite, natural gas or fuel oil. The weak correlation between income and per-capita coal consumption mitigates concerns that our treatment variable is identified from differences in *average* income across states. In panel estimates where the dependent variable was per capita bituminous coal consumption for heating, the independent variable was income, and state fixed effects were included, the elasticity for the period up to 1945 was 0.148. The low elasticity reflects the fact that much of the increases in fuel consumption are coming from fuel oil and natural gas and not from increases in bituminous coal.

Table 2 presents summary statistics from the data set. Overall and infant death rates were falling over time. Consistent with Figure 5, annual per capital consumption of bituminous coal for heating fell slightly between 1920 and 1940 and dramatically between 1940 and 1959. Average (daily) heating degree days, as measured at a base of 65 °F, for the year were 14.5-15.8. In January, the coldest month, they were 34.5-41.4. This implies that the average day in January was between 34.5 and 41.4 °F below 65 °F. That is, the temperature was between 23.6 and 30.5 °F.

5. Identification

Our identification strategy draws on two types of variation. The first is cross-state variation in the temperature-mortality response function as it relates to the use of bituminous coal. The second is within-state changes in the temperature-mortality response function over time as it relates to changes in coal consumption within states over time. The first source of

[32] The pooled correlation is 0.01 for the period up to 1945. The cross sectional correlations are -0.13 in 1931, 0.03 in 1945, -0.0018 in 1959.

identifying variation may be biased if average coal consumption is correlated with other health inputs that affect a population's susceptibility to cold weather shocks. This concern is mitigated by the fact that the variation in bituminous coal consumption across states is closely related to proximity to coal deposits.[33] The second source of identifying variation may be biased if within state changes in coal consumption are related to other changes in health inputs relative to the rest of the U.S. We will address these concerns by testing for observable differences across states and within states over time as they relate to coal consumption.

We focus the on state-month model, as opposed to a state-year model, to exploit the intra-annual variation in cold weather that affects coal consumption. As illustrated in Figure 3, this identification strategy relies on the fact that coal consumption is higher during cold weather months.

Our two basic empirical models for estimating the coal-mortality relationship are:

(1a) $Y_{smy} = \alpha HDD_{smy} + \beta\ COAL_{smy} + \alpha\ TIME_s + \theta_{sm} + \eta_{my} + \varepsilon_{smy}$

(1b) $Y_{smy} = \alpha HDD_{smy} + \beta\ COAL_{sy} + \gamma\ COAL_{sy} \text{ x } HDD_{smy} + \alpha\ TIME_s + \theta_{sm} + \eta_{my} + \varepsilon_{smy}$

where Y is the log of the mortality rate in state s at month m of year y; HDD is heating degree days with a base of 65, which is a measure of cold weather; COAL is the amount of coal consumed in state s in year y or in state s in year y in month m; $TIME_s$ is a state specific linear time trend, θ_{sm} is a vector of state-month fixed effects that account for the possibility that different states have different health outcomes in different months independent of coal consumption. η_{my} are year-month fixed effects to control for spurious time-series correlations

[33] We recognize that proximity to coal consumption may have affected states growth path over time.

between the error term and health outcomes. The error term (ε) is clustered at the state-level to account for time series correlation within states.

In each year, households choose the heating technology based on expected heating degree days, expected price per BTU, depreciation costs of technology, and income. Technology determined how much useable heat could be extracted from a given unit of fuel. For example, coal moved from being burned in open fireplaces, which was relatively inefficient, to being burned in stoves to being burned in furnaces, which was relatively efficient. Lower prices and higher income allowed households to consume more heat holding heating degree days constant. The outcome of this decision process was quantities of bituminous coal, anthracite coal, wood, natural gas, and heating oil.

This decision process implies that the effects of heating degree days will depend on the fuels that are being consumed to generate heating-related BTUs. While other fuels do emit some particulates, the predominant factor for heating-related pollution will be the amount of bituminous coal used for heating. Baseline pollution levels will also depend on other (nonseasonal) uses of bituminous. In some specifications, they are controlled for directly. These are likely to be controlled for by the fixed effects and time trends. For example, aggregate demand for industrial goods is likely to be uncorrelated with unexpected changes in heating degree days near the factory.

We add numerous controls to mitigate possible omitted variables bias. Year-month fixed effects capture any macroeconomic shocks that might be related to coal consumption and mortality. State-month fixed effects control for the possibility that states' seasonal mortality relationships are correlated with weather and coal consumption. State time trends address the fact that mortality is falling within states over time (see Table 2). Different states may be experiencing different rates of decline and this decline might be related to changes in coal consumption. Some specifications also control for per capita income, consumption of bituminous coal for non-heating purposes and these variables interacted with heating degree days.

There are a few important caveats regarding the causal interpretation of our estimates. First, our model is identified from short-run variation in pollution exposure. If, for example, pollution affects health capital in the long run (e.g. next year), then our estimates will underestimate mortality effects. Second, the effects of HDD are assumed to be linear and constant across states. We investigate this by running alternative specifications that vary the heating degree day base and the sample based on states' coal consumption in 1920.

6. Results

Table 3 presents an initial analysis of the relationship between bituminous coal, heating degree days, and the log of the mortality rate for 1920-1959. Column 1 examines the relationship between heating degree days and monthly mortality between 1920 and 1959, controlling for year-month fixed effects, state-month fixed effects, and state time trends. The coefficient on heating degree days is positive, significant, and large. It is worth noting that heating degree days averaged about 15 for the whole year, and around 35 in January. These are helpful benchmarks for illustrating the effects of heating degree days on mortality. In months with 15 and 35 heating degree days, the mortality rates increase by 7.5 and 17.5 percent. These estimates are consistent with Anderson and Bell (2009) and other research showing an increase in mortality in when weather is unusually cold. Column 2 controls for monthly consumption of bituminous coal for heating. The coefficient on per capita consumption is positive and statistically significant. It indicates that decreasing bituminous consumption by 0.10 tons per capita for heating – the average decline in January consumption between 1945 and 1959 – decreased January mortality by 5.1 percent. Across all months, the average decline was 0.06 tons, implying annual declines of 3.1 percent.[34]

The next two columns show the effects of annual per capita coal and annual coal interacted with heating degree days, a proxy for monthly coal consumption. In column 3, the coefficient on annual coal is positive significant and slightly greater than one-twelfth of the monthly coefficient. In column 4, the coefficients on heating degree days and per capita consumption of bituminous remain positive and statistically significant, although the magnitudes of the coefficients are slightly smaller than in column 3. The interaction term is positive and significant, suggesting that relatively more individuals die in colder months in state-years with relatively higher bituminous coal use. Per capita bituminous coal consumption declined by 0.75 tons between 1945 and 1959. The regression estimates suggest that this decline reduced average annual mortality (15 HDD) by 3.5 percent and January mortality (35 HDD) by 4.3 percent.[35]

Columns 5-8 replicate the regressions using quarterly rather than monthly data. This addresses the concern that the effects of pollution are merely 'harvesting' those who would die soon anyway, but not having an overall effect on mortality. If this were true, the coefficients on monthly coal and the heating degree day-coal interact terms should fall. This specification also relaxes the restrictive assumption that individuals die in the month in which high coal consumption occurs. If individuals fall sick and die in the following month, the monthly estimates may be biased downward. This would imply that the coefficients on monthly coal and

[34] Coal is measured in 1000s of tons, so .10 ton is 0.0010. At 15 HDD the effect is 0.0006*508.8 = 0.031. At 35 HDD the effect is 0.0010*508.8 = 0.051.

[35] Coal is measured in 1000s of tons, so .75 ton is 0.00075. At 15 HDD the effect of coal on mortality is 0.00075(39.002+0.517*15) = 0.035. At 35 HDD the effect is 0.00075(39.002+0.517*35) = 0.043. One might want to focus just on the interaction effect, if there were concerns about the endogeneity of per capita consumption of bituminous coal. At 15 HDD the interaction effect is 0.00075(0.517*15) = 0.006. At 35 HDD the interaction effect is 0.00075(0.517*35) = 0.014. Analysis later in the paper suggests that endogeneity is not a significant issue.

the heating degree day-coal interaction terms should increase. In fact, the point estimates increase slightly, suggesting that lagged mortality effects outweigh any harvesting effects.[36]

Table 4 examines infant mortality and overall mortality for the period 1940-1959. These estimates suggest that infant mortality is more responsive than overall mortality to increases in bituminous coal consumption for heating. Column 1 examines the relationship between heating degree days and infant mortality at the state-month level, controlling for consumption of bituminous coal for heating. The coefficient on heating degree days is positive, significant, and similar in magnitude to the coefficient on overall mortality in Table 3. The coefficient on per capita consumption of bituminous for heating is positive and statistically significant. The point estimate indicates that the reduction in mortality would be 4.4 percent in January and 2.7 percent annually. [37] Column 2 provides a direct comparison with overall mortality for the same period. The coefficient on monthly coal consumption is positive and statistically significant. The point estimate indicates that the reduction in mortality would 3.6 percent in January and 2.2 percent annually.

In columns 3 and 4, the base effects of coal are positive but not significant. The marginal effects are positive and significant and much larger for infants than overall (1.07 vs. 0.46). This is consistent with the infants being more sensitive to environmental insults. For a decline of the magnitude of the 1945-1959 decline, the annual effect on infants would be to decrease mortality by 1.6 percent and January mortality by 3.1 percent. The annual effect overall would be to decrease mortality by 2.5 percent and to decrease January mortality by 3.2 percent.

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[36] The effects are also similar, that is the coefficients are slightly higher than in columns 2-4, if a two month moving average of heating degree days is substituted for a one month measure of heating degree days.

[37] At 15 HDD the effect is 0.0006*442.7 = 0.027. At 35 HDD the effect is 0.0010*442.7 = 0.044.

Columns 5-8 present the results at the quarterly level. As in Table 3, the coefficients on monthly consumption are slightly larger and the coefficients on heating degree days interacted with coal are substantially larger.

Table 5 considers alternative specifications including using 50 degrees as the baseline for heating degree days and controlling for the log of real income interacted with heating degree days and for non-heating uses of bituminous coal, including per capita consumption for electricity generation, by industry, and by railroad, interacted with heating degree days. The coefficients on the interaction term are remarkably robust to these alternate specifications. They remain uniformly positive and statistically significant. Further, the magnitudes of the coefficients are similar to their magnitudes in Tables 3 and 4.

Tables 3-5 are consistent with the use of bituminous coal for home heating having an adverse effect on overall and infant mortality. One concern is that the tables include both heating degree days and coal consumption for heating. Coal consumption is estimated at 5-year intervals based on national totals and state shares in 1917, 1927, 1957 and interpolated to the annual level, so it does not directly reflect coal consumption. Even so, coal consumption may be at least partially endogenous.

To address endogeneity, states' 1920 per capita bituminous coal consumption was interacted with a flexible (two segment) time trend that varies linearly in time with a break at 1945. This specification choice accords with Figure 6, where we see a break in per capita consumption around 1945.[38] As discussed in the identification section, the effect of consumption of bituminous coal is unclear in the period up to 1945, because the protective heat effect offsets the pollution effect to some unknown degree. The effect should be strongly negative, however,

[38] Note that the data is linearly interpolated for years not ending in 0 and 5 so we cannot be sure of the exact break point.

in the post-1945 period, since heat consumption had leveled off and households were switching to cleaner fuels.

Table 6 presents the analysis. Column 1 controls for heating degree days and includes two 1920 coal linear time trends -- a trend for the whole period and a differential trend for post-1945, each interacted with heating degree days. The coefficient on heating degree days is positive and significant. The coefficient on coal 1920 x HDD is negative and significant. States with low coal consumption in 1920 are have lower mortality per HDD than states with low coal consumption. The coefficients on the coal time trends are both negative and statistically significant. Notably, the coefficient for the post-1945 trend is statistically significantly more negative than the trend for the full period (-0.0027 steeper than -0.0029). Column 2 shows the same specifications for infant mortality. The pattern is very similar to the pattern for overall mortality. Columns 3 and 4 show the effects for heating degree days interacted with time (without coal). The trend has very little slope and the post-1945 trend is not statistically significantly different than the trend for the entire period. The main point is that the effects in columns 1 and 2 reflect the effects of coal and not merely the effects of heating degree days interacted with time trends. The coal-heating degree day time trend and the heating degree day time trend are, by construction, highly collinear. So in columns 5 and 6, when both are included, the coefficients on the variables are insignificant.

Table 7 presents an instrumental variables model analog to Table 6. We estimate this model to address concerns that the state-year coal consumption measures are endogenous and are measured with error. Specifically, we instrument the change in mortality between 1945 and 1959 with the 1920 level of coal consumption. We expect states with higher coal consumption in 1920 would have higher consumption in 1945 and see a greater decline in coal consumption post

1945 due to coal strikes and increased availability of natural gas (see Background section). In this model, the dependent variable is the change in log infant mortality. The endogenous variables in the regressions are the *change* in annual per capita coal consumption interacted with HDD (DPC Bit x HDD65).

The specifications in columns 1 and 2 differ in their inclusion of state fixed effects. Without state fixed effects, identification comes from differences across states and months, whereas with state fixed effects, identification comes from differences within state across months. Colder months experienced bigger declines in coal consumption than warmer months. The coefficients on the change in the interaction term are positive and statistically significant. Thus states with bigger declines in coal consumption in a given month experienced bigger declines in mortality.

Columns 3 and 4 are the instrumental variables specifications. The first stage for column 3 is columns 2 and 3 in Table 7b. Without state fixed effects, there are two variables to instrumented DPC Bit and DPC Bit x HDD65, and two instruments Coal 1920 and Coal 1920 x HDD65. The F-statistics are high, suggesting that the instruments are not weak. The first stage for column 4 is column 3 in Table 7b. With the state fixed effects, DPC Bit drops out. This leaves one variable to be instrumented DPC Bit x HDD65 and one instrument, Coal 1920 x HDD65. They imply declines in infant mortality ranging from 1.7 to 2.1 percent. Columns 5-8 present the same specifications for overall mortality. They imply declines in overall mortality ranging from 1.8 to 2.0 percent.

The IV estimates of the coefficient on the interaction term are very close to the OLS estimates. There are at least two reasons why this may be true. The first is that per capita bituminous was constructed by using 1927 and 1957 state shares and national coal consumption estimates, which already removes some of the endogenous within-state variation. The second is that 1920 consumption is a very strong predictor of coal consumption in 1945.

7. Conclusion and Discussion

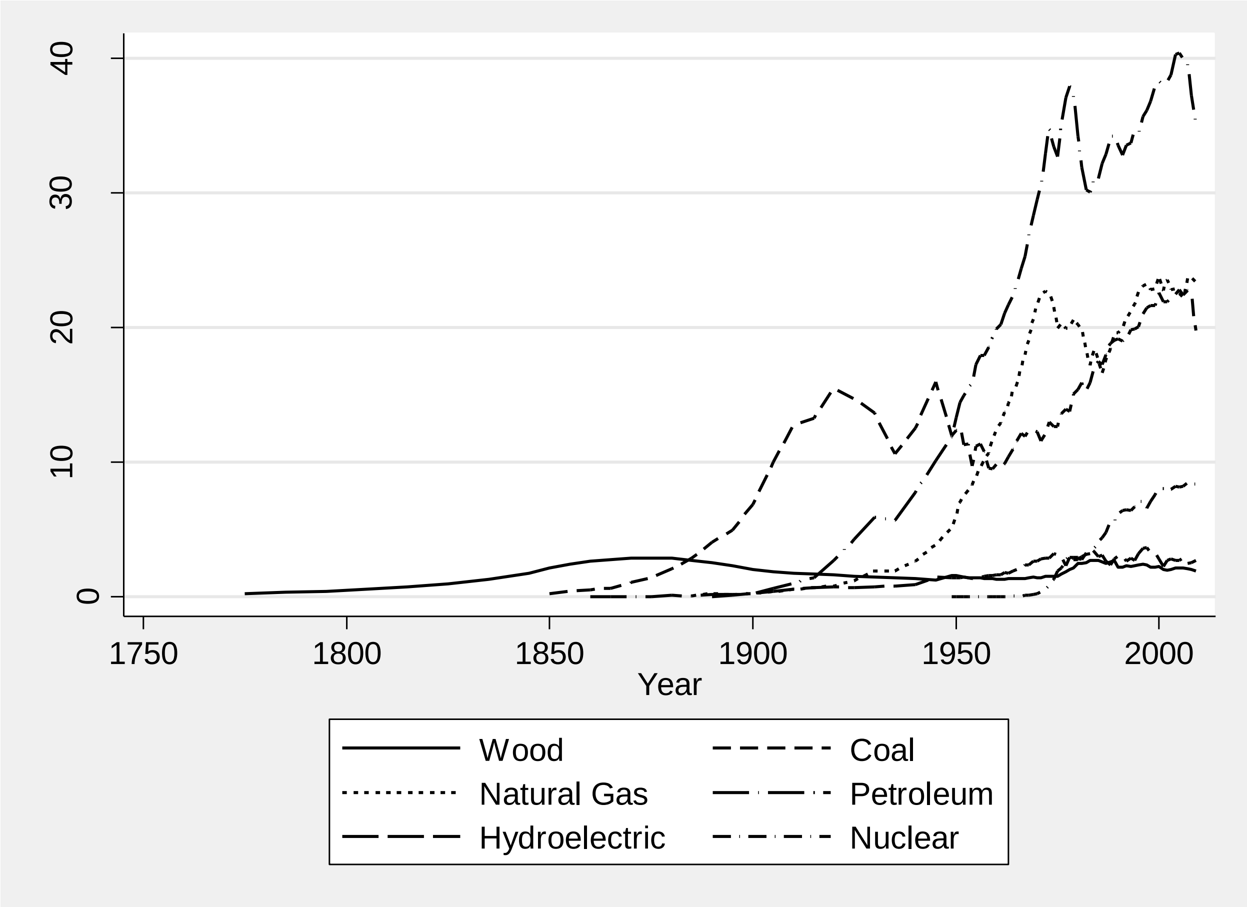
This paper found that colder weather and the use of coal for home heating increased state-monthly mortality during the period 1920-1959. Our regression results imply that reductions in the use of bituminous coal decreased annual average mortality by 2.2-3.5 percent, January mortality by 3.2-5.1 percent, annual average infant mortality by 1.6-2.8 percent and January infant mortality by 3.1-4.6 percent. Our estimate is likely a lower-bound, since it only captures short-run relationships between coal and mortality and implicitly assumes that coal consumption for heating was zero in months with zero heating degree days.

The use of coal for home heating accounts for a greater share of the decline for overall mortality than for infant mortality. For example, overall mortality declined 9.8 percent between 1945 and 1959. Thus, decreased use of coal for heating accounted for 22-36 percent of the decline in overall mortality. Infant mortality declined 23.0 percent between 1945 and 1959. Decreased use of coal for heating accounted for 7.0-12.2 percent of the decline in infant mortality.

To get a clearer sense of the meaning of the magnitudes, it is also helpful to look at the related literature. Arceo-Gomez, Hanna, and Oliva (2012) present a table, which is reproduced in Table 7. showing the elasticities for particulate matter (PM_{10}) and infant mortality. Unfortunately, the measurement of particulates in the U.S. in the 1920-1959 period was very limited. Our back of the envelope estimate is that a reduction in consumption of bituminous coal for heating would yield a decline of 22-50 percent in January particulates. The 22 percent estimate reflects the fact that bituminous coal for heating fell from 22 to 11 percent of bituminous coal between 1945 and 1959 and assumes that bituminous coal for heating was burned in half the year. The 50 percent estimate assumes that all of the increase in Figure 4 is due to the use of coal for heating. The implied elasticity for infant mortality in January is fairly small relative to contemporary estimates: 0.062-0.209. In comparison, the elasticity for Mexico, where particulate levels were relatively high, was estimated to be approximately 0.325-0.415.

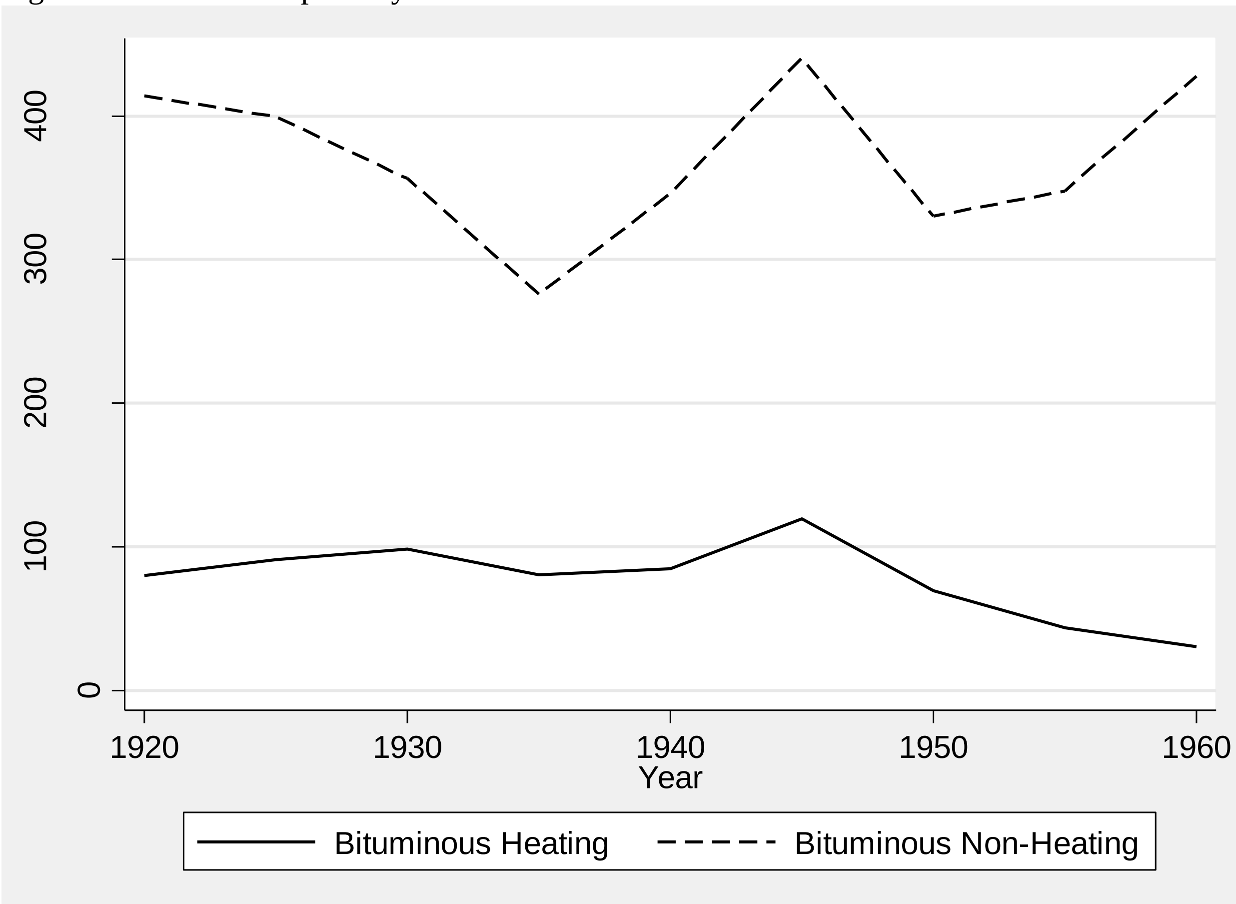
Our estimates are lower than the two other papers with high levels of PM10 and infant mortality (Arceo-Gomez et al 2012, Chay and Greenstone 2003a) for at least three reasons. First, coal consumption, especially for infants, represented a benefit to health from indoor heating. Other papers use variation in pollution that carried little or no health benefits, such as pollution from traffic and industrial production. Second, in the U.S. between 1940 and 1959, infant mortality was high, and interventions for premature or low birth weight babies were extremely limited. A relatively larger share of babies was dying for other reasons. Third, Chay and Greenstone (2003a) examines permanent declines in particulates. Their elasticity estimates are long-run. Our study captures short-run effects and elasticity.

Figure 1: Energy Consumption by Source, 1775-2009



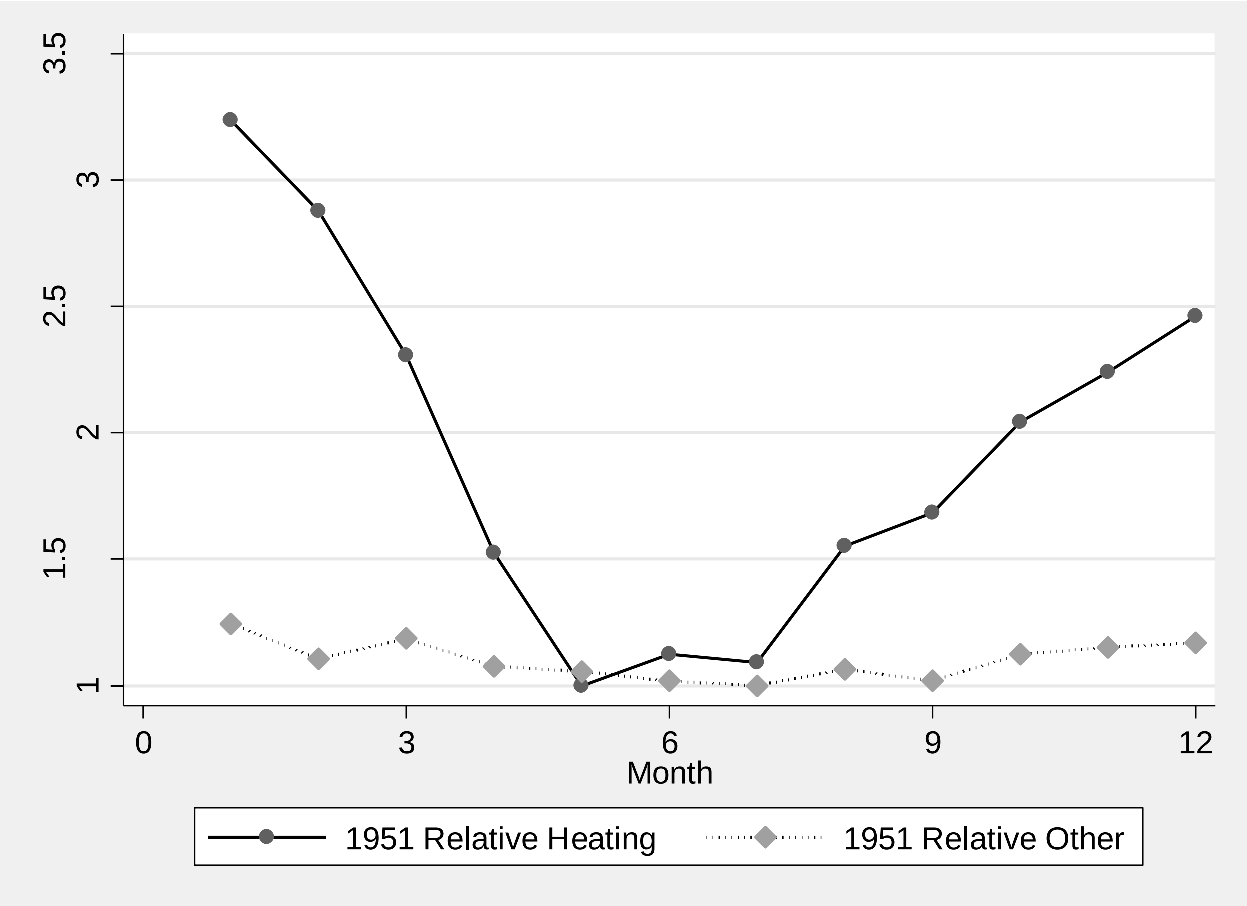
Notes: Created from U.S. Energy Administration, History of Energy Consumption in the United States 1775-2009. http://www.eia.gov/todayinenergy/detail.cfm?id=10

Figure 2: Coal Consumption by Use



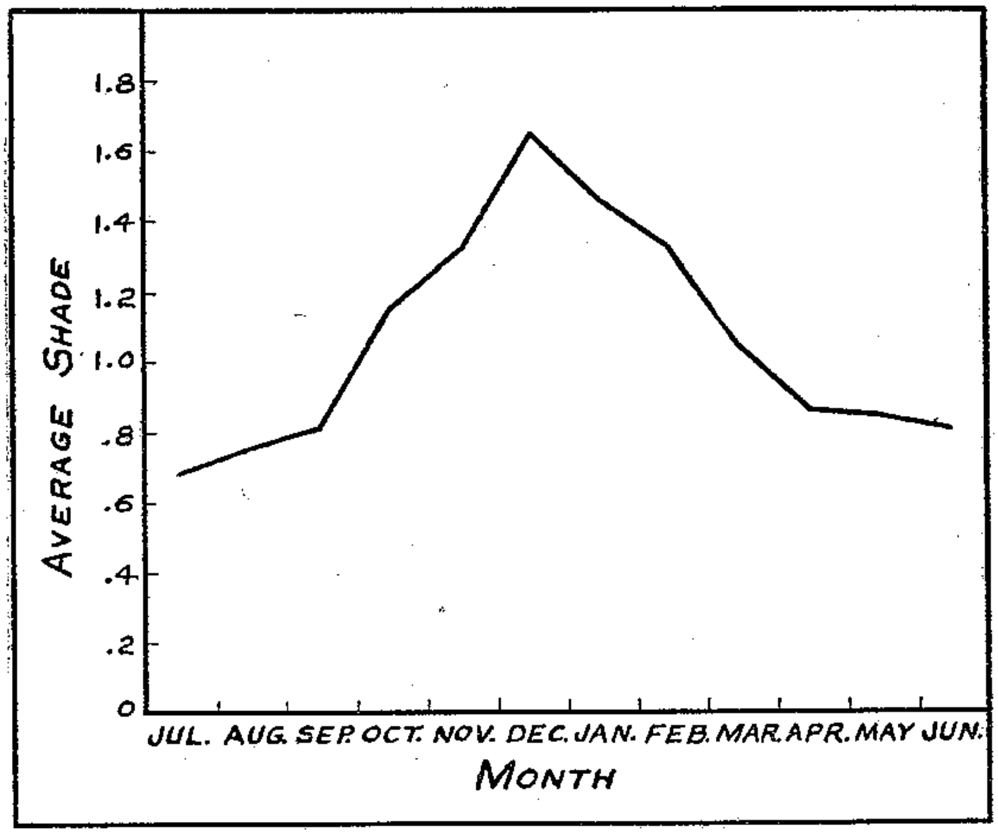
Notes: Values by use are from the *Historical Emissions Report* and are interpolated for years not ending in 0 or 5. Non-heating includes bituminous coal used for electricity, industry, coke, and railroads.

Figure 3: Seasonality of Retail (Heating) and Other Coal Consumption in 1951



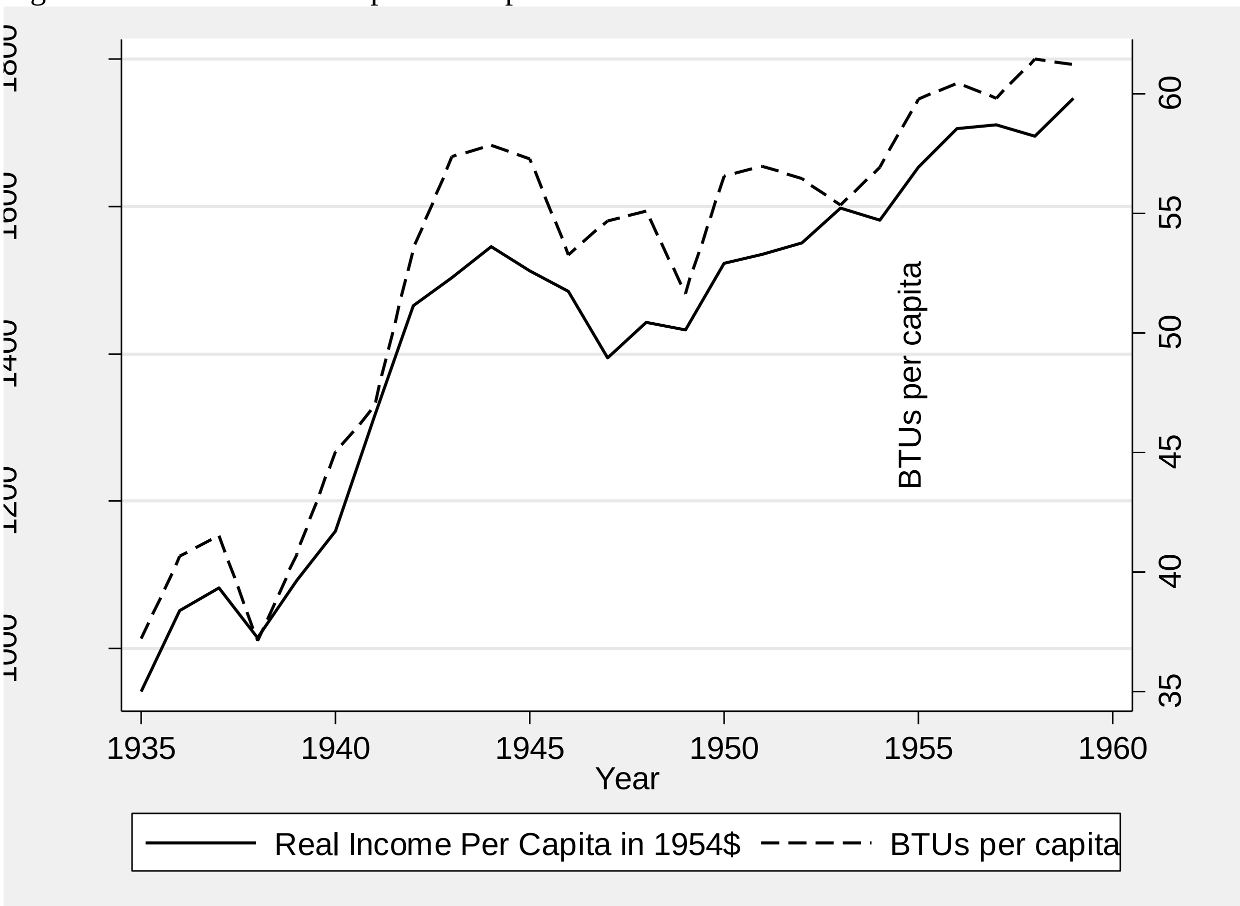
Source: *Minerals Yearbook* 1952. Other coal consumption includes bituminous coal used for electricity, industry, coke, and railroads.

Figure 4: Seasonality of Air Quality in 10 U.S. Cities, 1931-1933



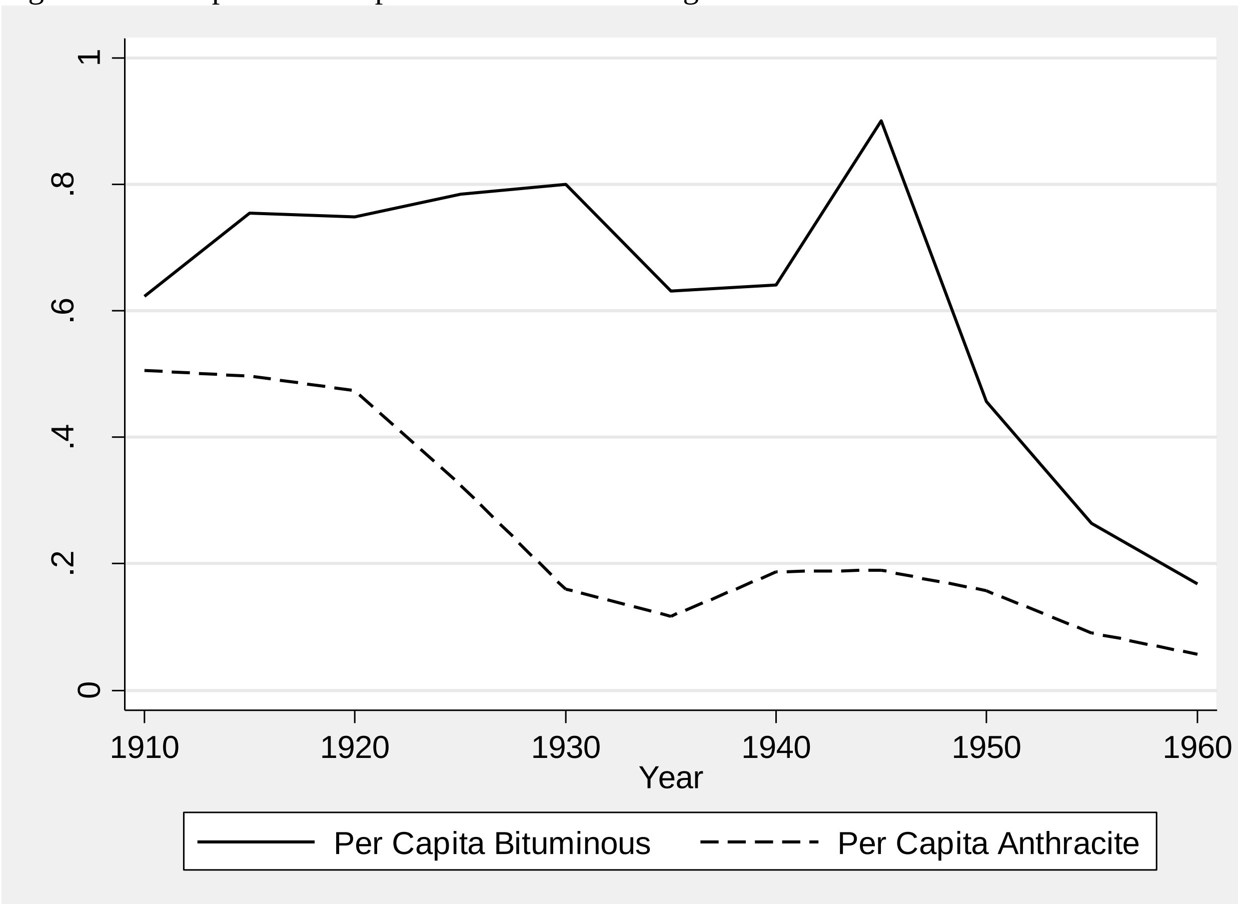
Notes: Ives et al (1936), p. 31. Figure 9: Average atmospheric pollution in American cities for different months of the year for 1931 to 1933, as determined with the Owens automatic air filter. TSP was also sampled, although with lower frequency. It was highly correlated with the shade of the Owens automatic air filter. Average TSP in the winter months in these cities was 510.

Figure 5: Real Income and Space Heat per Resident



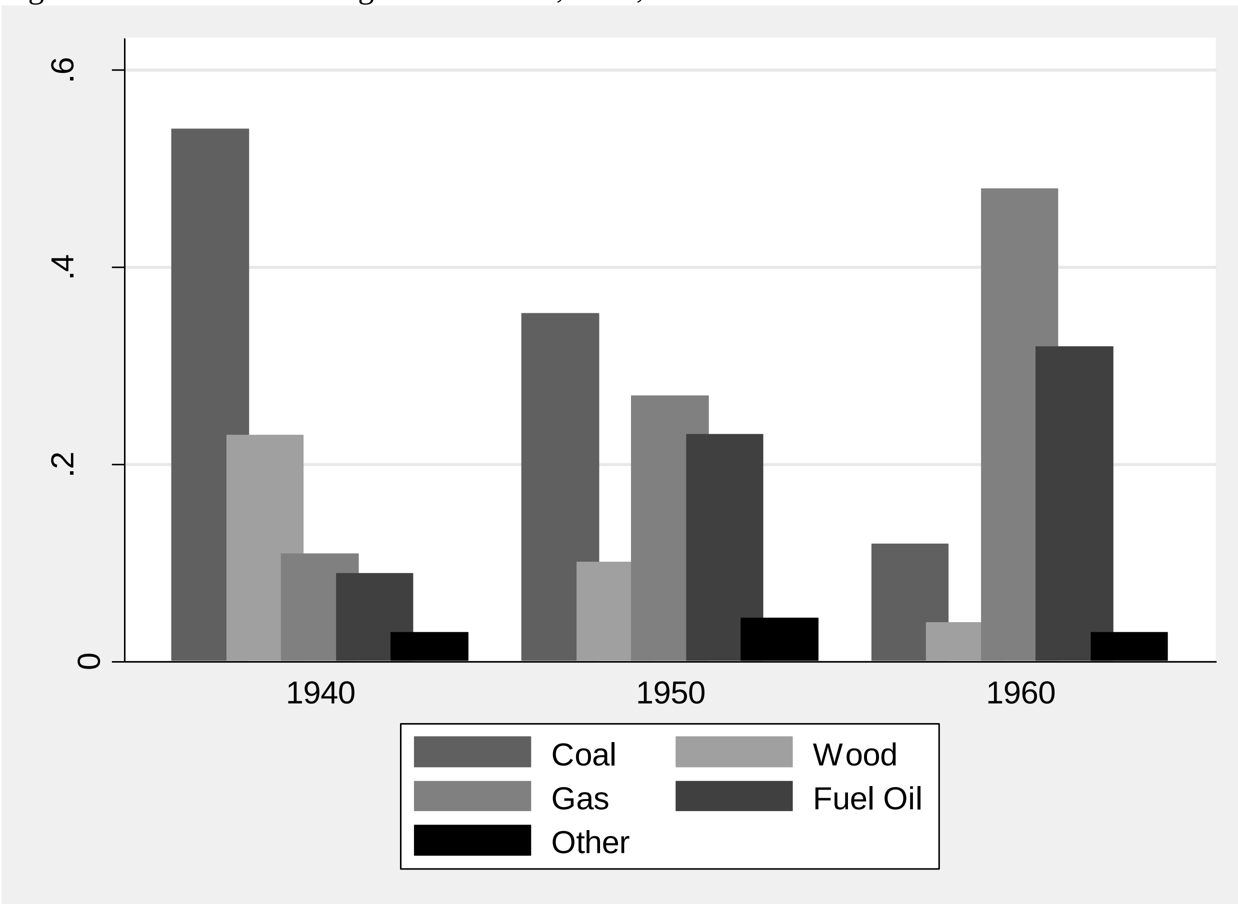
Source: Strout 1961, Table 1.

Figure 6: Per Capita Consumption of Coal for Heating



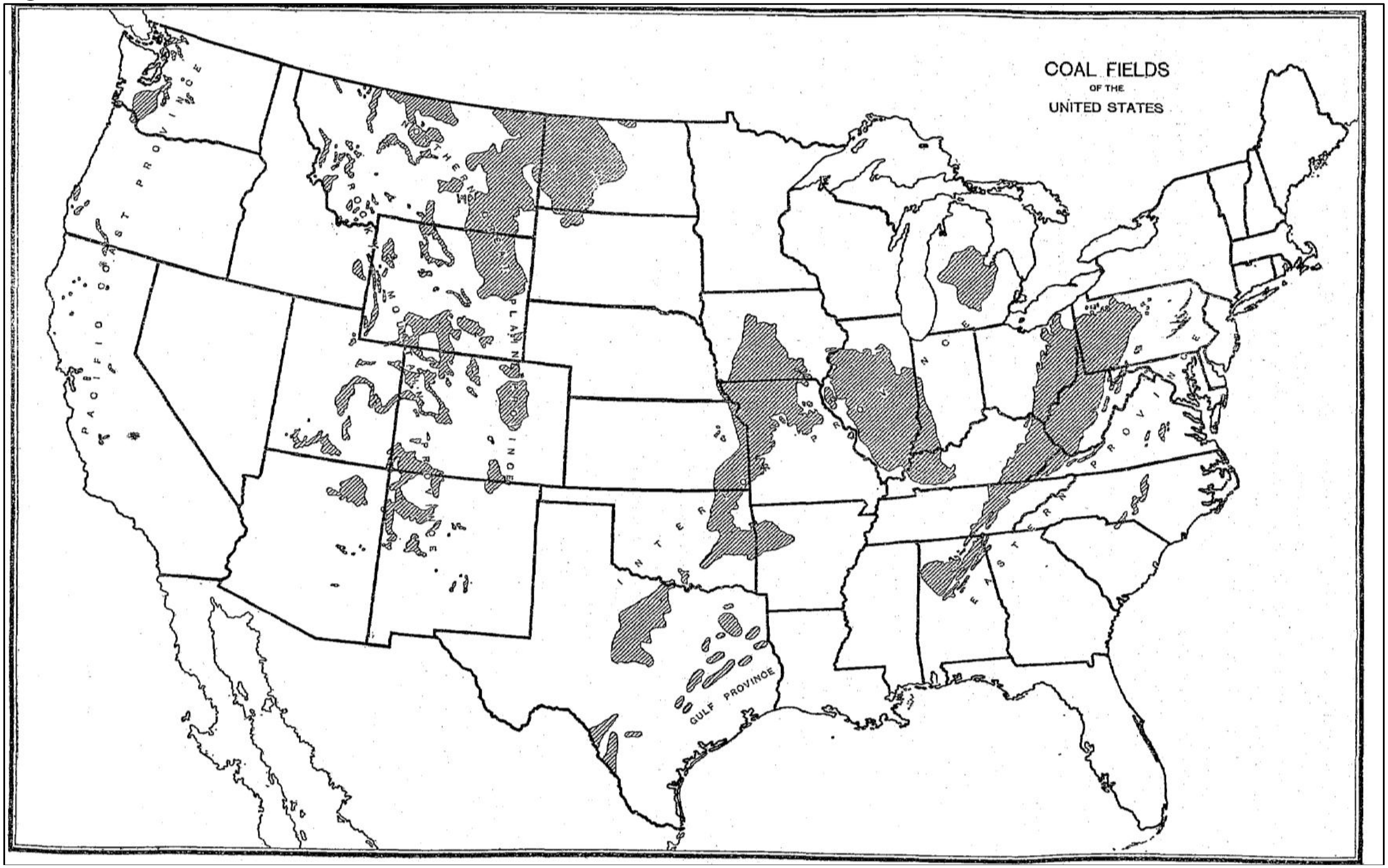
Notes: Values for bituminous and anthracite are from the *Historical Emissions Report* and are interpolated for years not ending in 0 or 5. National population values are from the Decennial Censuses and are interpolated for years not ending in 0. Retail (as opposed to sales for electricity, industry, coke, and railroads) sales of anthracite coal are not available until the 1950s. At that point, they were 20 percent of retail coal sales on a tonnage basis (*Minerals Yearbook*). Estimates in the mid 1920s suggested that 65 percent of anthracite was being used for heating. Department of Commerce (1929), p. 6. The series in Figure 6 uses this 65 percent estimate.

Figure 7: Household Heating Fuels in 1940, 1950, and 1960



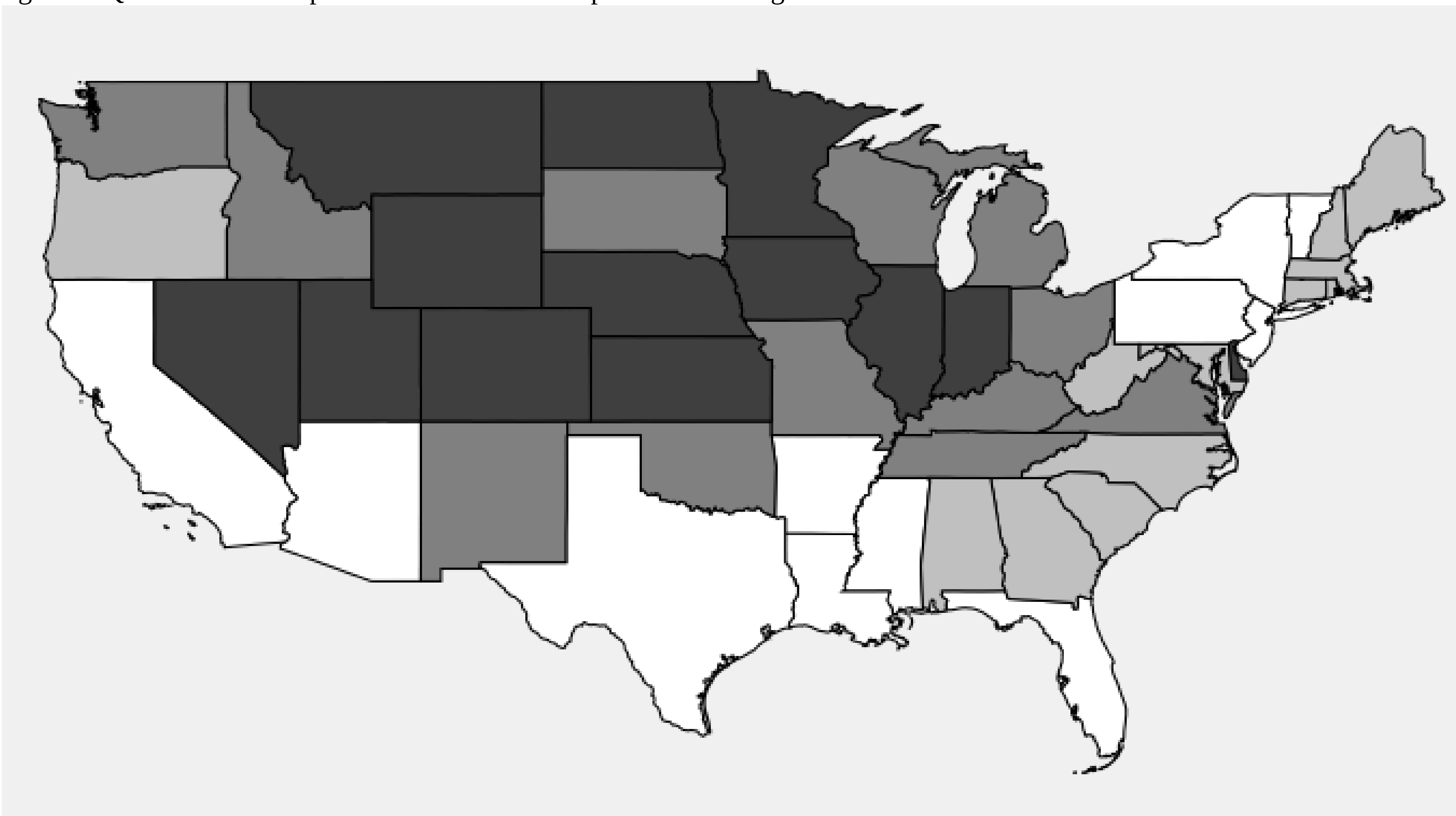
Source: *1940, 1950, 1960 Censuses of Housing*.
Notes: For 1940, Table 60, p. 101 available at http://www2.census.gov/prod2/decennial/documents/36911485v2p1ch1.pdf . For 1950, Table 20, pp. 127-130 available at http://www2.census.gov/prod2/decennial/documents/36965082v1p1ch1.pdf . For 1960, Table 7, pp. 1-29-1-33 available at: http://www2.census.gov/prod2/decennial/documents/41962442v1p1ch04.pdf . Other includes households with electrical (baseboard) heat and no heat.

Figure 8: Coal Fields of the United States



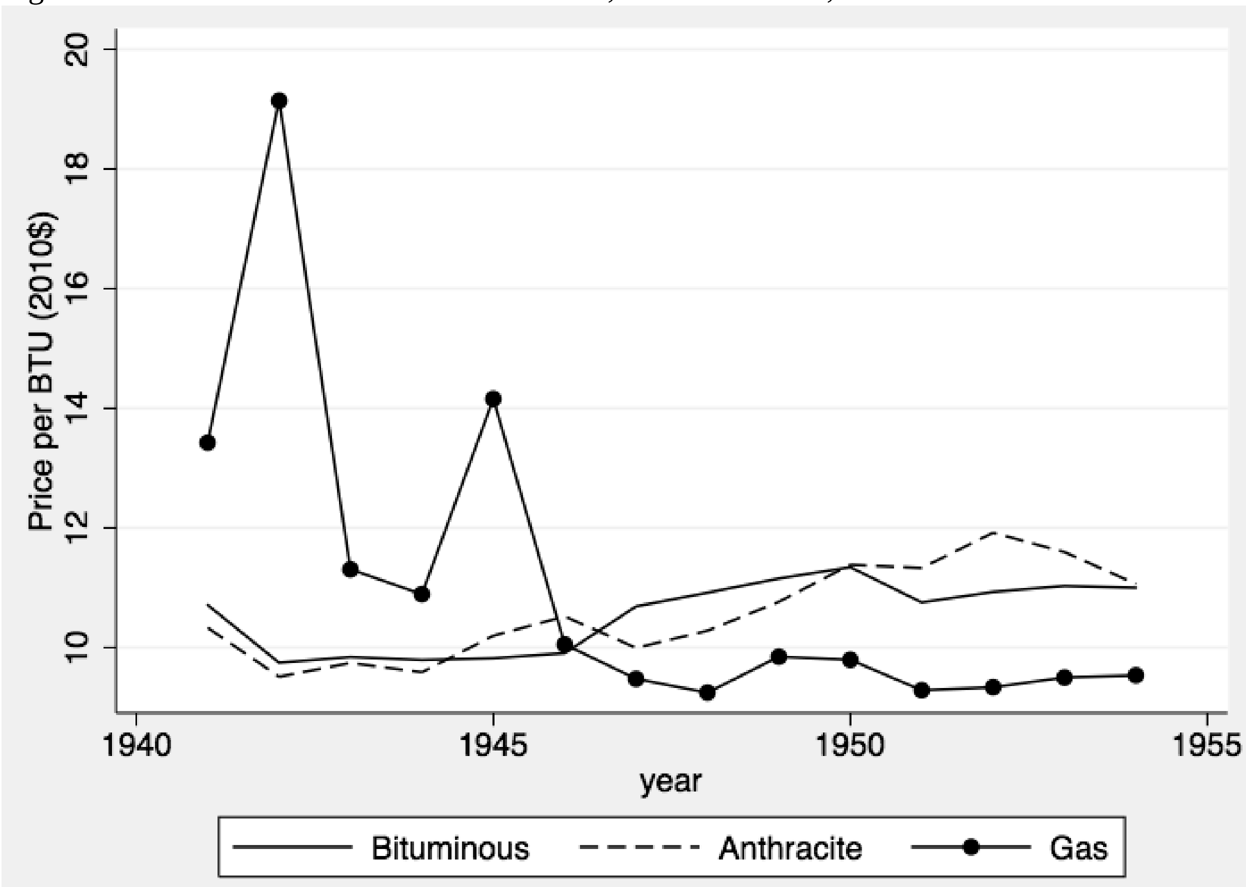
Notes: From *Fourteenth Census of the United States, Volume XI Mines and Quarries, 1919, General Report and Analytical Tables and Selected Industries*, p. 254. http://www2.census.gov/prod2/decennial/documents/23010460v11ch4.pdf

Figure 9: Quartile of Per Capita Bituminous Consumption for Heating in 1920



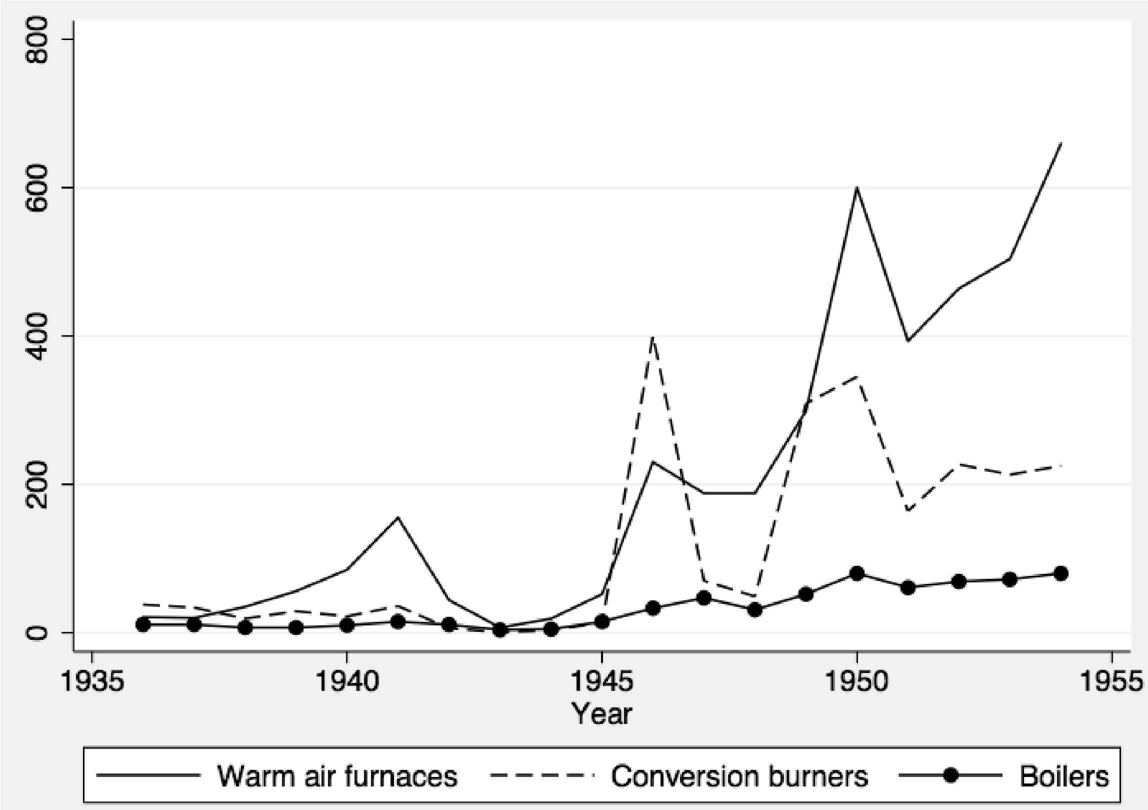
Notes: States were grouped into quartiles, with the shading ranges from lightest (Q1) to darkest (Q4).

Figure 10: December Price of Bituminous Coal, Anthracite Coal, and Gas



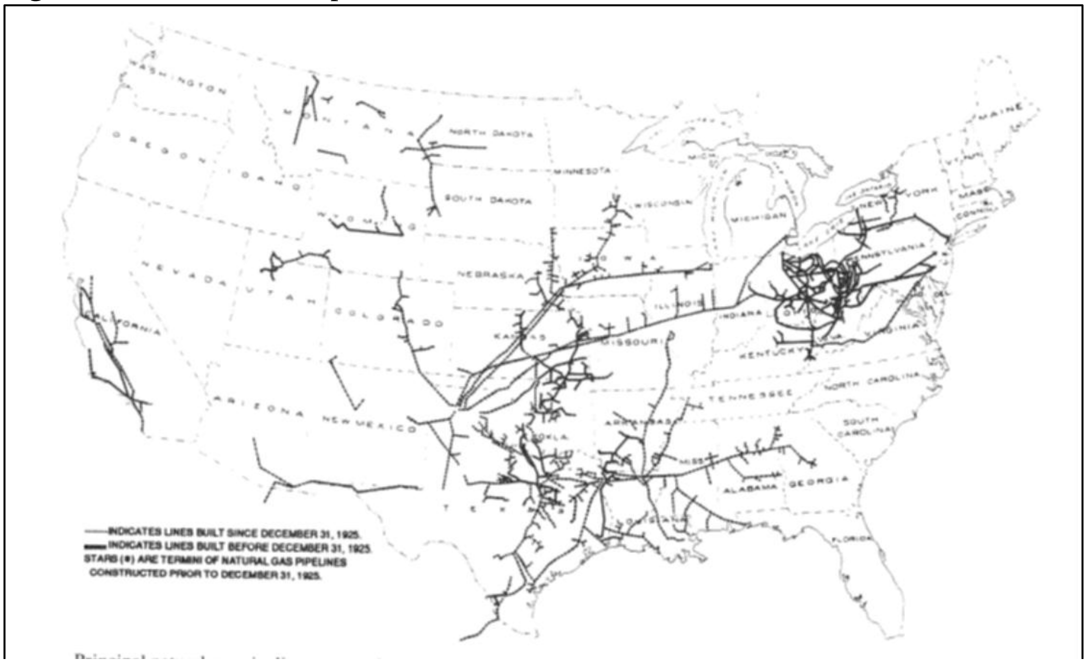
Source: *Historical Statistics of the American Gas Association*, Table 231, p. 3
Notes: Prices are in cents per million BTU. The following 20 cities are in the sample: Atlanta, Baltimore, Boston, Chicago, Cincinnati, Cleveland, Detroit, Houston, Kansas City, Los Angeles, Minneapolis, New York, Philadelphia, Pittsburgh, Portland, San Francisco, Scranton, Seattle, St. Louis, Washington DC.

Figure 11: Gas Heating Equipment Sales, in Thousands of Units



Notes: *Historical Statistics of the American Gas Association*, Table 143, p. 239

Figure 12: Natural Gas Pipelines in 1940 and 1949



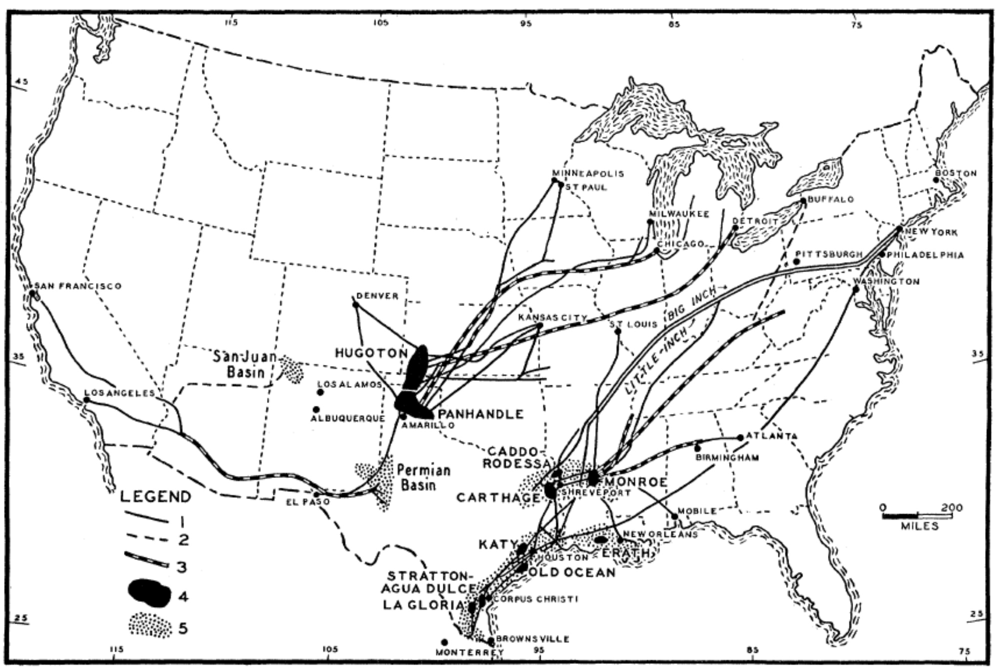


FIG. 1. Major interstate gas pipe lines in the United States, 1949. Legend: 1, pipe lines of 16-inch diameter or more originating in Mid-Continent and Gulf Coast areas; 2, pipe lines proposed or authorized; 3, double pipe lines; 4, principal gas fields; 5, other areas of scattered production supplying major interstate transmission lines.

Notes: 1940 Map: Federal Trade Commission Monograph no. 36 on Natural Gas Pipelines in the United States. Reproduced in Castaneda (1993) p. 19. 1949 Map: Parsons (1950), p. 165.

Table 1: Estimates of Total Suspended Particulates (TSP)

Location	*Time*	*TSP*	*Source*
Chicago	1912-1913	760	Eisenbud (1978)
14 Large US Cities	1931-1933, Winter	510	Ives et al (1936)
US Urban Stations	1953-1957	163	U.S. Department of Health, Education and Welfare (1958)
US Urban Stations	1960	118	Lave and Seskin (1972)
US National Average	1990	60	Chay and Greenstone (2003a)
58 Chinese Cities	1980-1993	538	Almond et al (2009)
Worldwide	1999	18% of urban pop > 200	Cohen et al (2004)

Table 2: Summary Statistics

Year	*Overall Death Rate per 100,000*	*Infant Death Rate per 100,000 Live Births*	*Per Capita Bit Coal Consumption for Heating in Tons*	*Real Income per capita in 2010 dollars*	*Heating Degree Days relative to 65F*	*January Heating Degree Days relative to 65F*
1920	107.7		0.84		15.8	37.6
	(31.7)		(0.71)		(14.7)	(13.0)
1940	88.7	4844.02	0.67	8,592	15.3	41.4
	(14.0)	(1636.38)	(0.53)	(3282)	(15.0)	(11.3)
1959	77.7	2673.31	0.18	15,437	14.5	34.5
	(10.5)	(571.73)	(0.19)	(2973)	(14.1)	(11.7)

Table 3: Overall Mortality, 1920-1959

	(1) LnOverall Monthly	(2) LnOverall Monthly	(3) LnOverall Monthly	(4) LnOverall Monthly	(5) LnOverall Quarterly	(6) LnOverall Quarterly	(7) LnOverall Quarterly	(8) LnOverall Quarterly
HDD 65	0.0050***	0.0052***	0.0051***	0.0047***	0.0060***	0.0065***	0.0062***	0.0058***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Monthly pc bit		508.8412***				531.1250***		
		(141.006)				(145.203)		
Annual pc bit			47.6677***	39.0024***			47.9735***	34.4373**
			(14.024)	(13.678)			(14.026)	(13.887)
HDD 65 x Annual pc bit				0.5174**				0.8106***
				(0.247)				(0.284)
Year-month FE	Y	Y	Y	Y	Y	Y	Y	Y
State-month FE	Y	Y	Y	Y	Y	Y	Y	Y
State time trend	Y	Y	Y	Y	Y	Y	Y	Y
Observations	21,948	21,948	21,948	21,948	7,316	7,316	7,316	7,316
R-squared	0.883	0.885	0.885	0.885	0.907	0.909	0.909	0.909

Notes: Standard errors are in parentheses and are clustered at the state level. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels. All regressions are population weighted. A constant is estimated but not reported. Monthly and annual pc bituminous is measured in 1000s of tons, so a decline of one ton would be 0.001.

Table 4: Infant and Overall Mortality 1940-1959

	(1) LnInfant Monthly	(2) LnOverall Monthly	(3) LnInfant Monthly	(4) LnOverall Monthly	(5) LnInfant Quarterly	(6) LnOverall Quarterly	(7) LnInfant Quarterly	(8) LnOverall Quarterly
HDD 65	0.0044***	0.0054***	0.0038***	0.0051***	0.0076***	0.0073***	0.0068***	0.0068***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Monthly pc bit	442.71***	364.35**			461.51***	407.95**		
	(153.563)	(154.237)			(160.419)	(166.433)		
Annual pc bit			5.1990	29.2692			-1.8204	24.2784
			(22.536)	(20.231)			(22.704)	(20.287)
HDD 65 x Annual pc bit			1.0653***	0.4655**			1.5651***	0.8087***
			(0.392)	(0.196)			(0.499)	(0.239)
Year-month FE	Y	Y	Y	Y	Y	Y	Y	Y
State-month FE	Y	Y	Y	Y	Y	Y	Y	Y
State time trend	Y	Y	Y	Y	Y	Y	Y	Y
Observations	11,640	11,640	11,640	11,640	3,880	3,880	3,880	3,880
R-squared	0.879	0.910	0.879	0.910	0.935	0.938	0.935	0.938

Notes: Standard errors are in parentheses and are clustered at the state level. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels. All regressions are population weighted. A constant is estimated but not reported. Monthly and annual pc bituminous is measured in 1000s of tons, so a decline of one ton would be 0.001.

Table 5: Alternative Specifications

	(1) LnOverall Monthly	(2) LnInfant Monthly	(3) LnOverall Monthly	(4) LnInfant Monthly	(5) LnOverall Quarterly	(7) LnInfant Quarterly	(6) LnOverall Quarterly	(8) LnInfant Quarterly
Years	1920-1959	1940-1959	1929-1959	1940-1959	1920-1959	1940-1959	1929-1959	1940-1959
HDD 50	0.0042***	0.0028**			0.0043***	0.0058***		
	(0.001)	(0.001)			(0.001)	(0.001)		
PC Bit	44.282***	14.3252	12.2811	4.8747	40.544***	10.5622	2.4543	-4.9982
Heating	(13.609)	(20.983)	(19.705)	(23.327)	(13.898)	(21.525)	(20.235)	(23.695)
HDD 50 x PC	0.5394*	1.1351**			1.0201**	1.8662***		
Bit	(0.315)	(0.429)			(0.399)	(0.662)		
HDD 65			-0.0094*	0.0099			-0.0213***	-0.0084
			(0.005)	(0.012)			(0.007)	(0.015)
HDD 65 x PC			0.5434*	1.0605**			1.0481***	1.6031***
Bit			(0.317)	(0.416)			(0.377)	(0.546)
PC Bit Non-			37.231***	10.2209			33.567***	4.6698
heating			(9.761)	(15.267)			(9.866)	(15.542)
HDD 65 x PC			0.1728	-0.0670			0.3133*	0.1052
Bit Non-Heat			(0.126)	(0.190)			(0.161)	(0.248)
Ln(pc real			-0.0678	0.0444			-0.0838*	0.0165
income)			(0.048)	(0.052)			(0.048)	(0.055)
HDD 65 x			0.0014***	-0.0006			0.0027***	0.0016
Ln(pc inc)			(0.001)	(0.001)			(0.001)	(0.002)
Year-month FE	Y	Y	Y	Y	Y	Y	Y	Y
State-month FE	Y	Y	Y	Y	Y	Y	Y	Y
State time trend	Y	Y	Y	Y	Y	Y	Y	Y
Observations	21,360	11,640	17,280	11,640	7,120	3,880	5,760	3,880
R-squared	0.883	0.879	0.886	0.879	0.908	0.935	0.913	0.935

Notes: Standard errors are in parentheses and are clustered at the state level. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels. All regressions are population weighted. A constant is estimated but not reported. Monthly and annual pc bituminous is measured in 1000s of tons, so a decline of one ton would be 0.001.

Table 6: Mortality Controlling for Bituminous Coal Consumption in 1920

	(1)	(2)	(3)	(4)	(5)	(6)
	LnOverall	LnInfant	LnOverall	LnInfant	LnOverall	LnInfant
Years	1920-1959	1940-1959	1920-1959	1940-1959	1920-1959	1940-1959
HDD 65	0.0070***	0.0069***	0.0023*	0.0017*	0.0046***	0.0055***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)
Coal 1920 x HDD 65	-2.8592***	-3.9956***			-2.2971***	-3.6242***
	(0.744)	(0.905)			(0.708)	(0.880)
Coal 1920 x HDD Time	-0.0029***	-0.0079***			-0.0004	-0.0053**
	(0.001)	(0.002)			(0.001)	(0.003)
Coal 1920 x HDD Time (post 1945)	-0.0027*	-0.0036*			-0.0019	-0.0026
	(0.001)	(0.002)			(0.002)	(0.002)
HDD Time			-0.0000***	-0.0000***	-0.0000**	-0.0000
			(0.000)	(0.000)	(0.000)	(0.000)
HDD Time (post 1945)			-0.0000	-0.0000	-0.0000	-0.0000
			(0.000)	(0.000)	(0.000)	(0.000)
Year-month FE	Y	Y	Y	Y	Y	Y
State-month FE	Y	Y	Y	Y	Y	Y
State time trend	Y	Y	Y	Y	Y	Y
Observations	21,240	11,520	21,240	11,520	21,240	11,520
R-squared	0.884	0.880	0.884	0.880	0.885	0.880

Notes: Standard errors are in parentheses and are clustered at the state level. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels. All regressions are population weighted. Monthly and annual pc bituminous is measured in 1000s of tons, so a decline of one ton would be 0.001.

Table 7a: IV using 1945 and 1959

	(1) DLnInfant OLS	(2) DLnInfant OLS	(3) DLnInfant IV	(4) DLnInfant IV
DHDD65	-0.0025*	-0.0027*	-0.0023*	-0.0027*
	(0.001)	(0.001)	(0.001)	(0.001)
DPC Bit	-26.2804		-14.0477	
	(33.478)		(35.326)	
DPC Bit x HDD65	1.4623***	1.6442***	1.3359***	1.6283***
	(0.244)	(0.224)	(0.311)	(0.253)
State FE	N	Y	N	Y
Observations	576	576	576	576
R-squared	0.017	0.468	0.015	0.038
F-Statistic			63.38	181.23
	(6) DLnOverall OLS	(5) DLnOverall OLS	(8) DLnOverall IV	(7) DLnOverall IV
DHDD65	0.0071***	0.0056***	0.0070***	0.0056***
	(0.001)	(0.001)	(0.001)	(0.001)
DPC Bit	-0.6953		-2.0751	
	(14.497)		(15.120)	
DPC Bit x HDD65	1.4912***	1.3977***	1.5754***	1.4641***
	(0.343)	(0.319)	(0.335)	(0.301)
State FE	N	Y	N	Y
Observations	576	576	576	576
R-squared	0.212	0.702	0.212	0.301
F-Statistic			63.38	181.23

Notes: State-month observations were differenced to get the D-variables. Standard errors are in parentheses and are clustered at the state level. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels. All regressions are population weighted. A constant is estimated but not reported. The F-statistic is from the first-stage regression.

Table 7b: IV using 1945 and 1959, First Stage

	(1) DPC Bit First Stage	(2) DPC Bit x HDD 65 First Stage	(3) DPC Bit x HDD 65 First Stage
DHDD65	0.0000	0.0003***	0.0003***
	(0.0000)	(0.0001)	(0.0001)
Coal 1920	1.052***	0.0595	
	(0.091)	(0.5611))	
Coal 1920 x	0.0009	1.008***	1.030***
HDD65	(0.0005)	(0.0779)	(0.0765)
State FE	N	N	Y
Observations	576	576	576
F-statistics	72.89	90.05	181.23

Table 8: Elasticity of Pollution and Infant Mortality from Arceo-Gomez, Hanna, and Oliva (2012)

	Infant Mortality Rate per 100,000 live births	Mean Level PM10	Elasticity	Mean level CO	Elasticity
Arceo-Gomez, Hanna, and Oliva (2012)	1987 (overall)	66.9	0.415	2.71	0.227
Arceo-Gomez, Hanna, and Oliva (2012)	1899 (internal)	66.9	0.325	2.71	0.178
Barreca, Clay, and Tarr (2012)	3367	100-300	0.062-0.209		
Chay and Greenstone (2003a)	1179	35.3	0.284		
Currie, Neidell, and Schmieder (2005)	688	29.6	-0.008	1.58	0.040
Currie and Neidell (2005)	391	39.5	0.001	2.00	0.084
Knittel, Miller, and Sanders (2011)	280	28.9	1.827	1.01	0.146

Notes: Based on Table 8 of Arceo-Gomez, Hanna, and Oliva (2012).

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