Pollution and Maternal Mortality: Evidence from the London Fog*

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Abstract

The WHO estimates that, in 2015, over 300,000 women died in childbirth. Yet, the causes of maternal mortality remain under-studied because most of these deaths occur in data-sparse developing countries. This study provides new evidence showing that air pollution increases maternal mortality in settings where mothers do not have access to modern medical care. Our evidence comes from London using data for 1866-1935, a period characterized by high levels of maternal mortality and severe pollution. We analyze newly collected weekly data covering over 7 million births and 26,000 maternal deaths. For identification, we exploit week-to-week variation in fog events that trapped pollution in London. To track these events, we reviewed over 24,000 daily weather reports. Because the formation of fog depends on a complex set of climatic variables, we argue that the timing of these events on a week-to-week basis is as good as random after appropriate controls are included. Our results show that the occurrence of heavy fog in a week was associated with a 5.8-7.4% increase in maternal mortality in that week. This response is 4.5-7.6 times larger, in percentage terms, than the response of total mortality or mortality among all adults. Thus, pregnancy and childbirth were associated with a substantial increase in vulnerability to the effects of air pollution. To our knowledge this is the first study to draw a direct causal link between air pollution and maternal mortality.

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1 Introduction

The World Health Organization estimates that, in 2015, 303,000 mothers died as a consequence of childbirth. Many others suffered childbirth complications of varying levels of severity.[1] Maternal deaths represent a catastrophe for families and are accompanied by a range of negative economic consequences; maternal mortality cuts down women in their prime productive years, can affect the development and human capital of surviving children, and also has effects on investments in female education (Jayachandran & Lleras-Muney (2009)). Improving maternal health is considered so important for development that it was included as one of eight Millennium Development Goals, with reducing maternal mortality as a primary target. Given the continuing prevalence of maternal mortality, and the personal, social, and economic costs that it imposes, it is important that we understand risk factors that may influence maternal mortality rates.

In this paper, we examine one potential maternal mortality risk factor: air pollution. One reason to study air pollution is that a growing set of medical and public health studies suggest that there may be a link between air pollution and maternal mortality risk factors such as pre-eclampsia.[2] Pollution is also particularly interesting from an economics perspective because it represents a byproduct of economic activity. Because maternal mortality has both health and economic consequences, it is necessary to understand how pollution affects maternal mortality in order to measure the true costs and benefits of the underlying economic activities that produce it.

Studying the link between pollution and maternal mortality directly has proven difficult because maternal mortality rates are extremely low in modern developed countries, while mortality and pollution data are often unavailable in locations where maternal mortality remains high. As a result, our knowledge about the link between pollution and maternal mortality is limited. This matters in part because rapid urbanization and industrialization have led to high levels of air pollution in locations, such as Africa and India, where maternal mortality rates remain high.[3]

This study provides the first direct evidence linking pollution to maternal mortal-

[1]WHO (2015).

[2]See Hu *et al.* (2014) and Pedersen *et al.* (2014) for recent reviews of this literature. Further discussion of this literature is available near the end of this section.

[3]Data on particulate pollution at the national level are available from the WHO at `http://gamapserver.who.int/gho/interactive_charts/phe/oap_exposure/atlas.html`.

ity (as opposed to maternal mortality risk factors). To do so, we turn to a historical setting – London in the 19th and early 20th century – which was characterized by high levels of maternal morality and severe air pollution. To track maternal mortality in this setting, we have digitized weekly data tracking maternal deaths from 1866 to 1935. These new data include 3,437 weekly entries covering 7.5 million live births and 26,414 maternal deaths, a very large sample relative to other studies of maternal mortality.

To identify the causal effect of air pollution, we exploit a specific set of weather conditions – heavy fog events – which trapped polluted air over the city, generating sharp short-term increases in pollution exposure.[4] To track fog events, we read daily weather reports for each of the 24,059 days covered by our mortality data and identified weeks in which heavy fog events occurred. Our main analysis compares the occurrence of these fog events to maternal mortality while controlling for year and week-of-the-year effects. Thus, identification relies on random variation in the week-to-week timing of fog events to generate increased pollution levels. The occurrence of these fog events in any given week depended on a variety of climatic factors, including humidity levels, temperature, and wind velocity. Thus, we argue that the week-to-week variation in fog events is as good as random conditional on year and the week-of-the-year. To strengthen identification we also include controls for temperature, which influenced the formation of fog and could have also impacted maternal mortality.

Our results suggest that the occurrence of heavy fog during a week increased maternal mortality in that week by 5.8-7.4%. To assess how pregnancy affected women's vulnerability to air pollution relative to other populations, we calculate similar results for all-age mortality and mortality among adults 20-40 years old.[5] While fog events increased mortality among all age groups, as well as just among adults, we find that the response of maternal mortality was 4.5-7.6 times larger, in percentage terms, than the response of comparable populations. These results show that pregnancy or recent childbirth substantially increased vulnerability to the effects of pollution.

[4] For evidence on the impact of fog events on mortality in London, see Logan (1953), Troesken & Clay (2011) and Ball (2015).

[5] We consider adults 20-40 years old because this was the most comparable group to the population of childbearing women available in the weekly mortality data.

We also examine how maternal mortality responds in the weeks just before or just after fog events. We find no evidence of an elevated level of maternal mortality in the weeks before heavy fog events, which provides confidence in our identification strategy. Maternal mortality peaks in the week in which fog events occurred, while there is also evidence of elevated maternal mortality levels in the following three weeks, and particularly in the third week after a fog event. This pattern looks very different from what we observe for all-age mortality or mortality among adults aged 20-40. Among those populations, mortality peaks in the week after the fog event and remains significantly elevated until the fourth week after the fog. This difference highlights how pregnancy fundamentally changes the way that pollution affects a mother's health.

Our study offers five main contributions relative to the existing literature. First, by drawing on a historical setting we are able to study the link between air pollution and maternal mortality directly. In contrast, because of data constraints, existing studies focus exclusively on the link between pollution and risk factors such as pre-eclampsia. Second, we exploit a much larger data set than previous studies, both in terms of the total number of births as well as the number of maternal deaths. Third, we offer an identification strategy that allows us to more cleanly elucidate the causal impact of air pollution on maternal mortality. Fourth, we compare the impact of pollution on maternal mortality to the impact on other populations in order to assess the extent to which pregnancy and childbirth increase vulnerability to the effects of pollution. Fifth, our study design allows us to look at both the contemporaneous and lagged effects of pollution exposure on maternal health. This reveals some interesting dynamics in the way that air pollution affects maternal mortality which can help inform our understanding of the channels through which these effects occur. However, working in a historical setting does impose some limitations on our study. Most importantly, we do not have high-quality diagnostic information which could help shed light on the channels through which pollution increased maternal mortality. Thus, we view our study as complementary to existing work.

Our results contribute to existing studies looking at the relationship between air pollution and maternal health, as well as a much larger literature examining the impact of pollution on other populations.[6] Most of the recent studies of pollution

[6]The literature documenting the impact of pollution on other populations is too large to cite here. Seminal contributions include Chay & Greenstone (2003) and Currie & Neidell (2005). For a

and maternal health use information on the mother's place of residence together with observations from nearby pollution monitors to model maternal pollution exposure and then compare this to diagnosis data. Recent examples of studies of this type include Wu *et al.* (2009), Rudra *et al.* (2011), Vinikoor-Imler *et al.* (2012), Lee *et al.* (2013), Dadvand *et al.* (2013), Malmqvist *et al.* (2013), Pereira *et al.* (2013), Olsson *et al.* (2013), Savitz *et al.* (2015).[7]

Overall these studies show mixed results, though most find that air pollution exposure is associated with an increased risk of pre-eclampsia and several studies suggest that third trimester exposure has a particularly strong effect. However, reliance on the mother's address to construct the pollution exposure measures used in these studies raises some identification concerns because less healthy populations may sort into more polluted areas. Also, for data reasons, these studies focus almost exclusively on developed country settings where pollution levels are low. As a result, they may be less informative about the relationship between pollution and maternal health in developing or middle-income industrial countries, where most maternal mortality occurs. One study that offers a somewhat similar approach to the one used here is Assibey-Mensah *et al.* (2016), which looks at the impact of the reduction in pollution in Beijing during the 2008 Olympics. However, this event occurred over a relatively short period of time which leaves their study with too few observations to draw strong conclusions.

In addition to the studies cited above, this paper contributes to a long line of papers investigating the acute mortality impacts of polluted fog events. One famous example is Logan (1953), which focused on the famous Great London Smog of 1852. Logan suggests that the 1852 London fog events resulted in 4,000 additional deaths. More recent work by Bell & Davis (2001) suggests that the true death toll may have been as high as 12,000, while Ball (2015) documents the long-term effects of the fog on those in utero during the event. Townsend (1950) studies a smog event in Danora, Pennsylvania in 1948 which he estimated affected 6,000 people. Similar results have been documented for a fog in the Muese Valley, Belgium in the 1930s (Nemery *et al.*

recent review, see Graff Zivin & Neidell (2013).

[7]Another related study, Mannisto *et al.* (2015), compares air pollution levels at the time of hospital admission and up to four hours before to mother's blood pressure measured at admission and diagnoses of hypertensive disorders. They find evidence that elevated air pollution levels were associated with increased blood pressure. There is also some evidence that this impact was more pronounced among mothers with gestational hypertension or pre-eclampsia.

(2001)). Finally, our study builds on work by Troesken & Clay (2011) which describes the incidence of London fogs in the late 19th and early 20th century.

Our work is also related to recent studies looking at the health impacts of acute pollution events. Our study most resembles Arceo *et al.* (2016) and Hanna & Oliva (2015), which look at the impact of temperature inversions that trapped pollution in Mexico city on infant health and labor supply, respectively. Their use of temperature inversions to study the effects of short-term pollution exposure is very similar to the identification strategy used in this study.[8]

In the next section, we describe the empirical setting and the primary causes of maternal mortality during our study period. In Section 3 we review the data. Our empirical approach is described in Section 4, and Section 5 presents our results. In Section 6 we discuss the magnitude of the effect of pollution on maternal mortality and their implications for maternal mortality today. We discuss conclusions and directions for future work in Section 7.

2 Empirical setting

2.1 Maternal mortality

At the beginning of our study period, maternal mortality in London ranged from roughly 4-5 deaths per thousand live births, comparable to the levels experienced in Sub-Saharan Africa today.[9] By the end of the study period, in the 1920s and 1930s, maternal mortality in London was between 2.5-3.5 deaths per thousand births, comparable to maternal mortality in all developing regions today (2.39 in 2015 according to WHO (2015)). These patterns are described in Figure 1. These rates are extremely high compared to modern developed countries, were the maternal mortality ratio was 0.012 per thousand births in 2015.

A number of conditions contributed to maternal mortality in Britain during the 19th and early 20th century.[10] The largest single cause was puerperal fever, a strepto-

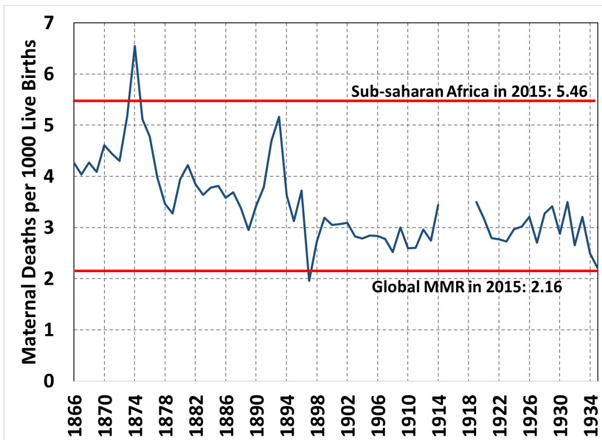
[8]Another fairly similar study is Jayachandran (2009) which looks at the impact of exposure to pollution from wildfires on infant health in Indonesia. Schlenker & Walker (2016) is another example of a recent paper looking at the effects of acute pollution exposure.

[9]See WHO (2015).

[10]The discussion in this and the following three paragraphs draws heavily from Loudon (1992)

coccal infection that afflicted mothers in the postpartum period.[11] Puerperal infection was contagious and was often spread by midwives or doctors. Thus, the prevalence of this disease was likely reduced by the introduction of antiseptic practices after 1880. The sharp spikes in maternal mortality observed in 1874 and 1893 shown in Figure 1 are generally attributed to the spread of particularly virulent strains of streptococcal bacteria.[12]

Figure 1: Maternal mortality in London, 1866-1935



This figure describes the annual number of maternal deaths in London from 1866-1935 using data gathered from the weekly reports published by the Registrar General's Office. Data were not reported during WWI. For further details on these data, see Section 3. For comparison, this figure includes lines indicating the maternal mortality ratio in Sub-Saharan Africa in 2013 as well as the global average in 2013. Both of these come from *Trends in Maternal Mortality: 1990 to 2013.* WHO Press (2014).

A second important cause of maternal mortality during this period was pre-eclampsia.[13] Pre-eclampsia is a hypertensive disorder that generally occurs in the last trimester of pregnancy. Pre-eclampsia accompanied by convulsions is called eclampsia. Eventually death can occur through an eclamptic fit, kidney damage,

[11] Other terms for the same condition include metria, puerperal sepsis, and puerperal septicemia.

[12] See Loudon (1992) p. 75-77. One piece of evidence that he presents in favor of this hypothesis is that the spike in deaths in 1874 in England & Wales was a matched by similar spikes in Scotland in 1874, Sweden in 1874-75, Paris and Amsterdam in 1875, Belgium in 1873-74, Massachusetts in 1874, and Norway in 1874.

[13] This disease also goes under a variety of other names including toxaemia, puerperal convulsions, puerperal nephritis, pregnancy associated hypertension, or more recently, pregnancy-induced hypertension.

or cerebral haemorrhage. Eclampsia can be prevented, though pre-eclampsia cannot. The disorder almost always resolves at delivery of the placenta.

A third important cause of maternal mortality was obstetric hemorrhage, a complication of pregnancy that could result in death due to blood loss.[14] Hemorrhage could occur either before or after delivery. Loudon (1992) claims that historically many deaths due to haemorrhage were at least partially attributable to poorly trained doctors or midwives.

Among the remaining causes of maternal death was induced abortion, which could lead to death through puerperal fever or haemorrhage, as well as complications related to contracted pelvis.[15] The causes present in our setting continue to be the main causes of maternal mortality today, though with some changes in relative importance. In particular, Say *et al.* (2014) find that today, haemorrhage accounts for 27% of maternal deaths, hypertensive disorders (pre-eclampsia and eclampsia) account for 14%, infections account for 11%, and the remainder are due to abortion, embolism and other causes.

Pregnancy complications also contributed to maternal morbidity, including chronic infection, kidney disease, and the loss of reproductive function. While figures on maternal morbidity are necessarily rough, sources from the early 20th century suggest that the number of women who died in childbirth was just a fraction of those who suffered long-term disability. For example, Bell (1931) suggests that pregnancy led to the disablement of 60,000 women in Britain, roughly 20 times the number that died in childbirth. Kerr (1933) (p. 147) notes that, "This is a difficult figure to assess, but that the number is very considerable will not be disputed by anyone having charge of hospital beds where such patients receive treatment." There appears to have been a particularly strong association between the development of albuminuria, a kidney disorder associated with pre-eclampsia, and subsequent disablement. Young (1929) provides evidence from a follow-up study conducted out of the Simpson Memorial Maternity Hospital in Edinburgh that 40% of women who experienced albuminuria

[14]Because of the severity of bleeding this condition was sometimes referred to as *flooding*.

[15]The latter was primarily due to rickets which was caused by vitamin D deficiency. This, in turn, may be attributed to the scarcity of sunlight in heavily polluted cities. UV light is required to the convert pro-vitamin D3, a precursor molecule present in the skin, into vitamin D. Vitamin D on the other hand facilitates dietary calcium absorption in the intestine, thus mediating bone development. Deficiencies may lead to rickets and osteomalacia. In women, these may manifest in malformations or fragility of the pelvic bone, which may cause birth complications.

during pregnancy experienced moderate to severe health problems afterward. Based on this figure, and a rate of albuminuria of 3-4%, Young estimated that 7,000-10,000 British women experienced post-partum disability through this channel at the time of his study.[16]

A number of medical improvements related to obstetrics took place during our study period though, as we can see from Figure 1, none of them led to major reductions in maternal mortality. The most important innovations were the introduction of antisepsis in the 1880s, which probably accounts for most of the modest reduction in maternal mortality seen in the last decades of the 19th century in Figure 1.[17] Another important innovation, the caesarian section for obstructed labor, was introduced around 1890-1900.

The training of midwives and general physicians working on obstetrics also improved during our study period. In the 19th century, training in obstetrics among physicians was "appalling" and "grossly inadequate" (Loudon (1992), p. 191-2) while midwives, who probably attended the majority of births, did not require any formal training or licensing.[18] The most important change to this pattern came with the Midwives Act of 1902, which required new midwives to pass an exam and become certified. However, because the act allowed currently practicing midwives to continue, it would take many years before the majority of midwives had passed through the exam. One indicator of the ineffectiveness of doctors during this period is that women of higher social and economic classes, who presumably had more access to medical care, died of maternal mortality at higher rates than the poor.[19]

2.2 Fog days and air pollution

Contemporary reports provide ample evidence that pollution levels in London were high during our study period, particularly during fog events. An article in the Times on Feb. 7, 1882, described how, "A short time ago the London fog fell upon the

[16]For further discussion see Kerr (1933) p. 199-204.

[17]See Loudon (1992) p. 203-205 for a discussion of that antiseptic revolution.

[18]In the 19th century it is difficult to assess the share of births attended by midwives, but Loudon (1992) suggests that the ratio was about one-half. In the early 20th century, he provides evidence from Derbyshire that midwives attended 57.6 percent of births in 1909 and that this proportion rose to 74.9 percent in 1913 due to the improvement in midwife skills following the Midwives Act of 1902.

[19]Loudon (1986b) provides evidence suggesting that this pattern existed throughout our entire study period. Also see Loudon (1986a).

respiratory organs of the beasts in the Cattle Show at the Agricultural Hall, and many of them died. The fog at that period lasted nearly three weeks off and on, and the Registrar-General reported 2,400 more deaths than the ordinary returns."[20] These pollution problems were to continue with varying degrees of intensity until the middle of the 20th century.[21]

The development of thick fog in London required a specific set of climatic conditions, including sufficient humidity, appropriate air temperature, and relatively little wind. The worst London fogs were associated with temperature inversions, in which a cold layer of foggy air was trapped underneath a warmer upper layer of air. These conditions were more likely to occur in the winter and, as a result, thick fogs were more likely during this time. However, within a season, the week-to-week timing of heavy fog events was due to the interaction of a variety of climatic factors. Thus, we consider the specific timing of fog events from week-to-week to be as good as random. Moreover, fog itself poses no direct threat to health.

Figure 2 describes the distribution of fog days across the weeks of the year. We can see that these events were concentrated during the winter, and almost completely absent during the summer. This figure also includes the maternal mortality ratio across these weeks, which shows a seasonal pattern similar to that exhibited by the fog events.

Figure 3 describes the number of heavy fog days in each year covered by our study. Note that we are missing data during WWI, when the daily weather reports do not appear in the weekly mortality returns. The most striking pattern in this graph is the increase in fog days in the 1880s followed by the sharp decline in fog days in the first decade of the 20th century. This pattern has been previously documented by Brodie (1905) and Troesken & Clay (2011).[22] Because higher baseline levels of pollution could increase the chances of a thick fog occurring, some authors (e.g., Troesken &

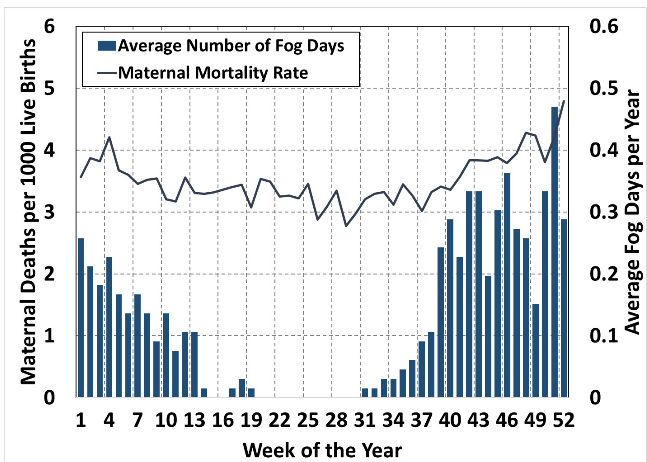
[20] The article goes on to quote Dr. J.M Fothergill, who stated that, "He had never heard of a person who resided long in London after whose death a *post mortem* examination had been held that there had not been found a certain amount of black matter on the respiratory organs."

[21] In an address to the Royal Sanitary Institute in 1953, following the Great London Smog of 1952, E.T. Wilkins stated that, "the bad effects of air pollution are, of course, not confined to periods of smog, for there is evidence that even the lower concentrations normal to many densely populated areas have persistent and insidious effects on public health, vegetation and...materials of all kinds. Thus the problem of smog is, in some respects, a short-term magnification of the general problem of atmospheric pollution." Quoted from Thorsheim (2006), p. 174.

[22] Also see Brimblecombe (1987) Ch. 6 for a useful discussion of the history of fog in London.

Clay (2011)) have argued that this may signal a reduction in air pollution levels in London after 1900.[23] An alternative explanation is that the reduction in fog may have been due to changing climatic conditions or that the standard of reporting changed. Because our identification strategy relies primarily on week-to-week variation within years, we do not need to take a stand on this debate, though at the end of the analysis we explore how our results are affected when we split our study period.

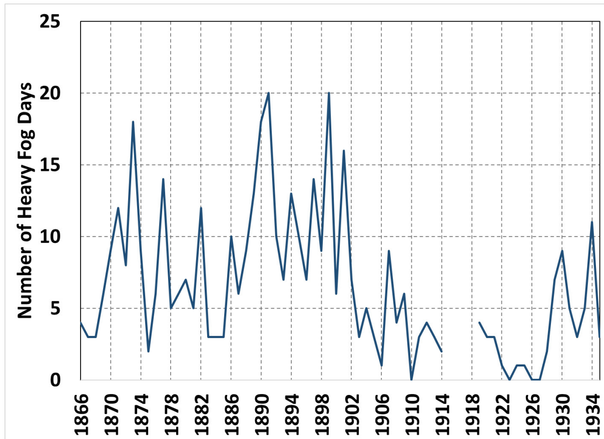
Figure 2: Fog days and maternal mortality across weeks of the year



This figure describes the distribution of maternal deaths and the number of fog days across the weeks of the year. In a few years there were 53 weekly observations, which we exclude from this figure. A description of the data used to construct this figure is available in Section 3.

[23]Such a decrease may have been due to regulations such as the passing of the Public Health (London) Act in 1891 or the formation of the Coal Smoke Abatement Society, which campaigned against air pollution, in 1899.

Figure 3: Heavy fog days per year across the study period



This figure describes the number of heavy fog days experienced in each year of the study period based on daily weather reports taken at Greenwich.

3 Data

The two main data sets used in this study were entered from the Weekly Reports produced by the Registrar General's Office, which include a wealth of information about mortality patterns and weather conditions in London.

The weather data used in this study are based on short daily reports of observations from the Royal Observatory in Greenwich, which is located just east of London along the River Thames. An example of one of these weather reports from the fifth week of 1880, which experienced three days of heavy fog, is provided in Appendix Figure 6. We manually reviewed the entries for every day from 1866-1935, searching for reports of fog with a description that indicated "dense," "thick," "heavy," or another indication of severity. We then recorded the number of days in each week on which heavy fog was reported.[24] Using this method we identified 434 heavy fog days, with 303 weeks including at least one heavy fog day, out of the 3,437 weeks covered by our data.[25] Weather reports were not included in the data during WWI, so those

[24]We focus on heavy fog because light fog was unlikely to have substantially changed the level of pollution exposure and in many cases light fogs observed at Greenwich may never have reached central London.

[25]In a week in which any heavy fog occurred there is an average of 1.4 heavy fog days and a maximum of 5 heavy fog days.

years are dropped from our study.

The mortality data used in this study also comes from the Registrar General's Weekly Report for London. The Registrar General's office collected mortality statistics (as well as births and marriages) through a set of local officials called the Registrars. Comprehensive mortality data collection started in the 1840s, so that by 1866, when our data begin, the Registrar General's office already had two decades of experience in the collection of mortality statistics.

Maternal mortality was of particular concern to the Registrar General's Office, which worked to improve the accuracy of these statistics in the 19th century.[26] For example, in 1864, just before our data begin, the Registrar General made it clear that associated deaths, those due to other diseases but occurring during pregnancy, should not be included under the maternal mortality categories.[27] Starting in 1874, the certification of deaths by physicians became mandatory. Prior to that change, physicians certified deaths on a voluntary basis, so some cause-of-death information was missing or based on the reports of relatives. However, Dr. Farr, the Registrar General reported in 1870 that in London 98 out of 100 deaths were already being reported by medical men. He also made a careful study of maternal deaths in London during six weeks of that year in which he found that 66 out of 67 deaths had been properly returned.[28]

Across most of our study years, maternal mortality was reported in two categories. The first category, Puerperal Fever, included deaths from streptococcal infection, the largest single cause of maternal mortality. The second category, "Accidents of Childbirth," contained all other sources of maternal mortality. This included pre-eclampsia, obstetric hemorrhage, etc.[29] There is clear evidence in the data that the boundary between deaths classified as puerperal fever and those classified as accidents of childbirth shifted over time.[30] To reduce issues related to the division of deaths

[26]For example, in his 1875 Annual Report, the Registrar General, Dr. Farr, asked with regard to maternal mortality, "How long is this sacrifice of lives to go on?" He followed in the next year's Annual Report with an in-depth study of maternal mortality.

[27]See Loudon (1986a).

[28]See the *Annual Report of the Registrar General for 1870*, p. 408-409. Cited from Loudon (1992).

[29]Deaths associated with intentional abortion would also fall into the accidents of childbirth category. It is very difficult to get an idea of how many of these there might have been. However, these deaths should not pose a problem for our identification strategy since there is little reason to expect that women should be more likely to obtain abortions on foggy days.

[30]Loudon (1992) suggest that this may be due in part to intentional miscategorization by doctors who didn't want to be associated with a maternal death due to puerperal fever.

among these classifications, our analysis will focus only on maternal mortality as a whole.

The data do not allow us to differentiate between mortality that occurred at different times during the pregnancy or after childbirth, but other studies indicate that most women died in the postnatal period.[31] Given this, the definition of the postnatal period plays in important role in maternal mortality statistics. A review by Loudon (1992) suggests that the postnatal period was one-month at the beginning of our study period. This lengthened to six weeks by the beginning of the 20th century, a window that became standard. Deaths occurring after this window would not be classified as maternal mortality.

An important issue in the collection of maternal mortality statistics is the treatment of associated deaths. These are deaths that occur while a woman is pregnant or during the postnatal period but which are due to a disease not directly related to pregnancy. For example, if woman dies of influenza or tuberculosis during of just after pregnancy, that is an associated death. In the British statistics that we use, these associated deaths are not included among maternal mortality. Of course, there are likely to be deaths in which the categorization into maternal mortality or some other associated death depended on a doctor's judgment. As long as these judgments were not influenced by fog events, which seems unlikely, they should not impact our results.

In addition to collecting data on the number of maternal deaths, we also collected information on the number of births in each week. These data include only live births; information on stillbirths was not collected by the Registrar's Office until 1927. This will matter if pollution exposure affected the number of stillbirths in a particular week.[32]

We have also collected new mortality statistics covering all ages, infants, and adults aged 20-40 (or 20-45 starting in 1911). The closest approximation that we can get to the fertile-aged population is the 20-40 age group (20-45 starting in 1911).

[31] See, e.g., Loudon (1992), p. 21. Also, using data from Canada in 1927-28, MacPhail (1932) finds that 60 percent of postnatal maternal mortality occurred within one week after birth, while 80 percent occurred within two weeks.

[32] It is worth noting that there was known to be some under-registration of births in England, particularly during the early part of our study period. However, by the 1870s evidence suggests that under-registration was a relatively minor concern. See Glass (1951) and Woods (2000), p. 38-46 for a discussion of birth under-registration.

These data provide a benchmark against which the maternal mortality effects can be compared. Finally, we have collected data on maternal mortality in three age groups: under 20, 20-40 (or 20-45 starting in 1911), and over 40 (or over 45 starting in 1911). These are the most detailed age categories for which the maternal mortality data are available. There are few maternal deaths among women under 20 or over 40, so it is not possible to analyze these data separately. Instead, the main use of the by-age maternal mortality data is to provide a set of statistics from an age group comparable to the available adult mortality statistics.

Our study period begins in 1866, at which point more reliable measures of maternal mortality were becoming available. We end our study period in 1935, a year that marked the beginning of a dramatic decline in maternal mortality, driven by the introduction of sulfa drugs (Jayachandran *et al.* (2010)). Our data are missing the years 1915-1918, during the First World War, when weather information was not included in the weekly reports.

We also collected data on the average temperature in each week reported by the Royal Observatory in Greenwich.[33] Because fog events tended to occur in the winter, we may worry that they were correlated with cold temperatures, which could have affected maternal health. Collecting temperature data allows us to address this potential concern. Ultimately we will see that temperature was not strongly related to maternal mortality.[34]

Summary statistics for the data used in our analysis are presented in Table 1. These show that there were, on average, 7.7 maternal deaths per week in London across the study period and just under 2,200 births, with an average maternal mortality ratio of 3.47 per thousand births. Among adults aged 20-40 there were on average 183 deaths per week, so maternal deaths constituted on average about 3.6% of total deaths among this group. It is likely that more than half of the deaths in this group were among men, so maternal mortality most likely made up over 7.2% of total deaths among women in the 20-40 age group. Towards the bottom of the table we can see that thick fog events were experienced in 8.8% of the weeks in our data. Note also that data on deaths by age group are available for a smaller set of weeks

[33]These temperature reports are missing for a small number of weeks in the study period because the printing was illegible. Other weather information is included in some of the reports, but average temperature is the only value available consistently across the full study period.

[34]Temperature is strongly related to other types of mortality, such as infant mortality.

than the other variables.

Table 1: Summary statistics for main analysis variables

Variable	**Mean**	**Std. Dev.**	**Min.**	**Max.**	**N**
Maternal deaths	7.685	4.018	0	27	3437
Maternal deaths in ages 20-40*	6.626	3.638	0	25	3183
Maternal deaths/1000 live births	3.471	1.618	0	11.33	3437
Live births	2193	460	663	3308	3437
Total deaths	1382	359.7	659	3761	3437
Adult deaths in ages 20-40*	183.5	37.1	94	609	2708
Infant deaths (0-1)	281.4	157.6	35	1107	3032
Deaths of children 0-5	602.5	157	226	1394	2134
Thick fog weeks	0.088	0.284	0	1	3437
Thick fog days	0.126	0.466	0	5	3437
Temperature	49.742	9.507	22.4	73.900	3437

Notes: All data are weekly. *Deaths age 20-40 and maternal deaths aged 20-40 include deaths in ages 40-45 for years starting in 1911.

4 Empirical approach

Our basic analysis approach relies on exploiting week-to-week variation in fog events while including year and week-of-the-year fixed effects to control for, respectively, changes over time and seasonal variation. The basic regression specification is:

$$MM_t = \beta FOG_t + X_t\Lambda + \xi_t + \phi_t + \epsilon_t \,, \tag{1}$$

where MM_t is a measure of maternal mortality in week t, FOG_t is an indicator for whether a heavy fog event occurred in a particular week, X_t is a set of control variables, ξ_t is a set of year effects and ϕ_t is a set of week effects. In some specifications we also allow the impact of week-of-the-year effects to vary by decade, to allow for changes in seasonal patterns over time.

Our primary outcome variable is the log of maternal mortality. This is a useful outcome to consider because it can be interpreted as the percentage increase in maternal deaths, which can then be compared to the percentage increase in other types of mortality due to fog events. One caveat in using the log of maternal mortality is that we lose a small number of observations (36 out of 3,437 weeks) for which maternal mortality is zero. As an alternative, we also consider results looking at the maternal mortality ratio (MMR), the number of maternal deaths per thousand live births in that week.[35]

Our primary dependent variable is an indicator for whether a heavy fog event occurred in a week. As an alternative, we also generate some results using the number of thick fog days that occurred. We prefer the simple indicator for a heavy fog week both because we expect measurement error in the number of fog days in a week and because we expect that each additional fog day may not have the same additional impact on maternal mortality.[36] It is worth emphasizing that this analysis approach will help us deal with concerns about the consistency of the data over our long study period. By including year effects, we are identifying the impact of fog weeks using a comparison across weeks within a year.

In most of the analysis we will include temperature and temperature squared as control variables. The square of temperature is included to account for the fact that both relatively high and relatively low temperatures could increase mortality; low temperatures were often associated with respiratory diseases such as pneumonia and influenza, while high temperatures were associated with increases in diseases such as cholera and dysentery. We have also generated results including the third or fourth root of temperature as controls; including these additional controls does not affect our results and they are never close to statistically significant, so we leave them out of our preferred specification.

In most specifications, we will also include the number of births in the week as a control variable (though not when using MMR as the outcome variable). The inclusion of this control is not crucial for our results, but it is useful because the number of births is a partial reflection of the the number of women at risk for maternal mortality in any period. We say partial here because births in a week will not perfectly reflect that at-risk population in that week because (1) women may die before childbirth,

[35]One reason that we do not use the MMR as our main specification is that, at the weekly level, the number of live births is not a perfect indicator of the number of women at risk of maternal mortality. This is because women can die before giving birth, while having a still birth, or more than a week after giving birth.

[36]Measurement error in the number of fog days will occur if, for example, some fogs occur at night and therefore are reported in two daily entries while other similar fog events occur during the day and are reported in only one daily entry. Additional days of thick fog may have less impact if much of the vulnerable population dies as a result of the first fog day.

with no birth occurring, though these deaths tended to be rare, (2) maternal mortality could occur more than a week after childbirth, (3) maternal mortality could be associated with a stillbirth, which were not included in our births data, and (4) a woman could have given birth to more than one child.

The fact that our data are structured as a time series raises the possibility that serial correlation could affect our standard error estimates. We will explore this possibility and provide evidence that serial correlation is not a substantial concern in the time series that we study.

5 Results

Table 2 presents our first set of regression results. In Columns 1-3 the dependent variable is the log of maternal mortality while in Columns 4-6 it is the maternal mortality ratio. The results in Column 1 include only the fog indicator variable as well as year and week-of-the-year indicator variables. In Column 2, we add additional controls for the number of births, temperature, and temperature squared. Births have a statistically significant relationship to the number of maternal deaths while temperature doesn't appear to matter. Overall, the inclusion of these variables has very little impact on the relationship between thick fog events and maternal deaths. In Column 3, we include week-of-the-year by decade effects in place of week-of-the-year effects, which allows the seasonality of maternal mortality to vary over time. This increases the R-squared values and we obtain a slightly higher estimate for the relationship between fog days and maternal mortality.

The results in Columns 1-3 imply that fog events raise maternal mortality by roughly 5.8-7.4%. These results are statistically significant at the 95% level and become larger as additional controls are added. The results in Columns 4-6 indicate that fog events raise the maternal mortality ratio by .17-.21 deaths per 1000 live births. As a point of comparison, this is roughly the difference in 2015 between maternal mortality in Canada or France and the level experienced in China or Russia.[37]

The regressions shown in Table 2 are calculated using robust standard errors.

[37]WHO (2015) estimates that the maternal mortality ratios in China and Russia, respectively, in 2015 were 27 and 25 per 100,000 births, while the ratios in Canada and France were, respectively, 7 and 8.

Table 2: Baseline regression results

Dep. var.:	Log Maternal Mortality			Maternal Mortality Ratio		
	(1)	(2)	(3)	(4)	(5)	(6)
Fog indicator	0.0564**	0.0568**	0.0716**	0.185*	0.173*	0.209**
	(0.0262)	(0.0264)	(0.0282)	(0.0952)	(0.0950)	(0.104)
Log births		0.576***	0.504***			
		(0.105)	(0.117)			
Temperature		-0.00760	0.000936		-0.0619**	-0.0292
		(0.00974)	(0.0104)		(0.0314)	(0.0338)
Temp. Sq.		0.000115	6.98e-06		0.000710**	0.000313
		(0.000101)	(0.000105)		(0.000316)	(0.000338)
Year effects	Yes	Yes	Yes	Yes	Yes	Yes
Week effects	Yes	Yes		Yes	Yes	
Week x decade eff.			Yes			Yes
Observations	3,401	3,401	3,401	3,437	3,437	3,437
R-squared	0.442	0.448	0.508	0.303	0.304	0.375
DW stat.	1.91	1.92	1.93	1.87	1.87	1.88

*** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses. The number of observations in Columns 1-3 is smaller than the number in Columns 4-6 because the log specification drops 36 weeks in which no maternal deaths occurred.

At the bottom of each panel we have included Durbin-Watson statistics in order to assess whether serial correlation may be a concern. In all cases, the Durbin-Watson statistics are very close to two, which indicates no serial correlation, and well above one, a level which typically suggest that serial correlation may be a problem. This provides strong evidence that serial correlation is not an important concern in our maternal mortality data once we account for year and week-of-the-year effects.

Given that births are included as a control in Table 2, it is natural to wonder whether the number of births in a week was affected by fog events. This relationship could conceivable go in either direction; fog events could decrease births if they caused miscarriages or stillbirths, or they could increase births if the pollution caused some women to go into labor early. We explore this issue in Appendix Table 9. Ultimately, we find no strong relationship between fog events and the number of births in a week. In all cases the estimated relationship is positive but the coefficients are very small and not statistically significant.

The next step in our analysis is to study how the response of maternal mortality to thick fog events compares to the response of other types of mortality. This can help us address the possibility that maternal deaths may have been increasing during fog events simply because all deaths were increasing. We offer two approaches to these comparisons. In the first, we run seemingly unrelated regressions that allow us to compare the impact of fog events on maternal mortality (in logs) to the impact on other types of mortality.

The results of this exercise are presented in Table 3. Columns 1-2 of this table compares the effect of thick fog events on maternal mortality and total mortality (all ages). We can see that fog events are associated with a statistically significant increase in both maternal and overall mortality, but the coefficients also show that the impact on maternal mortality, in percentage terms, is much larger than the impact on all-age mortality. Specifically, the coefficient on maternal mortality is 4.5 times larger than the coefficient on all-age mortality. Moreover, Chi-squared tests, presented at the bottom of the table, show that this difference is statistically significant at just below the 95% confidence level.

Columns 3-4 present similar results comparing maternal mortality to mortality among adults aged 20-40 (or ages 20-45 for years after 1911), the most comparable age group to expectant mothers for which separate mortality data are available. These results, which are generated using a smaller sample of weeks, show that the impact of fog events on maternal mortality was 4.7 times larger, in percentage terms, than the impact on adult mortality. The Chi-squared test at the bottom of the table shows that this difference is statistically significant at the 95% confidence level.[38]

Columns 5-6 present additional results for only those aged 20-40 (20-45 for years after 1911). This ensures that both the maternal mortality and adult mortality data are for the same population. These results, which are available for a slightly shorter period, provide even stronger evidence that maternal mortality was more sensitive to polluted fog events than the comparable adult population. In particular, the estimated impact on maternal mortality in these columns, in percentage terms, is 7.6 times larger than the impact on the comparable adult population and this difference is strongly statistically significant.

Overall, the results in Table 3 show that the impact of fog events on maternal mortality was much larger, in percentage terms, than the impact on mortality among

[38]The set of available weeks is smaller because we do not have mortality for the 20-45 age group after 1921.

other populations. Put another way, we find that mothers were substantially more vulnerable to the effects of air pollution during pregnancy or just after giving birth than the general population.

Table 3: Comparing the impact of fog events on mortality among different populations

	Comparison one		**Comparison two**		**Comparison three**	
Dependent variable:	Maternal mortality (all ages) (1)	Total mortality (all ages) (2)	Maternal mortality (all ages) (3)	Adult mortality (20-40*) (4)	Maternal mortality (20-40*) (5)	Adult mortality (20-40*) (6)
Fog ind.	0.0716**	0.0158**	0.0849***	0.0180*	0.109***	0.0144
	(0.0286)	(0.00774)	(0.0315)	(0.00942)	(0.0339)	(0.00949)
Log births	0.504***	0.235***	0.691***	0.100***	0.811***	0.149***
	(0.110)	(0.0297)	(0.125)	(0.0373)	(0.132)	(0.0369)
Temp.	0.000936	-0.0448***	-0.00475	-0.0264***	-0.00700	-0.0226***
	(0.00929)	(0.00252)	(0.0109)	(0.00326)	(0.0114)	(0.00318)
Temp. Sq.	6.98e-06	0.000433***	6.18e-05	0.000261***	3.80e-05	0.000179***
	(9.48e-05)	(2.57e-05)	(0.000113)	(3.39e-05)	(0.000116)	(3.25e-05)
Obs.	3,401	3,401	2,320	2,320	2,297	2,297
R-squared	0.508	0.828	0.408	0.643	0.332	0.620
Test for equality of fog effect						
Chi-sq. stat.	3.65		4.14		7.20	
p-value	0.0561		0.0419		0.0073	

*** p<0.01, ** p<0.05, * p<0.1. Seemingly unrelated regressions. Robust standard errors in parentheses. All regressions include a full set of year effects and week-of-the-year by decade effects. Note that the set of weeks for which adult mortality is available, which are used in Columns 3-6, is substantially smaller than the set of weeks for which total mortality is available. Maternal mortality data by age are not available for year before 1870. *Ages 20-40 for year up to 1911 and ages 20-45 after 1911.

An alternative way to compare the impact of fog events on maternal versus other mortality types is to look at the cause-specific death ratio (CSDR), i.e., the ratio of maternal deaths to deaths among other populations. These results are shown in Table 4. In Column 1, we look at the ratio of maternal deaths to all deaths. In Column 2, we compare maternal deaths to deaths among adults aged 20-40 (or 20-45 after 1911). In Column 3, we compare maternal deaths among mothers aged 20-40 (or 20-45 after 1911) to deaths among all adults in the same age group. Thus, Column 3 presents the ratio of maternal deaths to the most comparable age group. In all three cases we observe evidence that fog events were associated with a statistically significant increase in the log CSDR. Moreover, the results become stronger as we

Table 4: Cause-specific mortality rate results

Dependent var.:	Log (maternal deaths / total deaths) (1)	Log (maternal deaths / adult deaths in ages 20-40*) (2)	Log (maternal deaths in ages 20-40* / adult deaths ages 20-40*) (3)
Fog indicator	0.0560*	0.0628**	0.0901***
	(0.0287)	(0.0315)	(0.0339)
Log births	0.270**	0.554***	0.627***
	(0.127)	(0.148)	(0.159)
Temperature	0.0459***	0.0302**	0.0150
	(0.0107)	(0.0120)	(0.0114)
Temp. Sq.	-0.000429***	-0.000283**	-0.000150
	(0.000107)	(0.000119)	(0.000116)
Year effects	Yes	Yes	Yes
Week x decade eff.	Yes	Yes	Yes
Observations	3,401	2,685	2,453
R-squared	0.337	0.303	0.248
DW stat.	1.85	1.85	1.87

*** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses. * for years after 1911 the age group is 20-45.

compare more similar populations. Finally, note that the Durbin-Watson statistics at the bottom of the table indicate that serial correlation is not an important concern in these regressions.

Next, we explore results that include several leads and lags of the fog event variable. This allows us to look at whether there is evidence that the effects of pollution on maternal mortality persisted in the weeks after the fog events. These results are presented in Figure 4. In the left-hand panel, the dependent variable is the log of maternal mortality. For comparison purposes, in the right-hand panel we present results using the log of total mortality as the dependent variable.

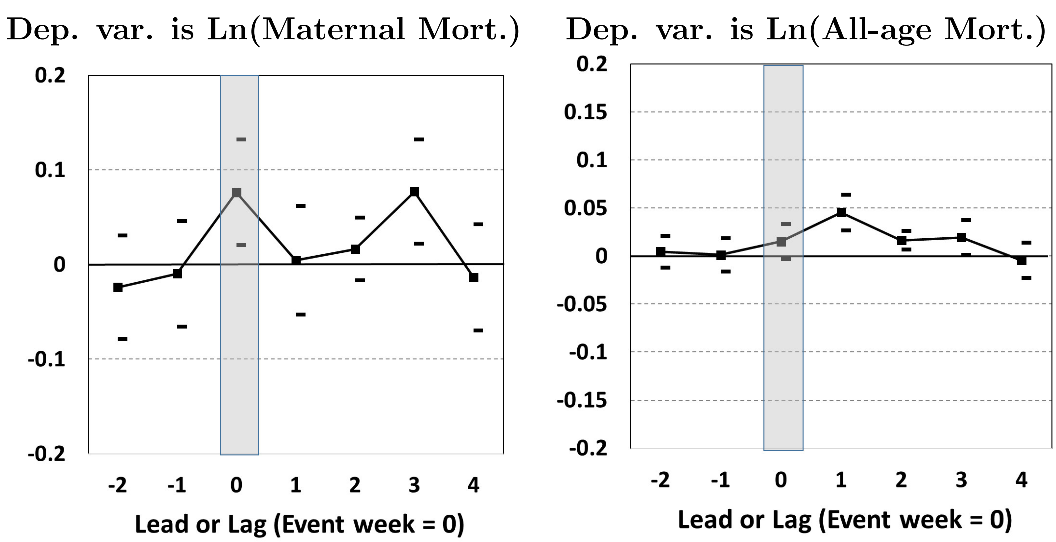
Several interesting patterns are visible in the left panel of Figure 4. First, we see no evidence that fog events were preceded by elevated levels of either maternal mortality or total mortality. This provides some additional confidence that our identification strategy is working well.[39] Next, we see a sharp spike in maternal mortality during weeks in which a fog event occurred. The two weeks directly following fog events do not exhibit elevated levels of maternal mortality, but there is evidence that maternal

[39] In Appendix Table 9 we show that the same is true if we estimate effects for additional leads.

mortality levels were elevated three weeks after the fog events. By week four, the impact of the fog events appears to have completely dissipated.

It is interesting to compare the patterns for maternal mortality shown in the left panel of Figure 4 to the patterns observed for total mortality in the right panel. For total mortality, the effect of fog events peaks later, 1-2 weeks after the events occur. This pattern is not being driven by infants; when we look at adult mortality we see a similar pattern, with the peak effects occurring one week after the fog events (see Appendix Figure 7). Like maternal mortality, however, the impact of fog events on total mortality completely dissipates after four weeks. It is worth emphasizing that the substantial differences between the patterns observed for maternal mortality and those observed for total mortality (or adult mortality) provide further evidence that the impact of air pollution on maternal mortality is fundamentally different than the impact on mortality among other populations.

Figure 4: Estimated lead and lag effects for maternal and total mortality



These figures describe estimated coefficients and 95% confidence intervals based on robust standard errors for the impact of fog events on maternal or total mortality. All regressions include a full set of year effects and week-of-the-year x decade effects as well as log births, temperature, and temperature squared. Left panel: N=3,390. Right panel: N=3,425. Note that there are a few missing weeks or weeks with zero maternal mortality in our data which cause us to lose additional observations when calculating leads and lags.

The pattern shown in the left-hand panel of Figure 4, in which maternal mortality is elevated in both the week a fog event occurs and three weeks later, appears to be quite robust. For example, we observe the same pattern if we estimate the effects of lagged fog events separately (Appendix Table 10), look only at years before 1901 or only at years after 1900, or if we only look at the lagged effect of fog events in weeks in which no contemporaneous fog event occurred (see Appendix Table 11). Thus, this pattern appears to be a salient feature of the relationship between pollution and maternal mortality.

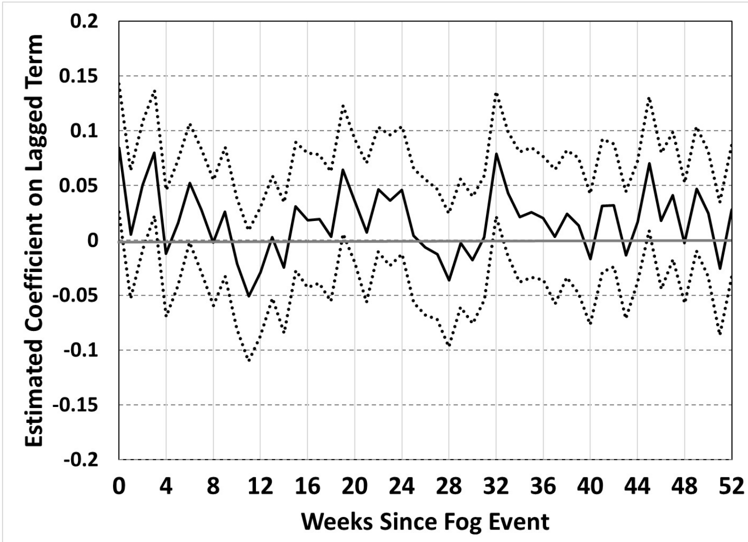
We can only speculate about the factors that may cause the double-peaked relationship shown in the left-hand panel of Figure 4. The most likely explanation for these patterns is that the air pollution exposure generated by heavy fog days had very acute effects on maternal mortality as well as effects operating through some channel that took time to develop. It may also be the case that maternal mortality was low in the two weeks just after a fog event due to a harvesting effect in which the population of mothers present in the week after the fog event was less likely to die from pollution effects because the most vulnerable among them had succumbed during the fog event week. Later we will present results that can help us assess whether harvesting is likely to be an important force in our setting.

It is also possible to include a longer set of lagged terms in order to assess whether there is evidence that short-run increases in pollution exposure due to fog events earlier in a pregnancy increased maternal mortality. Figure 5 presents the estimated response of maternal mortality to fog events up to 52 weeks earlier.[40] These results provide no evidence that fog events occurring earlier in the pregnancy increased maternal mortality later in the pregnancy.[41]

[40]In Appendix A we present similar results but for total mortality. These show that fog events increase total mortality for up to three weeks following the event.

[41]This pattern is consistent with the results of some existing studies, such as Dadvand *et al.* (2013) and Pereira *et al.* (2013), which find that third-trimester pollution exposure has a particularly strong influence on the development of pre-eclampsia, though this result is not found in all studies that look at impacts by trimester.

Figure 5: Effect of lagged fog events on maternal mortality up to 52 weeks later



This figure describes estimated coefficients and 95% confidence intervals based on robust standard errors for the impact of an indicator variable for heavy fog events in a week on maternal mortality. This regression includes a full set of year effects and week-of-the-year x decade effects as well as log births, temperature, and temperature squared.

Given the results shown in Figure 4, one might worry that the impact of a fog event on maternal mortality does not differ substantially from the impact on total or adult mortality if we look across both the week in which the event occurs as well as the three following weeks. To check this, Table 5 presents additional results where we analyze the impact of a fog event on mortality in the week that the event occurred together with the three following weeks. To do so we run regressions using as the key explanatory variable an indicator for whether a fog event occurred in a four week window starting with the fog event week.

Table 5: Comparing the impact of fog events over four week windows

Dependent variable:	Maternal mortality (all ages) (1)	Total mortality (all ages) (2)	Maternal mortality (all ages) (3)	Adult mortality (20-40*) (4)	Maternal mortality (20-40*) (5)	Adult mortality (20-40*) (6)
Fog ind.	0.0867***	0.0325***	0.111***	0.0183**	0.108***	0.0212***
(four week)	(0.0212)	(0.00572)	(0.0238)	(0.00714)	(0.0253)	(0.00707)
Log births	0.496***	0.232***	0.654***	0.0945**	0.761***	0.139***
	(0.110)	(0.0296)	(0.124)	(0.0373)	(0.132)	(0.0370)
Temp.	-0.000591	-0.0450***	-0.00592	-0.0268***	-0.00912	-0.0227***
	(0.00923)	(0.00249)	(0.0108)	(0.00323)	(0.0113)	(0.00315)
Temp. Sq.	2.22e-05	0.000436***	7.17e-05	0.000264***	6.68e-05	0.000182***
	(9.43e-05)	(2.55e-05)	(0.000112)	(3.37e-05)	(0.000115)	(3.23e-05)
Obs.	3,401	3,401	2,320	2,320	2,297	2,297
R-squared	0.509	0.829	0.411	0.643	0.334	0.621
Test for equality of fog effect						
Ratio of estimated coef:		2.7		6.1		5.1
Chi-sq. stat.		6.24		13.72		10.99
p-value		0.0125		0.0002		0.0009

*** p<0.01, ** p<0.05, * p<0.1. Seemingly unrelated regressions. Robust standard errors in parentheses. All regressions include a full set of year effects and week-by-decade effects. Estimates are obtained using seemingly unrelated regressions. Note that the set of weeks for which adult mortality is available, which are used in the regressions in Columns 3-4, is substantially smaller than the set of weeks for which total mortality is available.

The results presented in Table 5 suggest that fog events have a much stronger impact on maternal mortality across four week windows than on either total mortality or adult mortality. Specifically, the estimated impact on maternal mortality, in percentage terms, is 2.7 times larger than the impact on total mortality and 5-6 times larger than the impact on adult mortality. The Chi-squared tests presented at the bottom of Table 5 show that these differences are statistically significant at the 95% and 99% confidence levels.

Previously we mentioned the possibility that a fog event in one week may affect the impact of fog events in the following week through harvesting. The idea here is that a fog event in the past week might reduce the impact of a fog event this week if it reduced (through mortality) the vulnerable population exposed to fog this week. In this case fog events in the recent past should reduce the impact of current fog events. Alternatively, we may think that pollution exposure has a cumulative effect, so that a fog event in the past week makes people more vulnerable to fog events this week.

To explore these possibilities, we look at whether the impact of fog events changes depending on whether a fog event occurred in the past week. These results are shown in Table 6, where we separately estimate the impact of fog events depending on whether an event also occurred in the previous week or not.[42] The results in Table 6 provide some evidence in favor of a cumulative effect of fog events on maternal mortality; in general we observe larger estimated effects from fog events where a fog event also occurred in the past week. However, the differences between the estimated coefficients are never statistically significant, so we cannot draw strong conclusions from these results.

Table 6: Effect of fog events depending on whether one occurred in the previous week

Dependent var:	**Log Maternal Mortality**		**Maternal Mortality Ratio**	
	(1)	(2)	(3)	(4)
Fog event with event in previous week	0.0833*	0.0907*	0.281	0.263
	(0.0494)	(0.0522)	(0.180)	(0.192)
Fog event without event in previous week	0.0482*	0.0658**	0.147	0.194*
	(0.0291)	(0.0311)	(0.105)	(0.114)
Year effects	Yes	Yes	Yes	Yes
Week effects	Yes		Yes	
Week x decade eff.		Yes		Yes
Observations	3,401	3,401	3,437	3,437
R-squared	0.448	0.508	0.307	0.379

*** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses. All regressions include controls for temperature and temperature squared. The regressions in Columns 1-2 also include controls for log births.

Next, we consider some additional results which use the number of days in a week in which thick fog occurred in place of an indicator variable for whether any thick fog occurred in a week. These results provide a robustness check on our main specification and also allow us to look at the impact that additional fog days within a week had on mortality, which is done by including the square of the number of fog days in the week in the regressions. The results are presented in Table 7. All of these results suggest that maternal mortality was increasing in the number of fog days in a week. In addition, the results on the squared term in Columns 2, 4 and 6 provide

[42]In our data there are 81 fog events where fog events also occurred in the previous week, and 222 where no fog event occurred in the past week.

some evidence that the impact of each additional fog day decreased as the number of fog days increased, though this pattern is not statistically significant.

Table 7: Results using the number of fog days in a week

	Dependent variable: Log Maternal Mortality					
	(1)	(2)	(3)	(4)	(5)	(6)
Fog days	0.0314*	0.0668*	0.0336**	0.0624*	0.0395**	0.0767**
	(0.0165)	(0.0345)	(0.0163)	(0.0343)	(0.0182)	(0.0360)
Fog days squared		-0.0144		-0.0117		-0.0149
		(0.0125)		(0.0121)		(0.0128)
Log births			0.580***	0.577***	0.510***	0.506***
			(0.105)	(0.105)	(0.117)	(0.117)
Temperature			-0.00779	-0.00749	0.000722	0.000997
			(0.00973)	(0.00973)	(0.0104)	(0.0104)
Temp. Sq.			0.000117	0.000114	8.94e-06	6.31e-06
			(0.000101)	(0.000101)	(0.000106)	(0.000105)
Year effects	Yes	Yes	Yes	Yes	Yes	Yes
Week effects	Yes	Yes	Yes	Yes		
Week x decade eff.					Yes	Yes
Observations	3,401	3,401	3,401	3,401	3,401	3,401
R-squared	0.442	0.442	0.448	0.448	0.508	0.508
DW stat.	1.91	1.91	1.92	1.92	1.93	1.93

*** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses.

Thus far our analysis has been conducted across all available years. Because maternal mortality was highly variable, and because thick fog events were relatively rare, in order to obtain clear results we need to use as much data as possible. However, it is also interesting to study whether the relationship between maternal mortality and fog events changed across our study period. To do so, we estimate separate parameters for the impact of fog events for two roughly similar periods, from the beginning of our data through 1900 and from 1901 to the end of the data. These results are shown in Table 8. The results in Column 1 focus on maternal mortality. We can see that fog events are associated with increased maternal mortality in both the early and late periods. The effect of fog events appears to be slightly larger in the period after 1900, but the difference is not statistically distinguishable.[43] As a point of comparison, in Column 2 we estimate the impact on total mortality in the two

[43] A test of the difference between these two coefficients has an F-statistic of 0.28 and a p-value of 0.597.

periods. Again, we observe relatively similar effects across the pre-1901 and post-1900 periods, though these effects are not statistically significant (note that each estimate is derived from fewer observations than in our main results). Column 3 displays the ratio of the maternal mortality coefficient to the total mortality coefficient. The ratio is somewhat higher in the early period, but the difference is not large. Overall, these results suggest that the impact of fog events on mortality was relatively stable across the study period. In Appendix Table 11 we conduct a similar exercise including the lagged effects of fog events up to three periods. Those results show similar patterns in both the pre-1901 and post-1900 periods.

Table 8: Effect of fog events before and after 1901

	Ln(Maternal mortality) (1)	Ln(Total mortality (2)	Ratio of maternal /total mortality effect (3)
Pre-1901 × fog event	0.0614* (0.0318)	0.0129 (0.0108)	4.8
Post-1900 × fog event	0.0959* (0.0573)	0.0247 (0.0183)	3.9
Observations	3401	3437	

*** p<0.01, ** p<0.05, * p<0.1 Robust standard errors in parentheses. All regressions include a full set of year effects and week-of-the-year by decade effects as well as log births, temperature, and temperature squared. The maternal mortality results use slightly fewer observations because there are a small number of weeks in which there were zero maternal deaths and those observations are dropped in the log specification.

One implication of the results shown in Table 8 is that the medical advances achieved during the study period had relatively little impact on the relationship between air pollution and maternal mortality. This finding can be useful for thinking about the channels through which pollution increased maternal mortality. Most of the medical improvements that took place during our study period were directed at reducing the prevalence of puerperal fever (e.g., antisepsis). Improved training of doctors and midwives may have also helped them avoid or treat haemorrhages. The fact that these improvements did not seem to substantially influence the relationship between pollution and maternal mortality suggests that these channels, particularly puerperal fever, are less likely to have been the key link.

6 Discussion

The results presented above suggest that pregnancy and childbirth substantially increased mothers' vulnerability to the effects of severe air pollution. But how important are these effects likely to be in modern developing countries, where maternal mortality rates remain high and women are often exposed to high levels of air pollution? Answering this question is complicated by the lack of direct pollution measures in our setting, as well as in many modern developing countries.

To make progress, we focus on the increase in maternal deaths associated with fog events relative to the increase in infant mortality. This allows us to form a rough estimate of how many additional maternal deaths we should expect for each infant death attributable to the acute effects of air pollution exposure. Relating the maternal mortality effects of pollution to the infant mortality effects allows us to draw on the larger set of existing studies focusing on infant mortality in order to make a guess at the impact of pollution on maternal health in poor developing countries where (as in our setting) mothers do not have access to modern medical care.

In Appendix Figure 8, we present results describing the *acute* impact of fog events on infant mortality.[44] Looking over four week periods starting with the week in which a fog event occurred, we find that the annualized increase in infant mortality associated with a fog event is equal to 643 deaths per 100,000 live births.[45] Using a similar approach, a fog event is associated with an annualized increase in maternal mortality of 58 deaths per 100,000 live births. Under the assumption that the relationship between infant deaths, maternal deaths, and pollution in our setting is similar to that found in poor developing countries today, this implies that for every 100 additional infant deaths associated with pollution exposure we should expect there to be 9 maternal deaths. Of course, this assumption is not reasonable in places with access to modern medical care, but it may be reasonable in poorer developing countries and

[44] These results focus on the acute effect only and do not speak to the impact of exposure early in the pregnancy on later maternal mortality. Our data are not well-suited for looking at how exposure early in pregnancy affected infant mortality after birth.

[45] By annualized, we mean that that this is the impact of a fog event in one week divided by 7 and multiplied by 365. We need to annualize these results in order to allow a comparison between the impact on the infant mortality rate and the impact on the maternal mortality rate. This is because we calculate the infant mortality rate in a week relative to the number of live births in the past year (as in Arceo *et al.* (2016)) while the maternal mortality ratio in a week is calculated relative to the number of births in that week.

particularly among disadvantaged populations.

We can now use estimates from modern studies looking at infant mortality due to pollution to generate some back-of-the-envelope calculations of the importance of pollution for maternal mortality. One relevant study is Jayachandran (2009), which looks at the impact of air pollution generated by wildfires that blanketed Indonesia with smoke in 1997 on infant mortality.[46] This is a relevant setting because maternal mortality remains high in Indonesia today, with an estimated 6,400 women dying in childbirth there in 2015 (WHO (2015)).[47] Jayachandran estimates that exposure to wildfire pollution resulted in 15,600 missing children in the cohort born during this period. If we take these to be reflective of infant deaths, then applying our results would suggest that the wildfires also resulted in the deaths of over 1,400 mothers.

Another relevant study is Arceo *et al.* (2016) which uses temperature inversions in Mexico city to estimate the impact of pollution on infant mortality. This is not a perfect setting to apply our results because Mexico is a middle-income country where most women have access to modern medical care, which could reduce the impact of pollution on maternal mortality. So results based on this study should be taken with a grain of salt. Bearing this in mind, the estimates from Arceo *et al.* (2016) suggest that the declines in pollution in Mexico City from 1997-2006 reduced infant mortality by 325 deaths per 100,000 births. Given our results, this could imply a reduction in maternal mortality of 29 deaths per 100,000 births. This is almost certainly an overestimate, but even half of this effect would be large. For comparison, maternal mortality in Mexico fell by 31 deaths per 100,000 births (from 85 to 54) between 1995-2005.

7 Conclusions

This study provides evidence that high levels of air pollution have acute effects on maternal mortality. To our knowledge this is the first study to draw a direct causal link between air pollution and maternal mortality, which is made possible by the

[46]One caveat in comparing our estimates to Jayachandran's results is that the harmful chemicals released by burning wood may differ from those released by burning coal, the primary pollutant in the setting that we study.

[47]In 1995, the maternal mortality ratio in Indonesia was estimated to be 326 (WHO (2015)). For comparison, the average in developed countries today is around 12.

unique features of the historical setting that we consider. These findings expand our understanding of how pollution affects the human system. Further work is needed to isolate the physiological channels through which these effect occur.

While we exploit fog events to isolate the causal effects of pollution on maternal mortality, mothers in London and other industrial cities were exposed to air pollution throughout the year. Thus, we hope that future work can go beyond fog events to estimate the impact of pollution on maternal health more broadly. Such estimates could prove valuable in understanding the larger social and economic consequences of maternal death.

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A Appendix

Figure 6: Weather reports from the week ending Feb. 7, 1880

SKY AND ATMOSPHERE.

Hoar frost and dense fog in morning; fine in afternoon and evening; very foggy at night.

Hoar frost and dense fog in morning; fine with light cloud till evening; overcast at night and a little thin rain fell then.

Overcast.

Hoar frost in morning; foggy during the greater part of the day; sky cloudless throughout. (In the lower parts of the Park and in the town of Greenwich the fog was extremely dense at times.)

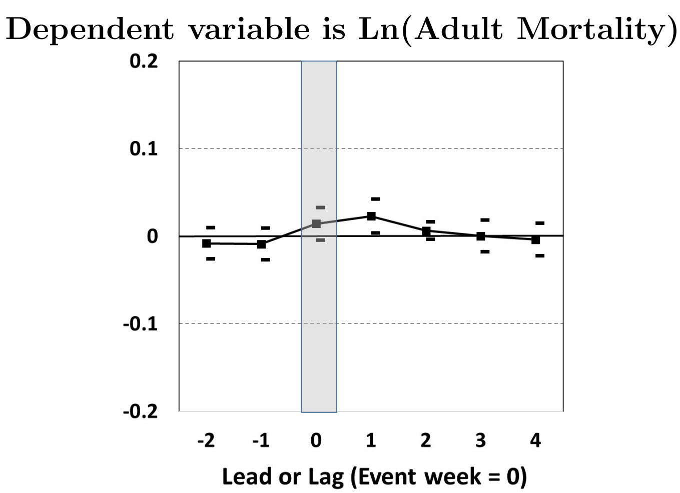
Misty in morning; very fine and generally cloudless till afternoon; overcast afterwards. A little thin rain fell at night.

Overcast. Frequent thin rain.

Overcast. Frequent rain.

Source: *Weekly Return of Births and Deaths in London* for the week ending Feb. 7, 1880, published by the Registrar General's Office.

Figure 7: Estimated lead and lag effects for adult mortality



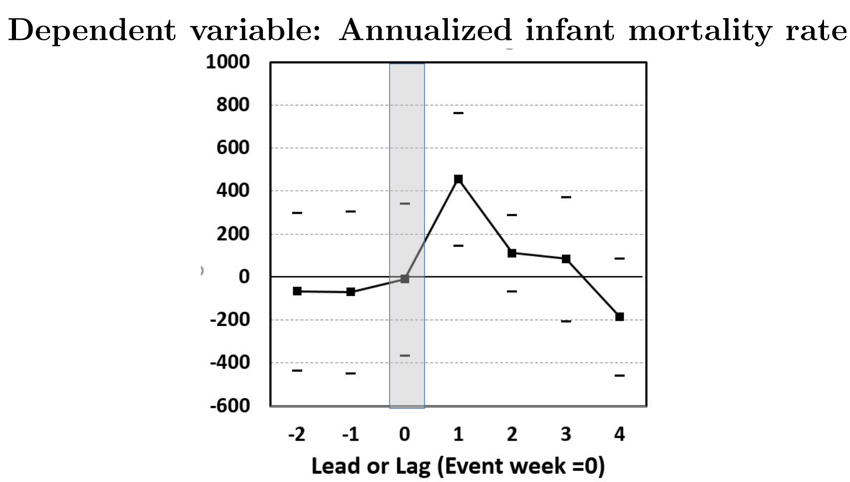
This figure describes estimated coefficients and 95% confidence intervals based on robust standard errors for the impact of fog events on adult mortality. Adult mortality is based on mortality among the 20-40 age group prior to 1911 and the 20-45 age group after 1911. The regression includes a full set of year effects and week-of-the-year by decade effects as well as log births, temperature, and temperature squared. N=2,698.

Table 9: Impact of fog events on births

	DV: Log births			
	(1)	(2)	(3)	(4)
Fog event	0.00172	0.00650	0.00114	
	(0.00521)	(0.00510)	(0.00525)	
Fog event in past 4 weeks				0.00418
				(0.00381)
Temperature		0.0114***	0.0138***	0.0138***
		(0.00179)	(0.00166)	(0.00166)
Temp. Sq.		-0.000104***	-0.000138***	-0.000138***
		(1.73e-05)	(1.61e-05)	(1.60e-05)
Constant	7.750***	7.461***	7.299***	7.298***
	(0.0114)	(0.0461)	(0.0441)	(0.0439)
Year effects	Yes	Yes	Yes	Yes
Week effects	Yes	Yes		
Week × decade eff.			Yes	Yes
Observations	3,437	3,437	3,437	3,437
R-squared	0.915	0.917	0.932	0.932
DW stat.	1.73	1.70	1.90	1.90

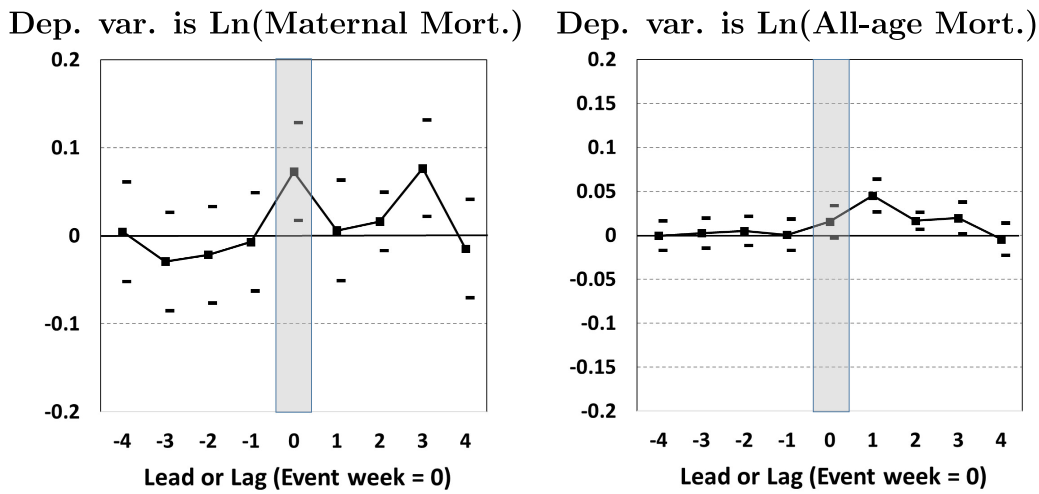
*** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses.

Figure 8: Estimated lead and lag effects for infant mortality



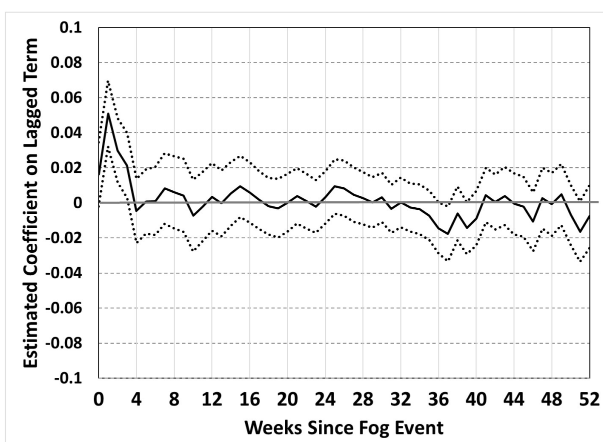
This figure describes estimated coefficients and 95% confidence intervals based on robust standard errors for the impact of fog events on annualized infant mortality per 100,000 live births. The regression includes a full set of year effects and week-of-the-year by decade effects as well as log births, temperature, and temperature squared. N=3,024.

Figure 9: Estimated lead and lag effects with additional pre-fog weeks



These figures describe estimated coefficients and 95% confidence intervals based on robust standard errors for the impact of fog events on maternal or total mortality. All regressions include a full set of year effects and week-of-the-year by decade effects as well as log births, temperature, and temperature squared. Left panel: N=3,390. Right panel: N=3,421. Note that there are a few missing weeks or weeks with zero maternal mortality in our data which cause us to lose additional observations when calculating leads and lags.

Figure 10: Effect of lagged fog events on total mortality up to 52 weeks later



This figure describes estimated coefficients and 95% confidence intervals based on robust standard errors for the impact of heavy fog events on total mortality. This regression includes a full set of year effects and week x decade effects as well as log births, temperature, and temperature squared.

Table 10: Separate estimates of the lagged effects of fog events

	DV: Log maternal deaths					
	(1)	(2)	(3)	(4)	(5)	(6)
Fog event this week				0.0717**	0.0709**	0.0735***
				(0.0283)	(0.0283)	(0.0284)
Fog event last week	0.0119			0.00970		
	(0.0290)			(0.0289)		
Fog event two weeks ago		0.0193			0.0180	
		(0.0172)			(0.0171)	
Fog event three weeks ago			0.0786***			0.0800***
			(0.0275)			(0.0276)
Observations	3,399	3,397	3,396	3,399	3,397	3,396
R-squared	0.507	0.507	0.508	0.508	0.508	0.509

*** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses. All regressions include controls for log births, temperature and temperature squared as well as year effects and week-of-the-year by decade effects.

Table 11: Additional results looking at the lagged effects of fog events

	DV: Log maternal deaths		
	Years before 1901	Years after 1900	Dropping weeks when fog events occurred
	(1)	(2)	(3)
Fog event this week	0.0449	0.0797	
	(0.0298)	(0.0542)	
Fog event last week	-0.00863	-0.0128	-0.00815
	(0.0291)	(0.0579)	(0.0336)
Fog event 2 weeks ago	0.00282	0.0444	0.0230
	(0.0189)	(0.0296)	(0.0209)
Fog event 3 weeks ago	0.0739***	0.0718	0.118***
	(0.0282)	(0.0575)	(0.0305)
Fog event 4 weeks ago	-0.00471	-0.0420	-0.0208
	(0.0271)	(0.0645)	(0.0327)
Observations	1,801	1,593	3,095
R-squared	0.248	0.272	0.508

*** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in parentheses. All regression include controls for log births, temperature and temperature squared, as well as year effects and week-of-the-year by decade effects.