The Impact of Industrial Pollution Exposure on Hospital Admissions: Evidence from a Cement Plant in Russia

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Abstract

The effect of individual-level daily silicon dust exposure from cement production on the probability of hospital admissions for respiratory-related reasons is examined. We use an aerodynamic dispersion model to calculate pollutants' exposure. The dataset was collected at the cement plant in Bryanskii region, Russia. We find significant impact of silicon dust on hospitalizations for children and elderly adults. We identify a non-linear response of the individual probability of hospital admissions to

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the average daily inhaled concentrations in the city area where exposure is higher. Our findings contribute to better inform policymakers aiming at reducing industrial air pollution exposure in Russia.(*JEL* I10, Q51, Q53)

Air pollution is the single largest environmental health risk in Europe, responsible for 307 thousand premature deaths in 2019 (EEA (2021)). Most pollutants are released as by-products of human activities, namely in transport, agriculture, generation and use of energy, industry, and waste management. For instance, when accounting for the full social costs of energy production, air pollution largest costs to society result from health impacts, which dominate the non-carbon external costs. Soot and other pollutants such as sulfur dioxide (SO2), carbon monoxide (CO), and nitrogen oxides (NOx), which lead to ozone, all threat well-being by increasing mortality rates and hospital admissions, restricting activity days, and increasing health expenditures associated to respiratory problems. Although emissions from many air pollutants have decreased significantly in the past decades, resulting in improved air quality across the region, air pollutant concentrations are still too high conditional on the location. The EU air quality for key local pollutants, such as particulate matter (PM2.5 and PM10, which include smoke, dust, soot, among others), nitrogen dioxide (NO2) and ozone (O3) still exceed the ambient air standards, as well as the critical loads of nitrogen in many ecosystems. Exposure to fine particulate matter is responsible for about 400 000 premature deaths in Europe every year. In particular, the central and eastern European countries, where regulations are typically less stringent, and monitoring is less reliable, are more severely affected (EEA (2019)). Both the World Health Organization (WHO) and the European Union (EU) directives have been recently revised to reflect the empirical evidence collected since the previous update in 2005. The new WHO recommendations focus on defining new, more stringent, regulatory thresholds for air pollution from agriculture, industry, transport, buildings, and energy (EEA (2021)).

According to the USA Environmental Protection Agency, the cement sector is the third largest industrial source of pollution (EPA (2022)). Chatham

House (2018) states that the cement production accounts for 8% of global CO2 emissions every year even though the improvements that have been widely adopted, specifically in developed countries. During Covid-19 related lockdowns the emissions from the cement production were not lower than during the pre-Covid (Andrew (2022)), and the industry is projected to grow 5.1% annually by 2029 (Fortune Cement Market (2022)).

The epidemiological literature has investigated the health consequences on local communities that live or work near the cement production facilities. A meta-analysis conducted by Fell and Nordby (2017) pointed out to a reduction in lung function levels above 4.5 mg/m^{-3} of total dust and 2.2 mg/m^{-3} of respiratory dust in cross-sectional studies). Also, a recent review by Raffetti, Treccani and Donato (2016) supports the hypothesis that exposure to cement dust and other pollutants may have a toxic activity on respiratory airways, reducing the dynamic lung function, increasing the risk of respiratory symptoms and diseases with a possible carcinogenic effect.

The impact of cement plant emissions on the nearby communities also depends on the filtration and abatement system, the wind direction, and the location specific geographical characteristics. Besides, cement plant emissions may contaminate the soil, enter the food chain causing human intoxication through diet exposure (Schuhmacher, Domingo and Garreta (2004)). These authors also found positive associations of cement plant exposure with respiratory symptoms, emphysema, lung function decline and mortality for respiratory diseases in several studies. An excess risk of cancer incidence and mortality, mainly respiratory tract cancer, was also found in some studies.

However, as the authors highlight, most of the studies lack precise measures of exposure which can produce misclassification and selection bias of the cohorts or local populations for which exposure is assessed. In most of the studies exposure to cement emissions is based on the distance of the individual' s home to the plant. Thus, no measures of ambient air pollutants nor dispersion models of cement plant emissions were used.

Silicon dust (SiO2) is a specific pollutant emitted by cement production. It belongs to the family of PM10 pollutants, that is, those with a diameter of 10

μm or less. The silicon dust, by penetrating the skin and the respiratory system, is responsible for consistent damage to the respiratory and cardiovascular human systems with very negative consequences on the health condition of the exposed populations. In fact, it is a well-known cause of specific respiratory diseases, such as chronic obstructive pulmonary disease (COPD) and acute asthma. While the World Health Organization (WHO) sets the 24-hour standard for that pollutant at 50 $\mu g/m^3$, Russia has a less stringent standard: 60 $\mu g/m^3$.

This paper estimates the impact of individual-level daily exposure to two types of silicon dust which differ in the concentration of SiO2, that is, type A with 20 – 70% of SiO2, and type B with less than 20% of SiO2, on the individual probability of hospital admissions due to respiratory-related reasons, between January 1, 2014, and December 31, 2017, assessed at the local hospital level.[1] In this case, silica emissions are produced at a cement plant "Malcovskii portland cement" in the city of Fokino, Bryanskii region, central Russia, located 350 km southwest of Moscow, on which activity the region's economy is highly dependent.[2] The city average daily inhaled concentration of type A silicon dust is 5.3 $\mu g/m^3$ and of type B is 211.4 $\mu g/m^3$. Moreover, due to their physical characteristics[3], they do not travel long distances; therefore, the impacted area is limited.

Our unique emissions dataset was collected at the cement plant "Malcovskii portland cement" in the city of Fokino, Bryanskii region, central Russia, as mentioned before. The high-frequency daily data on outpatient admissions to Fokino hospital were collected at the Territorial Compulsory Health Insurance Fund (TCHIF) of the Bryanskii region. The weather data consist of daily weather conditions for the city of Fokino: mean temperature, level of precipitation, atmospheric pressure, wind speed and wind direction for the whole period considered.

Our identification strategy is based on the location-specific calculation of

[1]Hereinafter, we denote silicon dust with 20 – 70% of SiO2 by type A and with less than 20% of SiO2 by type B.

[2]The city of Fokino is representative of Russian cities where local populations are largely dependent on a local employer.

[3]Such as mass.

the daily concentrations of silicon dust inhaled by the individual at the street level where she lives. In contrast to most of the extant literature, we use an aerodynamic dispersion model which allows for calculating daily pollution exposure at the individual-location specific level, accounting for geographically explicit air pollution estimates[4]. This model includes the distance between the source and each individual patient, the wind direction, the wind speed on the day of interest, also controlling for the height difference in the landscape and the possible physical barriers in the way, such as buildings. Typically, the instrumental variable approach mitigates the measurement error and the mismatch between the estimated and the actual concentrations inhaled by local communities. The wind speed, the wind direction, and the thermal inversion are the common instrumental variables for the pollutants' concentrations registered by monitoring stations (Schlenker and Walker (2016); Deryugina et al. (2019); Halliday, Lynham and de Paula (2019)). Yet, there are no air quality monitoring systems in Russia except for a few stations in Moscow.

Based on the aerodynamic dispersion model mentioned above it is possible to capture the variability of the concentrations inhaled by the local community at the street level. Since our results are based on high frequency data (daily basis) in the city of Fokino, any potential confound would have to vary exactly in the same way for the period at stake, which turns out to be very unlikely (Halliday, Lynham and de Paula (2019)).

We find that for the elderly adults between 86 and 90 years old, an extra 1 mg/m^3 in the daily inhaled concentration of type A silicon dust increases the individual probability of hospital admission due to COPD by 0.8% two days after the increase in the inhaled concentration. This result is driven by the male adults of the cohort, for which an extra 1 mg/m^3 in the daily inhaled concentration of type A silicon dust increases the individual probability

[4] To the best of our knowledge, there are two papers that use the aerodynamic dispersion models to calculate pollutants' exposure. Filippini, Masiero and Steinbach (2019) use a dispersion model that replicates atmospheric conditions and accounts for several emission sources to estimate the impact on hospital admissions in Switzerland. Hernandez-Cortes and Meng (2022) use the HYSPLIT NOAA dispersion model to estimate the emissions' spatial changes in the "environmental justice" gap following the evidence from California's carbon market.

of hospital admission by 2.7%, two days after the increase in the inhaled concentration. In this paper we confirm previous findings according to which the impact of pollutants like PM2.5 and PM10 occurs shortly after the increase in the concentrations inhaled (Deryugina et al. (2019)). In our model, we use one and two-day lags of the pollutant's daily concentration inhaled. We have also considered lags of 5 and 7 days, but the coefficients for more than two days were not significant. However, as we show below, these results change when the analysis is undertaken at a more local level.

The granularity of our data allows us to divide the city into areas with different average daily inhaled concentrations of silicon dust. Four areas are considered. The distinction is based on the daily silicon dust concentration inhaled by the local population.[5] Area one is chosen as the benchmark as the average daily concentration of silicon dust inhaled there is close to the city average. The average daily concentrations of silicon dust in areas two, three and four are higher when comparing to those observed in area one (Table 7). The areas were labelled according to the ranking of the average daily concentration of silicon dust inhaled, where area four presents the highest level.[6]

Most of the local population lives in area one, where the majority of young children (mode age < 1 year old) live. Areas two, three and four have larger shares of the elderly population (between 65 and 85 years old) relative to area one (Table 7). Regardless of the location of the streets in the different areas, what actually explains the differences found between daily concentrations inhaled by those living there, are the locations of the sources of silicon dust, the wind direction and the distance between the cement plant and the specific street under consideration, where the different physical barriers are also accounted for. We compare the average daily inhaled concentrations of the two types of silicon dust between area four and area one, where the highest and the lowest daily

[5] We consider four areas to have enough data in each of them to run the econometric model in each area.

[6] The city of Fokino was divided into areas with different average daily inhaled concentrations of silicon dust. Area one has the average daily concentration of silicon dust inhaled close to the city average. The average daily concentrations of silicon dust in areas two, three and four are higher than in area one.

inhaled silicon dust concentrations are observed, respectively. We find evidence that for type B it is 2.3 higher while for type A is 12.9. Moreover, conditional on the location, we provide evidence of a non-linear response of the probability of hospital admissions to the individual daily inhaled concentrations of silicon dust, depending on the number of days of exposure. More importantly, the range of daily silicon dust inhaled concentrations for which we find evidence of a significant effect on the health of local communities can be identified.

In general, the studies aiming at estimating long-term impacts of local pollutants on local populations health condition focus on contexts where a persistent influence of them can be found, allowing to infer about the causal effect of air pollution on mortality rates. Anderson (2019) identified a significant negative effect of a consistent exposure[7] to highway-generated pollution on adults' three-year mortality rate in Los Angeles. The author found a higher negative effect on those who lived in the downwind direction from the highway relative to those who lived upwind. In our study, the wind direction changes with high frequency, and it could be expected that during longer than three days periods, all the city areas experienced similar average levels of pollutant exposure. However, this only occurs in some parts of the city. For these we define *persistent exposure* to silicon dust concentration as the average daily inhaled concentrations for day periods between 7 and 255. We find significant effects of persistent exposure only between 75 and 180 days before the hospital admission is observed.[8] This allows us to estimate the impact of the relative "long-term" exposure (associated to the "persistent exposure") of the local population to silicon dust in comparison to the next-day and after-two-day cases previously considered.

We find that for the elderly adult males living in area four, 1 mg/m^3 increase in the average concentration inhaled in the 95 days before the hospital

[7] Anderson (2019) finds evidence of consistent, predictable wind patterns in the Los Angeles Basin, based on which, the author estimates the effect of long-term exposure to air pollution on mortality rates.

[8] The average number of days between the hospital admissions due to COPD among the elderly male adults, 86 – 90 years old, is 95 days. We find a significant positive effect on the probability of hospital admissions for different number of days below and above 95.

admission increases the probability of hospital admissions due to COPD by 22.5%. If they were exposed on average to an extra 1 mg/m^3 concentration of type A silicon dust during the previous 120 days, the probability of hospital admission due to COPD increases to almost 24%. If this time range is increased to 180 days, the probability of hospital admission due to COPD increases to 25.1%. Thus, we find evidence that in the presence of persistent exposure, as defined before, for type A silicon dust concentration, the probability of hospital admission due to COPD increases at a decreasing rate in response to the exposure length, suggesting a concave relationship.

Children below 5 years old often visit hospitals due to regular prescribed check-ups, according to the general practice in the Russian health system; therefore, in this case, to estimate the impact of silicon dust on hospital admission due to general and/or specific respiratory-related reasons, we changed our dependent variable to the three-days count of hospital admissions. We explored non-linearity by considering the same four city areas. We found that a 1 mg/m^3 increase in three-day average inhaled concentration of type B silicon dust increases the three-day count of hospital admissions due to respiratory-related reasons by 52% among children between 2 and 5 years old who live in area four[9]. As the range of daily inhaled concentration of type B silicon dust in area four was found to be 10 times the standard value of 60 μg/m^3 for that local pollutant, the significant increase in children hospital admissions in this area can be explained by that fact.

In the literature, several papers have attempted to estimate a causal relationship between industrial sources of local pollutants and human health. In applied research in economics, several studies have used "natural" or quasi-random sources of pollution variation to overcome the biases present in epidemiological studies. These studies estimated the effect of pollution on health (Chay, Dobkin and Greenstone (2003), Ebenstein et al. (2015), Greenstone et al. (2015), Schwartz, Bind and Koutrakis (2017), Chen et al. (2013)), infant

[9]The estimates for the other areas are not significant, but we find a convex relationship between the three-day inhaled concentration of silicon dust and the count of hospital admissions due to respiratory-related reasons for areas two, three and four.

mortality (Greenstone and Hanna (2014), Chay and Greenstone (2003), Arceo-Gomez, Hanna and Oliva (2016), Currie and Neidell (2005), Currie, Neidell and Schmieder (2009)), and labor market (Greenstone (2002), Hanna and Oliva (2015)). Evidence suggests that air pollution has very negative consequences on human health, namely in children and elderly adults. In what concerns the results on healthy adults, recent research has focused on the impact on labor productivity, such as in Aragón, Miranda and Oliva (2016) for PM2.5 in Lima, Peru, and Holub (2021) that estimates the causal impact of air pollution (PM10) on the incidence of sick leaves in a representative panel of employees affiliated with the Spanish social security system.

Finally, there is also a corresponding medical literature focusing on the health effects of pollution. The most notable study that originated this strand of literature is Pope (1991), where the author considered the effect of PM10 pollution on respiratory related hospital admissions using a steel mill closure event in Utah Valley. The follow-up studies included the impact of air pollution on the mortality rate for six US cities (Dockery et al. (1993)). Current epidemiological research concentrates on the impact of air pollution on hospital admissions (Zhou et al. (2019); Slama et al. (2019); Chen et al. (2012)). Yet typically these studies only focus on correlation and not on causality.

Our contribution to the existing literature is fourfold. First, we explore the relationship between pollution exposure and morbidity, which has only recently received increasing attention. In our case, silicon dust is a source of particulate matter pollution that is specific to cement production, which reduces the likelihood of the presence of correlation between different pollutants when identifying the short-term effect of particulates on health.

Second, we consider the impact on hospital admissions for patients of all ages. Previous studies have mainly focused on the impact of morbidity and mortality on infants as the link between cause and effect is more immediate in that case (Arceo-Gomez, Hanna and Oliva (2016); Currie, Neidell and Schmieder (2009)).

Third, instead of using local wind direction as an instrument for air pollution exposure (Halliday, Lynham and de Paula (2019); Deryugina et al. (2019)), our aerodynamic dispersion model allows for calculating more precisely the level of pollutant's exposure at the individual location-specific level, decreasing the measurement error (Filippini, Masiero and Steinbach (2019)). Moreover, since the aerodynamic model already accounts for the typical instrumental variables considered in these studies, such as the wind speed, wind direction, distance and elevation, the calculated concentrations inhaled by the local community incorporate those. To check for robustness, at some specific dates we obtained the concentrations measured by the controlling agency at the plant level, and we found them to be close to the values obtained with the aerodynamic dispersion model. However, due to the small number of data points available at the agency's dataset, we could not compare their data with the figures of the daily inhaled concentrations calculated by the dispersion model.

Fourth, while in previous studies the finest level of analysis is census tract or zip code (Schlenker and Walker (2016)), in our case, it consists of high-frequency patient data at the street level. The city of Fokino does not have highways or any other long or wide streets; therefore, the geographical coordinates at the midpoint of the patient's street were used as the coordinates of her home address. To control for possible mismatches in such a setting, we have increased the distance between each plant's emission source and the individual patient by considering the average distance to the local shops. The results were robust to the newly adjusted concentrations.

Finally, we focus on cement production in Russia, which to the best of our knowledge has not been studied before in this context. Besides, as explained before, since cement production is what pollutes the city of Fokino, our results also contribute to better understanding how the chemical composition and characteristics of specific particulates affect human health, in particular, silicon dust (Pope and Dockery (2006); Halliday, Lynham and de Paula (2019)).

Cement production belongs to the group of industries[10] that represents city-forming enterprises and, therefore, where local populations face a trade-off

[10] There are several industries that due to the technology of the production process and the volume of production require facilities large enough to be the main employer in the region. Oil, gas, metal, steel, and cement production facilities belong to such group of city-forming enterprises.

between jobs and ambient air quality. Moreover, the conventional estimates of ambient air pollution concentrations, obtained, for instance, by averaging out estimates at regional or larger scales do not accurately assess the actual concentrations in cities that are affected by emissions specific to the production processes involved. Since abatement is costly, incentives for strategic behavior by pollutant firms in small-number cases may reinforce the need of undertaking accurate assessments of their impact on the health condition of local communities. In the case of Russia, as it is crucial for local authorities to attract facilities to their regions in order to take advantage of the important tax revenues that accrue to them, they have little incentive to act against those firms regardless of the impact of their emissions on the health of locals, given their strong bargaining power. Assessing the impact at a more granular level than census-block or zip code as well as investigating the presence of potential non-linearities as concentrations increase can contribute to a more cost-effective, if not efficient, allocation of public scarce resources.

The rest of the paper is organised as follows. Section 2 describes the data sources. Section 3 details the empirical methodology. Section 4 presents and discusses the results, and Section 5 concludes. Tables, figures and other ancillary material are included in the Appendix.

1 Background and Data

Our unique dataset was collected in the city of Fokino, Bryanskii region, central Russia, located 350 km southwest of Moscow, between January 1st, 2014, and December 31st, 2017 (Figure 1). This facility represents the largest cement production site of the Eurocement group[11] in the Central European region of Russia. The "Malcovskii portland cement" plant is the only source of this type of pollutant in the region.

The population of Fokino is around 13 000 people and was stable during the period considered. Table 1 presents the demographical and social characteristics

[11]Eurocement group is one of the leaders of the cement industry in Russia. They are present in 13 regions and own 16 cement production plants in Russia.

of the city of Fokino between 2014 and 2017. Fokino is located 30 km from the capital of the region, Bryansk. Many women find a job there; most of the city's male population works at the cement plant. Typically, if the elderly men worked at the plant, the younger follow them. All these factors contribute to a low migration from the city. In 2014 more people arrived in the city compared to the number of those who left. The number of citizens who arrived and those who left was nearly the same in the following years.

The city can be divided into two regions: an "older" one is located closer to the plant, and a "new" region is located further from the plant (Figure 2). The "new" region was built in the 1970s. Part of the citizens were relocated, but no changes occurred in the city after that. Therefore, we consider that sorting was not present during the period of analysis.

1.1 Air Pollution

The city of Fokino is surrounded by three plants: "Malcovskii portland cement", "Bryanskii asbestos cement plant", and "Fokinskii brickyard" (Figure 3). As mentioned before, the "Malcovskii portland cement" is the biggest cement producer in the region and a primary income source for the citizens of Fokino. "Malcovskii portland cement" is located to the south of the older centre of the city and to the northeast of the area that was built in the 1970s (Figure 3). The clay and chalk deposit has been in use since 1899. From then on, cement production was the main activity in the region. The current cement plant was built in the 1950s. The plant has 175 emission sources (110 acute and 65 not acute sources, Figure 4)[12]. In the production process, 51 pollutants are emitted, such as silicon dust, nitrogen oxide, and sulphur dioxide, among others.

The two types of silicon dust (type A and B) are emitted at different stages of the cement production process and are characterized by different air-gas mixture and strength of the emitted font characteristics. Type A silicon dust is

[12] Acute source is a source that has well defined technical characteristics except the area, for example, gas-air volume and speed or temperature of the gas-air mix. Typical representatives of acute sources are tubes. A not acute source has only area as technical characteristic, such as the pile of leftovers from the production.

emitted by the sources with lower speed and gas-air mixture volume; therefore, its impacted area is smaller than the one impacted by type B silicon dust. This explains why it is mainly concentrated in the old part of the city where elderly live.

The two other plants, “Bryanskii asbestos cement plant” and “Fokinskii brickyard”, were nearly closed during the period considered, but we collected data on the emissions there to control for other pollutants, which are not silicon dust. Emissions from these plants include nitrogen dioxide, sulphur dioxide and carbon oxide, they are accounted for when daily inhaled concentrations are calculated. Moreover, the city of Fokino is a relatively small city by Russian standards; therefore, no heavy traffic is present there. So, we focus on the industrial pollution in this study.

As mentioned before, Moscow is the only city in Russia that is equipped with a few air quality monitoring stations. Therefore, in the city of Fokino, we use the aerodynamic dispersion model to calculate the local population’s exposure to the different pollutants. This model was developed in the USSR in 1987, but it is still the most important tool in Russia for pollutants exposure calculations.

The emitted concentration for each pollutant was measured every quarter at each acute and non-acute source at the plant. The emissions are the same per day and quarter due to technical reasons, but they vary from quarter to quarter and from year to year. The cement plant is operating permanently (24 hours, seven days a week) using the same production technology in the period considered. Therefore, based on the expert advice of the employees at the plant, we can assume that the emitted values can be regarded as the daily emitted concentrations for each pollutant under consideration for a given quarter.

The aerodynamic dispersion model calculates the exposure level at a given location on a given day based on the level of the emitted pollutants, wind direction, wind speed and the distance between the emitter and the receiver. First, based on the technical characteristics of the source, such as the height, diameter, gas mixture speed, gas mixture volume and the temperature difference between the gas and the environment on a specific day, it calculates the maximum concentration for each distance from the source and wind speed. Then, it adjusts the calculated value by the actual distance and the wind speed on that day, and, finally, by the height difference and the possible physical barriers, such as buildings.

We geocoded both emission sources at all three plants and the patients' home addresses. This allows us to calculate the exact distances between each source and each patient's location (street level). Based on this information, we calculated the bearing angles[13] between the emission sources and the patients and compared the calculated values with the wind direction on that specific day. The wind direction was divided into 16 bins. When the bearing angle coincided with the wind direction, the figure obtained for the pollutant's exposure on that day was multiplied by 1, otherwise by 0. Therefore, daily variation in pollutants exposure is obtained for each patient and each pollutant.

The local department of the Ministry of Natural Resources and Environment of the Russian Federation is the regulatory agency for such types of pollutants. They visit the plant and measure the technical emission characteristics on "control days". Every year the control days[14] occur approximately at the same period, respectively in March, June, September and November. We obtained a few data points from the controlling agency reports and compared their calculated daily inhaled concentrations with those obtained from the aerodynamic dispersion model; the values obtained were not significantly different.

Due to its physical characteristics, such as mass, silicon dust cannot travel large distances, and, thus, the area that can be affected by industrial pollution is limited. Based on the technical characteristics of the cement production, the affected area corresponds to a circle with a radius of forty times the height of the tallest emission source. At the "Malcovskii portland cement" plant, the tallest source is 120 meters high; therefore, we consider a circle with a radius

[13]The bearing angle is the angle between the patient's and the source's geocoded locations.

[14]Control day is when the emissions measurements are taken at the plant, and the concentrations inhaled by the local communities are calculated by the representatives of the Ministry.

of 4 800 meters around the plant. The total affected area is the one covered by such circles, where one source is the centre of one circle (Figure 5). These circles include the city of Fokino and the villages nearby, such as Berezino and Pupkovo. Most of the affected population lives in the city of Fokino.

The 24-hour standard for the pollutants of the family PM10 in Russia is 60 $\mu g/m^3$. There is no specific standard for silicon dust of any type; therefore, we consider the standards set for PM10 as the benchmark. The average daily inhaled concentration of the first type of silicon dust of type A is 5.3 $\mu g/m^3$ with a standard deviation of 19.4 $\mu g/m^3$. The average daily inhaled concentration of silicon dust of type B is 211.4 $\mu g/m^3$ with a standard deviation of 606.7 $\mu g/m^3$ (Table 2). The inhaled daily concentration of type A silicon dust, on average, is below the daily standards, while the value for type B silicon dust is above the 24-hours standard of 60 $\mu g/m^3$. Recent economic research (Schlenker and Walker, 2016; Deryugina et al., 2019; Halliday et al., 2019) shows that even when the average level of the criteria pollutants' concentrations is below the standards, significant adverse effects on morbidity and mortality are present. At these levels of the inhaled concentrations, further reductions may not be feasible in the short-run due to high abatement costs; therefore, a more accurate estimation of the impact of pollution on health is crucial to better inform and design more sustainable public policies.

1.2 Hospital Data

The high-frequency daily data on outpatient admissions to the Fokino Hospital were obtained from the Territorial Compulsory Health Insurance Fund (TCHIF) of the Bryanskii region. The Fokino Hospital is the only hospital in the city of Fokino. Russian National Health System is free of charge, and all the data are collected by the regional Territorial Compulsory Health Insurance Fund (TCHIF). At this hospital, electronic data collection by TCHIF was introduced in 2014. The program collects personal data about patients, including their names, home addresses up to the street level, and information on the date, duration, reason and result of the outpatient hospital admissions. While this system does not collect information on admissions to private hospitals, it registers if a patient was admitted to the hospital of another region. Therefore, a high-frequency dataset on each patient's medical history is available. Moreover, the data on the tariff associated to each type of disease are available at the website of TCHIF. To obtain the "effective" cost per hospitalization tariffs are adjusted for gender, age, severity of the case. We were not able to obtain the micro-data to estimate the actual cost for each case. Therefore, we have used the available data on tariffs obtaining a back-of-the envelope lower bound for those costs per hospital admission.

The following data was obtained from January 1st, 2014, to December 31st, 2017: patient ID, age, employment status, registered and effective address at the street level, admission date, cause of admission, duration of admission, and the ICD 10 code of the disease that caused the admission. The region has many individual houses; therefore, the street level was the finest level possible due to personal data restrictions (Figure 6). In Table 3, we present the descriptive statistics for the population under consideration.

Between January 1st, 2014, and December 31st, 2017, 12 087 patients were admitted to the Hospital of Fokino, of which 5 407 were men and 6 680 women. We calculated the daily inhaled concentrations for each patient, we control for the daily weather characteristics and the information on the outpatient hospital admission if it happened on that exact day. Hence, we constructed a daily database per patient for every year for which there was evidence that he/she was present in the hospital's database. An individual is included in the database if she was admitted to the hospital in that year. In case she was not found in the hospital outpatient database all year round, she was not included in our dataset in that year as it is not clear if that person was still living in the city of Fokino.

Our unique dataset consists of 12,170,758 patient-day level observations, that is, approximately 943 observations per male and 1,059 observations per female. A slightly higher number of observations per female can be explained by the fact that women are generally more concerned with their health, so they go to the hospital more often than men. Also, since women live longer (average life expectancy at birth in the Bryanskii region is 76.4 years for women and 64.3 years for men) the prevalence of observations for women in the age cohorts above 70 years old follows.

Schlenker and Walker (2016) and Halliday et al. (2019) use the number of emergency room admissions due to respiratory- or cardiovascular-related reasons as the dependent variable. In our dataset, we do not specify the emergency/non-emergency outpatient hospital admissions due to the characteristics of the Russian health system. In Russia, if a patient wants to see the doctor in a given day, she does not need to visit the emergency room facilities. Instead, she can go to the hospital and book the appointment immediately. Therefore, the emergency room admissions in Russia are usually due to extreme cases like heart attacks, strokes, fractures, or severe traumas.

Among men, 1, 593 patients were employed and 1,943 among women. The prevalence of non-employed patients is due to children present in the sample. If we consider only those between 18 and 55 (for women) or 60 (for men) years old[15], 1,644 women are employed (out of 3 289 women, that is, 49.9%) and 1,525 men (out of 3 561 men, that is 42.8%). The average patient's age is 41.6 years old; the minimum age is 0 (between 0 and 1 years old), and the maximum age is 99 years old.

Due to possible heterogeneity across the age cohorts and for computational feasibility, we divided the sample into age cohorts with five years span each: 0 – 5 years old, 6 – 10 years old, etc. The first cohort is also divided into 0 – 1 year old and 2 – 5 years old to estimate the effect on infants and little children, respectively. The descriptive statistics for each of the cohorts are presented below. In the text, we discuss the descriptive statistics for the cohorts for which we found a statistically significant impact (Table 4, Table 5).

From Tables 4 and 5, we observe that the average daily exposure for the older population is higher than for children. As mentioned before, the city of Fokino consists of two areas, one area that was initially built near the plant, and the "new" area that was built in the 1970s when the wind rose was considered.

[15] 55 and 60 years old are the legal retirement ages for women and men in Russia, respectively.

Most of the elderly live in the "older" part, closer to the plant. Therefore, they are expected to be more exposed to dust (Figure 6).

1.3 Weather Data

The region under analysis has a temperate continental climate with warm summer and mildly cold winter. Table 6 presents descriptive statistics for weather conditions in the city of Fokino. Figure 7 illustrates the wind rose in the region of the city. The wind direction was divided into 16 bins. As we can see, there is no persistent wind direction in the region which supports our focus on high-frequency data and not on cumulative long-term effects of exposure to silicon dust.

2 Methodology

In this section the methodology is presented in detail. The text is divided into sub-titles corresponding to the issues addressed.

2.1 Daily concentrations inhaled and individual probability of hospital admission

We use a binary probability model to estimate the individual probability of hospital admissions due to respiratory-related reasons. We exploit the panel structure of our data and include both individual and time fixed effects in the following model:

$$\begin{aligned} Y_{it} = \alpha + X_{it}\beta_1 + X_{it-1}\beta_2 + X_{it-2}\beta_3 + \\ Z_{it}\gamma_1 + Z_{it-1}\gamma_2 + Z_{it-2}\gamma_3 + W_{it}\theta + \delta_i + \delta_t + \epsilon_{it} \end{aligned} \tag{1}$$

where the dependent variable Y_{it} is a dummy variable that equals 1 if on day t patient i was admitted to the hospital due to respiratory-related reasons, and 0 if she was there due to other reasons or was not at the hospital at all. The parameters of interest β_1, β_2, β_3 define the vectors of coefficients on daily silicon dust exposure on days t, *t-1* and *t-2*, that is, on the day, one and two days before the hospital admission. It includes coefficients for both types of silicon dust. γ_1, γ_2, γ_3 are the vectors of coefficients for control variables, such as concentrations of other emitted pollutants on the day, one and two days before the hospital admission day t. θ is the vector of coefficients for the other control variables, such as daily mean temperature, precipitation level and atmospheric pressure, weekend/workday, forest/no forest, and hospital attendance/no hospital attendance dummy variables. We expect people to spend more time outside on weekends and holidays, being more prone to be exposed to pollution. The two parts of the Fokino city are divided by a forested area, separating the "new" part of the city from the cement plant. The aerodynamic dispersion model considers the area's elevation level and the existence of barriers like buildings, infrastructures, among others. In the case of the forest, as it represents not only a physical barrier, but, more importantly, is a natural ecosystem we decided to separately control for its presence. We control for this natural barrier by adding the dummy variable forest/no forest. As the patients can be admitted to the hospital due to other than respiratory-related reasons or not attending the hospital on day t at all, we control for the hospital attendance event. The standard errors were clustered at the individual level. Finally, since an aerodynamic dispersion model is used, the instrument is already included in (1) above.

This estimation was performed for each age cohort for general respiratory-related reasons; the ICD 10 codes of these diseases start with J. Then, we performed the same analysis for the respiratory diseases associated explicitly with the cement production, such as chronic obstructive pulmonary disease (COPD) and asthma (ICD 10 codes are J12 – J18, J40 – J44, J45-J46). The analysis was performed for all the specific diseases as a group and then one by one. We explored the possible heterogeneity by gender in each age cohort.

We consider the impact of the daily inhaled silicon dust concentrations one and two days before the hospital admission to control for the lagged effects.

As a robustness check, we explored the possibility of controlling for the daily inhaled concentrations of silicon dust and other pollutants 5 and 7 days before the hospital admission, but the estimates were not significant. We find a two-days lag to be the optimal lag in line with the related literature (Deryugina et al. (2019)).

2.2 Non-linearities in the high-frequency health-pollution relationship

Schlenker and Walker (2016) raised the concern about the potential non-linear response of the health condition to the concentration levels inhaled. By examining the dose-response function between the year's season, winter and summer, and the pollution levels, they concluded that the relationship between the pollution level and its marginal effect on the number of hospital admissions was concave.

To identify possible non-linearities in our high-frequency database, as mentioned before, we require some level of "persistency" of the average silicon dust concentrations inhaled by the local community to identify heterogeneous areas in the city of Fokino. Our definition of persistency is different from what is typically considered in the literature when estimating the long-term impact of pollution on health. In our setting, and in contrast to Anderson (2019), we define persistency at much shorter periods than three years. We calculate the mode of the number of days (X) between the hospital admissions due to respiratory-related reasons for all the patients of a given age cohort and the average of the daily inhaled concentrations of silicon dust and other pollutants during these days. The moving average allows us to calculate the average concentrations inhaled by the local community in the preceding X number of days. Based on the calculated values, we found that in area four of the city of Fokino the average inhaled concentration of type A silicon dust is 12.9 times higher than in area one, and the average inhaled concentration of type B silicon dust is 2.3 times higher than in area one (Table 7).

The econometric model used to estimate the impact of this "persistent" exposure to high levels of silicon dust concentrations is as in (1). However, the explanatory variables are now the average concentration inhaled during the preceding X days for both types of silicon dust and other control pollutants, as follows:

$$Y_{it} = \alpha + X_{it}\beta + Z_{it}\gamma + W_{it}\theta + \delta_i + \delta_t + \epsilon_{it} \tag{2}$$

The dependent variable Y_{it} is a dummy variable. It takes the value 1 if an individual i was admitted to hospital on day t due to respiratory-related reasons and 0 if she was admitted due to other reasons or not admitted at all. β is the vector of coefficients of the average concentration of silicon dust inhaled by an individual during the X preceding days to day t, γ and θ are the vectors of coefficients of the average concentrations of controlling pollutants inhaled by an individual, and weather conditions, respectively, during the X preceding days to day t. We also include dummy variables that control if the person was admitted to the hospital during the preceding X days and if this happened more than once. This controls for different behaviors in hospital attendance. The standard errors were clustered at the individual level.

For the males of the cohort between 86 and 90 years old, the mode number of days between the hospital admissions due to COPD is 95 days. For each day, we calculated the average concentration of silicon dust inhaled during the preceding 95 days. Figure 8 presents the graphs that combine the events of hospital admissions due to COPD and the average concentration of silicon dust inhaled during the preceding 95 days for some of the male individuals who live in area four. We find evidence that the event of hospital admission due to COPD occurred approximately when the average concentration inhaled by the patient peaked.

We use the negative binomial model to estimate the impact of inhaled silicon dust concentration on the number of hospital admissions due to respiratory-related reasons at the street level. The estimated model is as follows:

$$adm_t = exp(\alpha + X_t\beta + Z_t\gamma + \eta_t) \tag{3}$$

The dependent variable adm_t stands for the number of hospital admissions due to respiratory-related reasons during the preceding three days to day t. The explanatory variables X_t include the three-day average value of silicon dust inhaled by the local community prior to day t. Control variables Z_t include three-day average values of other pollutants inhaled by the local community, weather conditions, and the season prior to day t. We perform this analysis for all the city and for each area individually.

3 Results

In this section the results obtained are presented and discussed. As before, the text is divided into sub-titles corresponding to the issues addressed.

3.1 Daily concentrations inhaled and probability of hospital admission

We start by examining the impact of the daily concentrations of silicon dust inhaled by the local community on the individual probability of hospital admission. Table 8 presents the estimation results for the hospital admissions due to COPD for the cohort between 86 and 90 years, considering both genders, and only the males, respectively.

Column (a) of Table 8 shows that 1 mg/m^3 increase in the daily inhaled concentration of type A silicon dust increases the individual probability of hospital admission due to COPD for people between 86 and 90 years old by 0.8%. The effect is present two days after the inhaled concentration has increased. Column (b) shows that the impact for the males in this cohort is 3.4 times higher. For them, a 1 mg/m^3 increase in the daily inhaled concentration of type A silicon dust increases the individual probability of hospital admission due to COPD by 2.7%. Both estimations are significant at the 5% level.

Based on the average daily inhaled concentration, as mentioned before, in area four daily inhaled concentrations of type A and of type B are 12.9 and 2.3 times higher, respectively, than the daily inhaled silicon dust concentrations in area one. The share of the daily inhaled concentration of type B silicon dust is nearly the same as when we have divided the city to explore for potential non-linearity in the impact. Yet, the share of the daily inhaled concentration of type A silicon dust is smaller due to high frequency in changes of the wind direction.

Table 9 shows the average daily inhaled concentration of silicon dust, the number of hospitalizations due to COPD, the number of individuals registered in the area and the number of hospitalizations per individual in the area. We observe that the number of cases per individual grows from 0.09 in area one to 4 in area four with a sharp increase from area three to area four. This is in line with our claim of a non-linear relationship between the daily inhaled concentration of silicon dust and the probability of hospital admission due to COPD.

Columns (c) and (d) of Table 8 show that 1 mg/m^3 increase in the daily inhaled concentration of type A silicon dust increases the individual probability of hospital admission due to COPD by 3.5% in area three, and by 4% in area four among the elderly males. Both results are highly significant. Table 9 shows that the daily inhaled concentration of this type of silicon dust is lower in area four than in area three, but the overall daily inhaled concentrations are higher in area four than in area three.

We claim that males are more affected than women due to their previous work experience at the cement plant and habits. As was already mentioned, it is typical for the male members of the family to work at the cement plant. Often, they start working around 20 years old until 60 years old, the legal retirement age in Russia for men. Also, their smoking and drinking habits can contribute to the negative impact of silicon dust on the respiratory system. In 2016, 49.8% of men reported current tobacco use in any form compared to 14.5% among women (WHO, 2016)[16].

The daily inhaled concentrations of silicon dust were calculated at the home

[16] 2016 data represent the latest evidence as the Global Adult Tobacco Survey of the World Health Organization was performed in Russia twice: 2009 and 2016. Unfortunately, micro-data is not available.(WHO (2016))

address of the local individuals. As a robustness check for our results, we calculated the average distance between the buildings and the local stores and "moved" our points of interest accordingly. We did not find evidence of any changes in our results.

We performed the same analysis when the dependent variable is equal to 1 if the patient was admitted to the hospital due to fractures and 0 if she was admitted due to any other reason or was not admitted at all. We did not find any significant impact of air pollution on this type of hospital admission. Hence, this result represents our placebo outcome.

3.2 Non-linearities in a high-frequency health-pollution relationship

Column (a) of Table 10 shows that for males between 86 and 90 years old who live in area four, 1 mg/m^3 increase in the average daily inhaled concentration of type A silicon dust in the preceding 95 days increases the individual probability of hospital admission due to COPD by 22.5%. Columns (b) and (c) show the results for the preceding 120 and 180 days, respectively. A 1 mg/m^3 increase in the average daily inhaled concentration of type A silicon dust during the preceding 120 and 180 days increases the probability of hospital admissions due to COPD for males between 86 and 90 years old by 24% and 25.1%, respectively. The estimations for 95 and 120 days are significant at the 1% level, and the estimation for 180 days is significant at the 5% level. We observe that the "persistent" inhalation of high levels of type A silicon dust increases the probability of hospital admission at a decreasing rate within the "persistent" period, suggesting a concave relationship (Figure 9).

3.3 Hospital admissions

In the previous sections, we identified a significant impact of type A silicon dust on the individual probability of hospital admissions among the elderly. However, we did not find any significant impact on the individual hospitalizations among the youngest. Since young children visit the doctor more often due to the pediatric procedures to control for their development, their frequent visits may reflect the previously estimated individual probability results[17]. When using the number of hospital admissions per street as the dependent variable and not the individual event of a hospital admission, we estimate the common "shock" to all who live in that street. This allows us to capture the impact of silicon dust on hospital admissions among the younger population without the influence of age-specific factors like the schedule of pediatric visits mentioned above.

To perform the estimation using the negative binomial model, we divided our patients into age cohorts with a span of 10 years, except for the very young children between 0 and 5 years old. The latter are divided into two cohorts as before, that is, 0 – 1 years old and 2 – 5 years old.

Table 11 presents the estimated coefficients for the count of hospital admissions due to respiratory-related reasons for children between 2 and 5 years old. All the coefficients, except for that in area one, are positive; the coefficient for the count of hospital admissions in area four is significant at the 1% level. 1 mg/m^3 increase in the three-day average inhaled concentration of type B silicon dust in area four leads to a 52%[18] increase in the number of hospitalizations due to respiratory-related reasons among the children between 2 and 5 years old[19]. We find evidence of significant impact of silicon dust type A (with 20-70% of SiO2) on the elderly and of silicon dust type B (less than 20% of SiO2) on the youngest. According to our results, we may conclude that while for the elderly the percentage of SiO2 is more relevant, for the youngest the quantity of SiO2 is what matters the most.

Between 2014–2017 there were 1,870 cases of hospital admissions due to

[17] Most of the visits have the ICD code starting with Z, when the symptoms a patient displays do not suggest a specific disorder but still warrant treatment. In our analysis we use ICD code starting with J, but many of such visits are still general pediatric ones, without respiratory-related reasons to be the actual reason of the visit.

[18] 52% were calculated by taking the exponent of the estimate value 0.42 in the negative binomial model (Table 11).

[19] Even though the coefficients for areas two and three are not significant, Figure 10 suggests a non-linear increase in the number of hospital admissions with the increase in the three-days average inhaled concentration of silicon dust.

respiratory-related reasons among children between 2 and 5 years old who live in areas two, three, and four of the city. According to the data on tariffs from the Territorial Compulsory Health Insurance Fund (TCHIF) of the Bryanskii region website, one day of an outpatient hospitalization due to respiratory-related reasons costs on average 944.3 RUB ($16.2, 2017 US dollars). A decrease in the average inhaled concentration of type B silicon dust from the high average values in these areas of the city to the Russian standard of 60 $\mu g/m^3$ would result in less 45 hospitalizations due to respiratory-related reasons in this age cohort living in these areas of the city per year, contributing to decrease the total number of hospitalizations in the four years-period by 9.6%. This would amount to about a 0.2% annual decrease in the regional public budget allocated to those purposes. Yet, this figure represents the lower bound of the potential benefits (or savings) obtained as the outpatient hospitalization cost used in these calculations is the average tariff for the respiratory-related hospitalizations[20] which is then adjusted based on age, gender, and severity. Therefore, the actual cost varies from case to case. Also, those values only account for the immediate health benefits, ignoring possible future benefits, such as improved cognitive abilities and higher productivity that can be associated to a better health condition. Moreover, the decrease in the average inhaled concentration of type B silicon dust will be beneficial for all age cohorts, also decreasing the daily inhaled concentration of type A silicon dust, as in some parts of the production process they are emitted simultaneously. Therefore, this will affect the probability of individual hospitalization among the elderly due to COPD and other specific silicon dust related diseases.

Finally, we show how the methodology in this paper can be used for policy purposes. In particular, we show how regulators and policy makers concerned with the consequences of exposure to local pollutants may take advantage of

[20]Using the information on tariffs for each disease type from the tariff data file of the Territorial Compulsory Health Insurance Fund (TCHIF) of the Bryanskii region website, we calculated average tariff per day for respiratory-related hospitalizations, 944.3 RUB ($16.2, 2017 US dollars). This figure was multiplied by 45 cases that would be avoided due to decrease in the daily concentration inhaled. The resulting savings constitute 0.2% of the annual budget of the region, 21 million RUB ($360 163, 2017 US dollars).

granular data sets to better understand how local populations are affected by them and, therefore, how regulations can be adjusted in order to improve their welfare. In line with what was discussed before, and for illustrative purposes, we considered the same four areas in which the city was divided. This division allowed us to perform consistent analysis for all the considered settings of individual probability and count number of hospital admissions due to respiratory-related reasons. However, this division is not the only possible, since the choice of the areas in which the city can be divided may depend on the purposes of policymakers. When exploring the granularity of our data, and, in particular, areas three and four, three subareas inside each of them were identified. Focusing now on the average daily inhaled concentrations of the type B silicon dust, we found a significant positive impact of that pollutant on the number of hospital admissions due to respiratory-related reasons. In particular, we find evidence that those impacts increase from subareas 3.3 to 4.1 (contiguous areas), presenting values above the average found for the whole area four (Table 12, Figure 11)[21]. This means that the division based on the average daily concentration of type B silicon dust is one among many different possible ways of treating the data and that can be also associated to a variety of distinct outcomes. Hence, the data treatment may depend on the specific goals of the regulator or the decision maker when searching for solutions to improve the health condition of local populations.

4 Conclusions

In this paper, we use high-frequency variation in the concentration of silicon dust (type A with 20 – 70% concentration of SiO_2, and type B with less than 20%) emitted by a cement plant and inhaled by the local population to infer on the impact on the probability of hospitalization due to respiratory-related reasons. Silicon dust is a specific pollutant, a by-product of cement production.

[21]From Table 12, it is also clear that the average concentration in subarea 4.4, though not significant due to not enough data, is well below the average concentration found for area 4 as a whole. Therefore, this does not entail any contradiction.

It belongs to the family of PM10 pollutants and penetrates the respiratory system of the body affecting the cardiovascular system negatively. As there is no monitoring stations´ network in the city of Fokino, we use an aerodynamic dispersion model to calculate daily concentrations of silicon dust inhaled by local communities, considering the technical characteristics of the emission source as well as the distance, wind speed, wind direction, physical and natural barriers, and elevation of the location.

The linear probability model is our chosen empirical method as the calculated values of the concentrations of silicon dust inhaled daily already include wind speed and wind direction that are typically used as the IVs in other studies in the field.

Our results suggest that a 1 mg/m^3 increase in the daily concentration of type A silicon dust leads to the increase in the probability of hospital admissions due to COPD by 0.8% among the elderly adults. The males of this cohort drive this result; for them the probability of hospital admission due to COPD grows by 2.7% in response to an extra 1 mg/m^3 in the daily inhaled concentration of type A silicon dust.

The high-frequency nature of our unique dataset also allowed us to explore for the short-term persistency in concentrations levels and to account for the heterogeneity of the different areas of the city. We identified four city areas with persistently different average inhaled concentrations of silicon dust. Area one was chosen as the benchmark for the comparisons as it describes the city average daily concentration of silicon dust inhaled by local community. The daily concentrations of silicon dust inhaled by the local communities in areas two, three and four are higher when compared to the benchmark. The average concentration of silicon dust inhaled in area four is 12.9 times higher for type A silicon dust and 2.3 times higher for type B than in area one. In area four, we have identified a non-linear (concave) response of the probability of hospital admissions due to respiratory-related reasons (COPD) for the elderly males to the average of persistently inhaled concentration levels.

We found that three-day concentration levels of type B silicon dust in area four lead to a significant increase in the three-day count of hospital admissions due to respiratory-related reasons among the youngest cohort, that is, of children between 2 and 5 years old. We estimate that a decrease in the average inhaled concentration level to the standard values will decrease the four-year count of hospitalizations due to respiratory-related reasons for this age cohort by 9.6%. Therefore, our findings are consistent with previous evidence suggesting that children and elderly adults' health condition are more vulnerable to air pollution, and thus may be affected at lower concentrations rather than healthy adults.

Finally, we did not find any significant impact of air pollution on hospital admissions due to fractures, representing our placebo outcome.

In summary, this paper uncovers the health impact of being exposed to daily emissions of a specific industrial pollutant (silicon dust) which is often not present in the typical setting. Yet, silicon dust is often responsible for high pollution levels at the local level as it is the case in places like Fokino where the local economy strongly relies upon that industrial activity. Therefore, our results can contribute to the development of more sustainable environmental policies to control for local pollutants which are one of the most important sources of non-carbon external costs worldwide with very negative consequences on the health condition of local populations and their well-being. In particular, we show how data granularity can be spatially and temporally explored for public policy purposes.

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A Appendix

A.1 Tables

Table 1: Summary Statistics, 2014 - 2017

	2014	2015	2016	2017
Population (# of indiv.)	13 285	13 190	13 100	13 020
Lifetime expectancy at birth (years)	70	70	70	70
Birth coefficient	4.6	7.2	7.5	7.7
Death coefficient	15.1	14.7	14.5	14.4
Natural loss ratio	-10.5	-7.5	-7.0	-6.8
Arrived to the city (# of indiv.)	503	437	435	432
Left the city (# of indiv.)	458	433	432	430
Migration coefficient (per 1000 indiv.)	3.4	0.3	0.2	0.2
Working (# of indiv.)	8 100	8 060	8 000	8 000
Between 18 and 55 years old (women) and 60 years old (men)	7 996	7 814	7 798	7 732
Economically active (# of indiv.)	7 080	7 000	6 980	6 980
School (# of children)	500	500	500	500
Unemployed at active working age (# of indiv.)	700	700	700	700
Unemployment rate (%)	1.0	1.5	1.6	1.5
Average salary (RUB)	20 744	22 230	22 350	22 600
Minimum living wage (RUB)	7 335	8 843	9 095	9 540

Summary statistics for the city of Fokino for the period between January 1, 2014 and December 31, 2017. 60 and 55 years are legal retirement age for males and females, respectively.

Table 2: Average daily inhaled concentrations of silicon dust, 2014 - 2017

Silicon dust, type A (μg/m^3)	5.3 (19.4)
Silicon dust, type B (μg/m^3)	211.4 (606.7)

The city average daily concentrations of silicon dust with 20-70% (type A) and less than 20% (type B) of SiO2 inhaled by local population in the city of Fokino between January 1, 2014 and December 31, 2017. Standard deviations are reported in parentheses.

Table 3: Summary statistics for hospital admission data, Fokino Hospital, 2014 - 2017

Number of unique patients	12 087
Male	5 407
Female	6 680
Number of patient-day observations	12 170 758
Employment	
Male	
Employed	1 593
Unemployed	3 814
Female	
Employed	1 943
Unemployed	4 737
Mean age (years)	41.6
Minimum age (years)	0
Maximum age (years)	99

Summary statistics of the hospital admission data in the hospital of the city of Fokino. Minimum age of 0 means less than 1 year old.

Table 4: Summary statistics for hospital admission data, 2 – 5 years old, 2014 - 2017

Age cohort	2 – 5 years old
Observations	524 668
Unique patients	686
Male	372
Female	314
Employment	
Unemployed	686
Most common disease, ICD 10 code	J06.9
	Mean
Silicon dust, with 20-70% concentration of SiO2 (μg/m^3)	
Both genders	4.0 (16.0)
Male	4.2 (17.0)
Female	3.8 (15.3)
Silicon dust, with less than 20% concentration of SiO2 (μg/m^3)	
Both genders	220.6 (630.7)
Male	219.2 (629.0)
Female	222.2 (632.7)

Summary statistics of hospital admissions to the hospital of Fokino for children between 2 and 5 years old between January1, 2014, and December 31, 2017. It reports general characteristics and the average daily inhaled concentrations of silicon dust.

Table 5: Summary statistics for hospital admission data, 86 – 90 years old, 2014 - 2017

Age cohort	86 – 90 years old
Observations	155 610
Unique patients	232
Male	184
Female	48
Employment	
Unemployed	232
Most common disease, ICD 10 code	I11.9
	Mean
Silicon dust, with 20-70% concentration of SiO2 (μg/m^3)	
Both genders	7.1 (22.2)
Male	7.7 (23.0)
Female	6.9 (22.0)
Silicon dust, with less than 20% concentration of SiO2 (μg/m^3)	
Both genders	232.5 (650.6)
Male	238.2 (662.2)
Female	230.8 (647.1)

Summary statistics of hospital admissions to the hospital of Fokino for the elderly between 86 and 90 years old between January1, 2014, and December 31, 2017. It reports general characteristics and the average daily inhaled concentrations of silicon dust.

Table 6: Summary Statistics for Weather Data, Fokino, 2014 - 2017

	Observations	Mean	Median	Min	Max	No data, # of days
Temperature (C)	1 461	7.4 (9.9)	6.3	-22.4	26.3	0
Min temperature (C)	1 461	3.7 (8.6)	3.3	-26.0	21.4	0
Max temperature (C)	1 461	11.4 (11.4)	10.6	-18.5	35.3	0
Pressure (mm)	1 461	743.1 (6.8)	742.9	715.9	769.7	0
Precipitation (cm)	1 461	0.8 (2.2)	0.01	0	41.8	5
Snow depth (cm)	1 461	10.4 (10.5)	7.0	0	35	1 078
Wind speed (m/s)	1 461	2.1 (0.9)	2.0	0.1	6.1	0

Summary statistics of the weather conditions for the city of Fokino between January 1, 2014, and December 31, 2017. Standard deviation is reported in parentheses.

Table 7: City areas based on the persistent inhaled concentrations

Panel A: General city areas' characteristics

Area of the city	Number of individuals	Percentage of male population, %	Percentage of people above 65 years old, %	Percentage of people above 85 years old, %
Area one	7 462	44	16	1
Area two	1 193	46	18	3
Area three	1 792	46	17	3
Area four	1 380	45	18	2

Panel B: City areas' daily inhaled concentrations of silicon dust

Area of the city	Type of silicon dust	Mean $\mu g/m^3$	Mode $\mu g/m^3$
Area one	Silicon dust, type A	0.9	1
	Silicon dust, type B	152	146
Area two	Silicon dust, type A	11.1	16
	Silicon dust, type B	258	243
Area three	Silicon dust, type A	14.6	18
	Silicon dust, type B	305	308
Area four	Silicon dust, type A	11.6	10
	Silicon dust, type B	351	325

Panel C: Persistent average concentration of silicon dust by city area

Area of the city	Type of silicon dust	Average concentration inhaled during the preceding 95 days ($\mu g/m^3$)
Area one	Silicon dust, type A	1
	Silicon dust, type B	152
Area two	Silicon dust, type A	16
	Silicon dust, type B	300
Area three	Silicon dust, type A	13
	Silicon dust, type B	338
Area four	Silicon dust, type A	12
	Silicon dust, type B	395

The average concentrations of silicon dust of two types inhaled by the local community in the city of Fokino between January 1, 2014, and December 31, 2017. The average concentrations were calculated for the 95 days preceding day t. Based on these average inhaled concentrations, the city of Fokino was divided into four areas.

Table 8: Effects of silicon dust on hospitalizations due to chronic obstructive pulmonary disease, 86 – 90 years old

	(a) Both genders	(b) Male	(c) Male, Area three	(d) Male, Area four
Silicon dust, type A				
On the day of the hospital	-0.001	0.006	-0.075	-0.068
admission	(0.003)	(0.008)	(0.058)	(0.055)
One day before the	0.002	-0.012	-0.003	0.176
hospital admission	(0.005)	(0.015)	(0.012)	(0.127)
Two days before the	0.008	0.027	0.035	0.040
hospital admission	(0.004)	(0.011)	(0.013)	(0.016)
Silicon dust, type B				
On the day of the hospital	0.00	-0.0002	-0.003	0.009
admission	(0.00)	(0.0002)	(0.003)	(0.006)
One day before the	-0.0001	0.0003	0.001	-0.007
hospital admission	(0.0001)	(0.0005)	(0.001)	(0.006)
Two days before the	-0.0002	-0.0006	0.003	0.005
hospital admission	(0.0001)	(0.0003)	(0.002)	(0.016)
Adjusted R^2	0.02	0.03	0.06	0.21
Observations	141 172	32 504	9 560	2 228

The linear probability model estimates from equation (1) in the main text. The dependent variable is the dummy variable that equals to 1 if a patient i from the relevant age group was admitted to the hospital due to chronic obstructive pulmonary disease (COPD) on day t and 0 if due to another reason or not admitted to the hospital at all. Silicon dust is measured in mg/m^3. All regressions include time and individual fixed effects; controls for other pollutants, average daily temperature, atmospheric pressure and precipitation on the day of the admission and two lags. Standard errors, clustered by individual, are reported in parentheses.

Table 9: City areas and hospitalizations due to COPD, 86 – 90 years old, male

Panel A: Mean inhaled daily concentrations of silicon dust by city area

Area of the city	Mean daily concentration of silicon dust of type A(μg/m^3)	Mean daily concentration of silicon dust of type B(μg/m^3)
Area one	1	140
Area two	8	296
Area three	17	315
Area four	9	375

Panel B: Hospital admissions due to COPD by city area

Area of the city	Number of hospital admission due to COPD	Number of unique patients	Number of hospitalizations due to COPD per individual
Area one	2	23	0.09
Area two	1	9	0.11
Area three	9	13	0.69
Area four	12	3	4.00

Average daily inhaled concentrations in four areas of the city for both types of silicon dust. It presents the number of hospitalizations due to COPD among males between 86 and 90 years old in each area of the city. COPD is chronic obstructive pulmonary disease.

Table 10: Effects of silicon dust on COPD hospital admissions, male, 86 – 90 years old, area four, by duration

Type of silicon dust	(a) 7 days	(b) 75 days	(c) 95 days	(d) 110 days	(e) 120 days
Silicon dust, type A	0.155	0.168	0.225	0.228	0.239
	(0.071)	(0.073)	(0.082)	(0.082)	(0.082)
Adjusted R^2	0.20	0.16	0.16	0.16	0.16
Observations	5 474	6 163	6 163	6 163	6 163
Type of silicon dust	(f) 140 days	(g) 160 days	(h) 180 days	(i) 240 days	(j) 255 days
Silicon dust, type A	0.288	0.280	0.251	0.238	0.297
	(0.098)	(0.094)	(0.126)	(0.111)	(0.147)
Adjusted R^2	0.16	0.16	0.16	0.23	0.23
Observations	6 163	6 163	6 163	5 818	5 818

Linear probability model estimates for the individual probability of hospital admission due to chronic obstructive pulmonary disease (COPD) among the male population between 86 and 90 years old relative to the duration of the "persistent" impact. Dependent variable is the dummy variable that equals to 1 if a patient i from the relevant age group was admitted to the hospital due to chronic obstructive pulmonary disease (COPD) on day t and 0 if due to another reason or not admitted to the hospital at all. Silicon dust is measured in mg/m^3. All regressions include time and individual fixed effects; controls for other pollutants, average daily temperature, pressure and precipitation during the period of the "persistent" impact. Standard errors, clustered by individual, are reported in parentheses.

Table 11: Effects of silicon dust on hospital admissions due to respiratory-related reasons, 2 – 5 years old, count model

Area of the city	Silicon dust, type B	Observations
Area one	-0.05	1 364
	(0.13)	
Area two	0.04	1 364
	(0.11)	
Area three	0.19	1 364
	(0.10)	
Area four	0.42	1 364
	(0.10)	

Negative binomial estimates of the impact of three-day average inhaled concentration of silicon dust. The dependent variable is three-day count of hospitalizations due to respiratory-related reasons among the children between 2 and 5 years old. Silicon dust is measured in mg/m^3. All regressions include time fixed effect; three-day averages of controls for other pollutants, average daily temperature, pressure and precipitation are included. Clustered standard errors are reported in parentheses.

Table 12: Effects of silicon dust on hospital admissions due to respiratory-related reasons, 2 – 5 years old, count model, subareas of areas three and four

Subarea of the city	Silicon dust, type B	Observations
Subarea 3.1	-0.03 (0.830)	1 144
Subarea 3.2	0.43 (0.115)	1 286
Subarea 3.3	0.41 (0.001)	1 332
Subarea 4.1	0.47 (0.010)	1 261
Subarea 4.2	0.42 (0.004)	1 181
Subarea 4.3	0.09 (0.541)	866

Negative binomial estimates of the impact of three-day average inhaled concentration of silicon dust. The dependent variable is three-day count of hospitalizations due to respiratory-related reasons among the children between 2 and 5 years old in subareas 3.1, 3.2, 3.3, 4.1, 4.2, and 4.3 of areas three and four. Silicon dust is measured in mg/m^3. All regressions include time fixed effect; three-day averages of controls for other pollutants, average daily temperature, pressure and precipitation are included. Clustered standard errors are reported in parentheses.

A.2 Figures

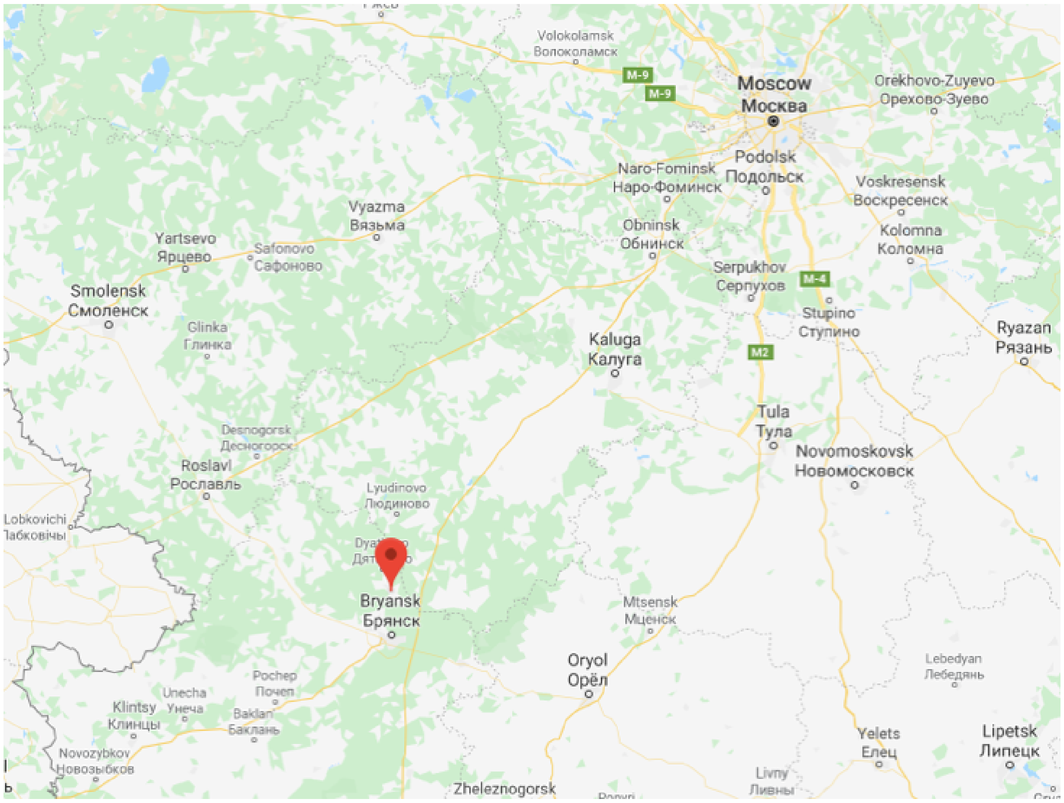


Figure 1: The city of Fokino, Bryanskii region, Russia.
Physical map of the south-western European part of Russia. Fokino is located 350 km to the south-west from Moscow, in the Bryanskii region. [Source] Google Maps.

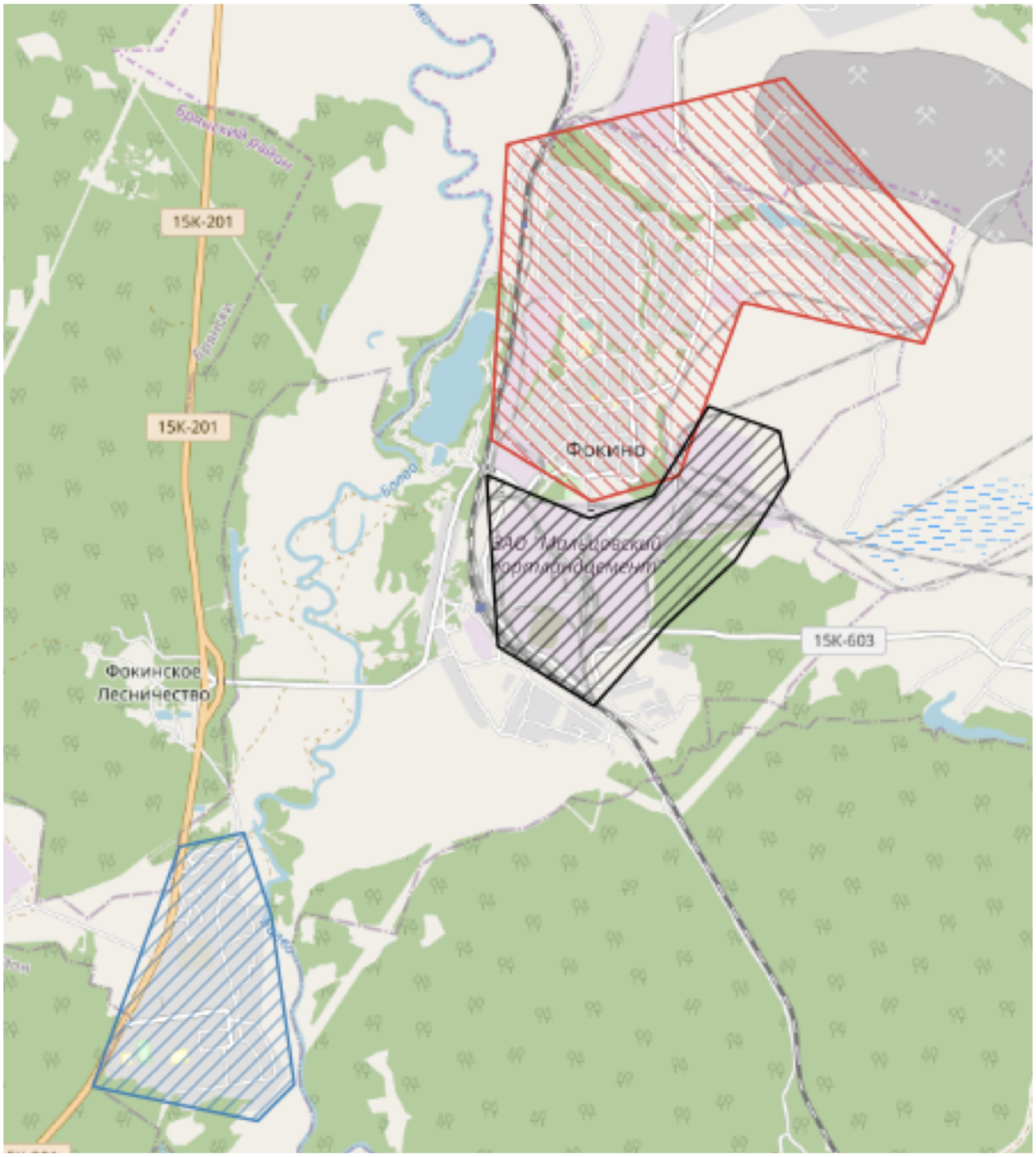


Figure 2: Two parts and the cement plant, the city of Fokino.
Two regions of the city of Fokino with the cement plant. The “older” region is in red, the “new” region is in blue, and the plant is the black hashed part. [Source] QGIS.

Figure 3: Borders of the city of Fokino.

On the left side, the boundaries of the city of Fokino are presented. On the right side, the location of the plants in the city is shown. “Malcovskii portland cement” is located to the south of one part of the city (upper part on the left side and middle part on the right side) and to the north-east from another part (lower part of the city on the left side). [Source] Yandex Maps.

Figure 4: Geocoded emission sources at the cement plant.
Sources of emission (green dots) at the cement plant "Malcovskii portland cement". Coordinates of each source were provided by the plant, we have used QGIS to geocode them.

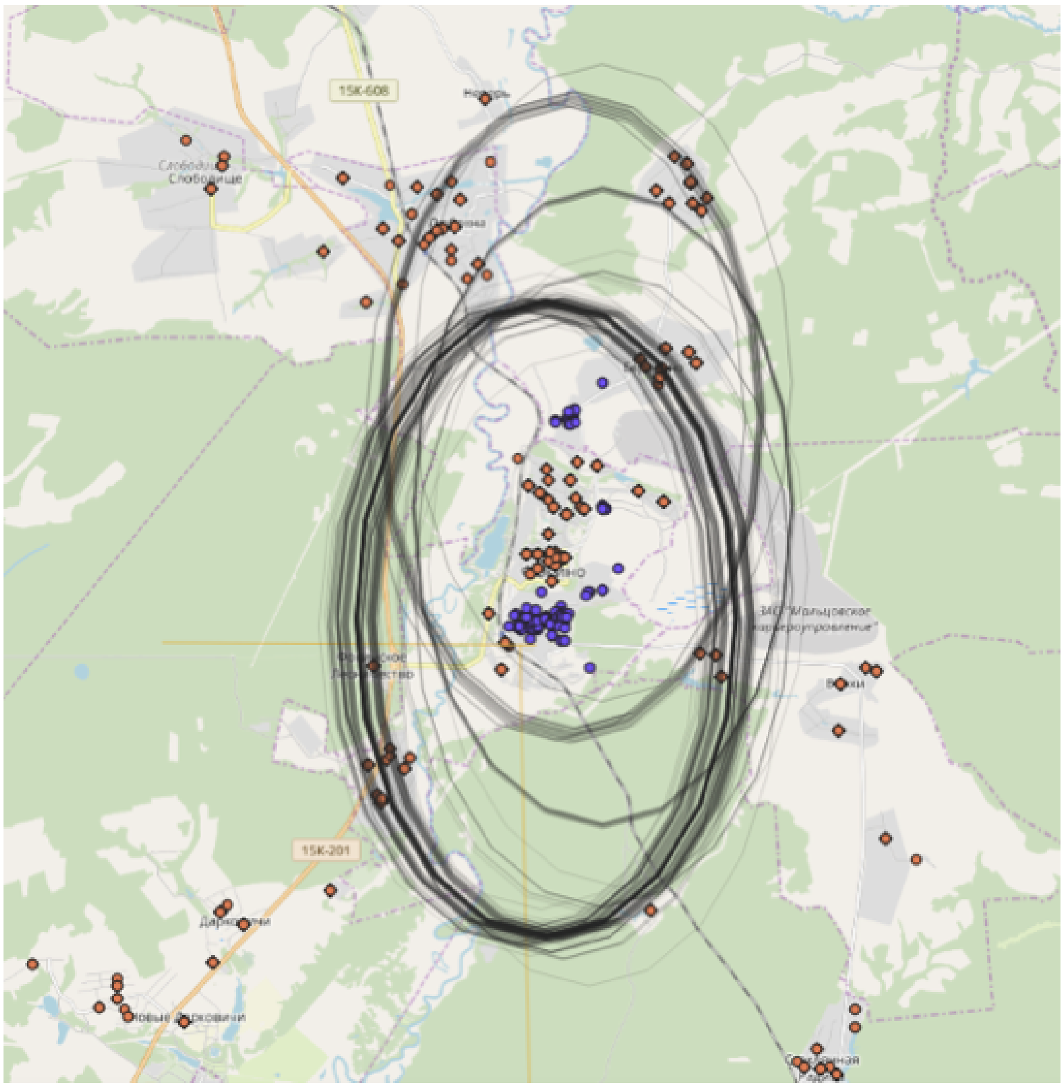


Figure 5: Borders of the impacted area.
Purple dots are sources of the emission of the cement plant, orange dots are geocoded patients. The black circles identify the impact area considered: less or equal 4 800 meters from each of the source of emission.

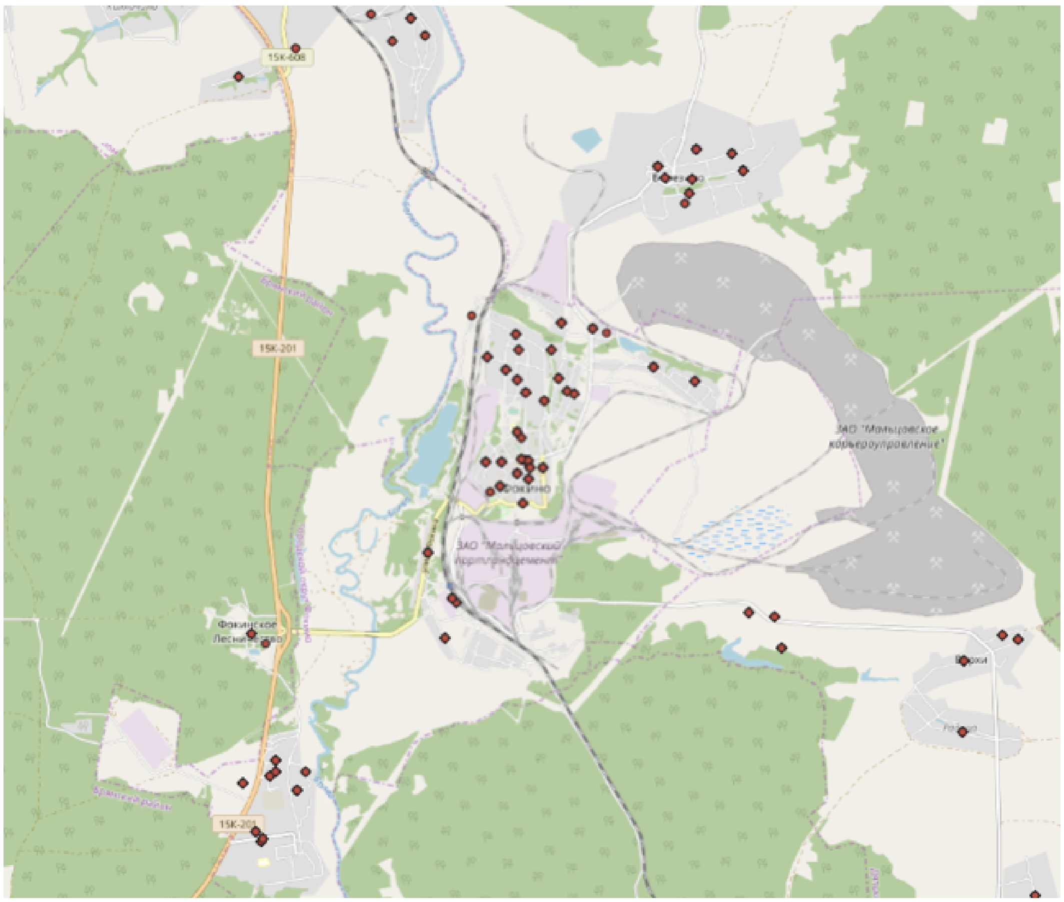


Figure 6: Geocoded patients in the city of Fokino.
Red dots are geocoded patients' home addresses (street level). As each patient's address was provided up to the street level due to personal data security reasons, each dot represents more than one patient.

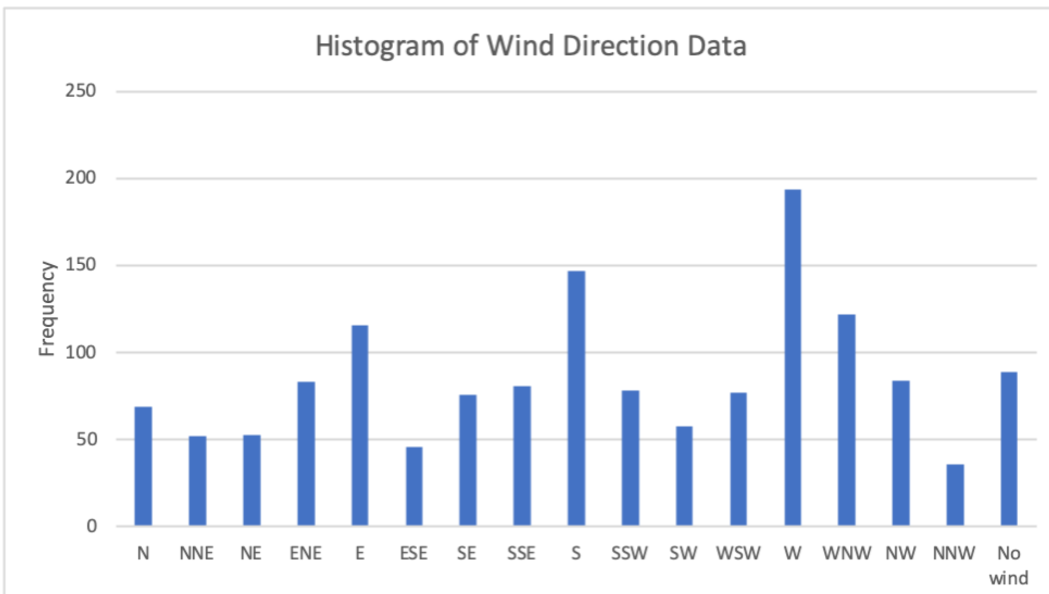
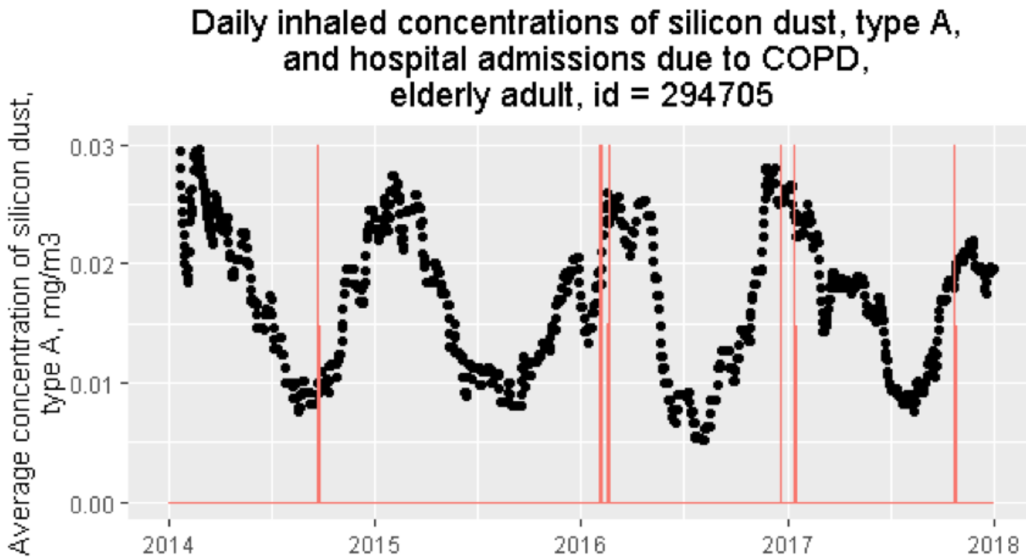


Figure 7: Histogram of wind directions in the city of Fokino. Histogram of wind direction data. Frequency is calculated as the number of days between January 1, 2014, and December 31, 2017.



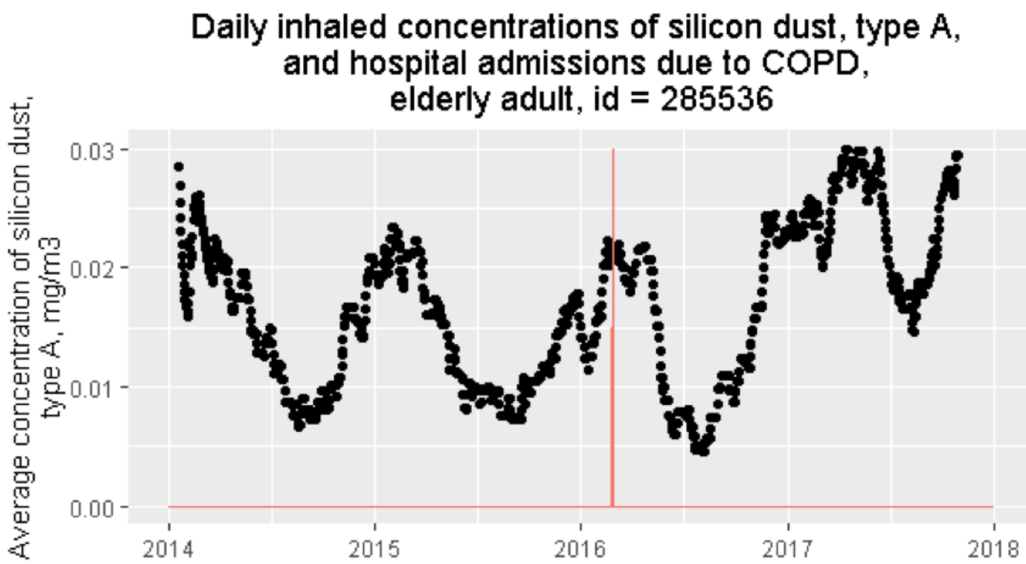


Figure 8: Silicon dust concentrations inhaled and COPD admissions for two patients.
Average concentrations of silicon dust inhaled during the 95 days preceding the hospital admissions due to COPD-related reason (red dashed lines). Individual data for elderly adults (86 – 90 years old age cohort).

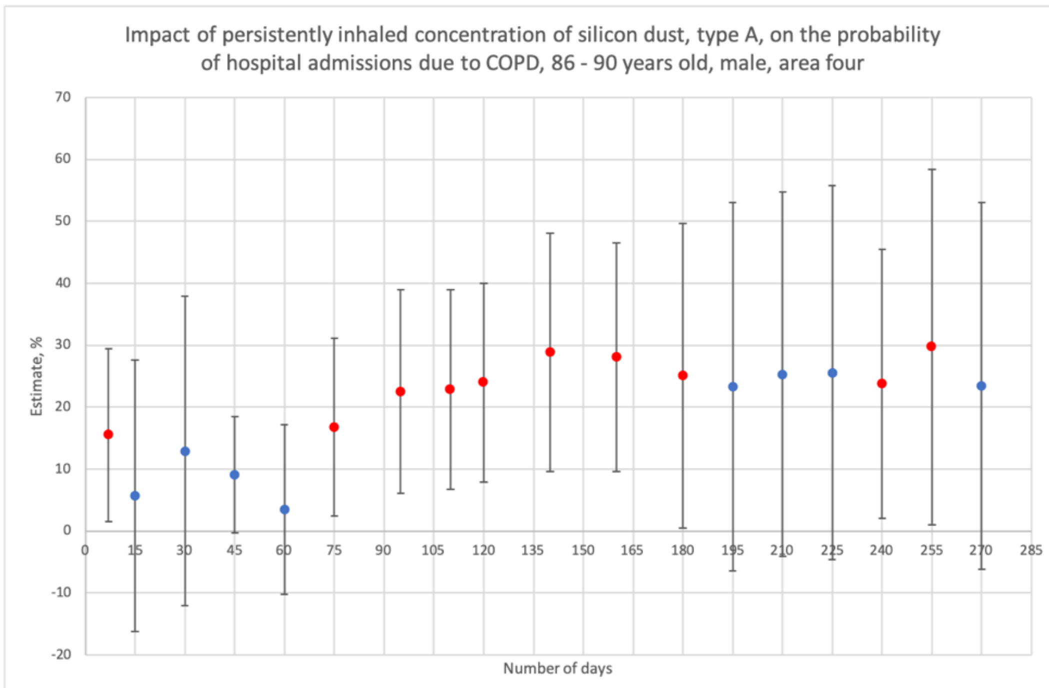


Figure 9: Persistent impact of silicon dust on hospital admissions due to COPD.
Estimated coefficients of the impact of persistently inhaled concentrations of type A silicon dust on the probability of hospital admissions due to COPD-related reasons for the elderly male population (86 and 90 years old) in area four during the preceding 7, 15, 30, 45, 60, 75, 95, 110, 120, 140, 160, 180, 195, 210, 225, 240, 255, and 270 days, respectively. The red dots are significant estimates, the blue dots are not significant. The bars represent 95% confidence intervals.

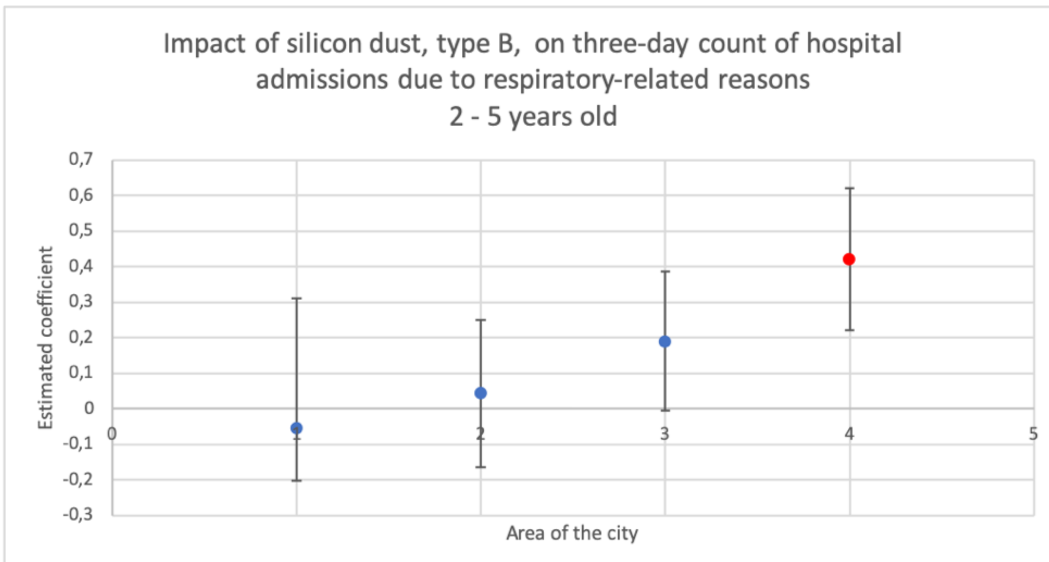


Figure 10: The impact of silicon dust on admissions die to respiratory-related reasons, four areas of the city.
Impact of 1 mg/m^3 increase in three-day average inhaled concentration of type B silicon dust on three-day count of hospital admission due to respiratory-related reasons among children between 2 and 5 years old per city area. The red dots are significant estimates, the blue dots are not significant. The bars represent 95% confidence intervals.

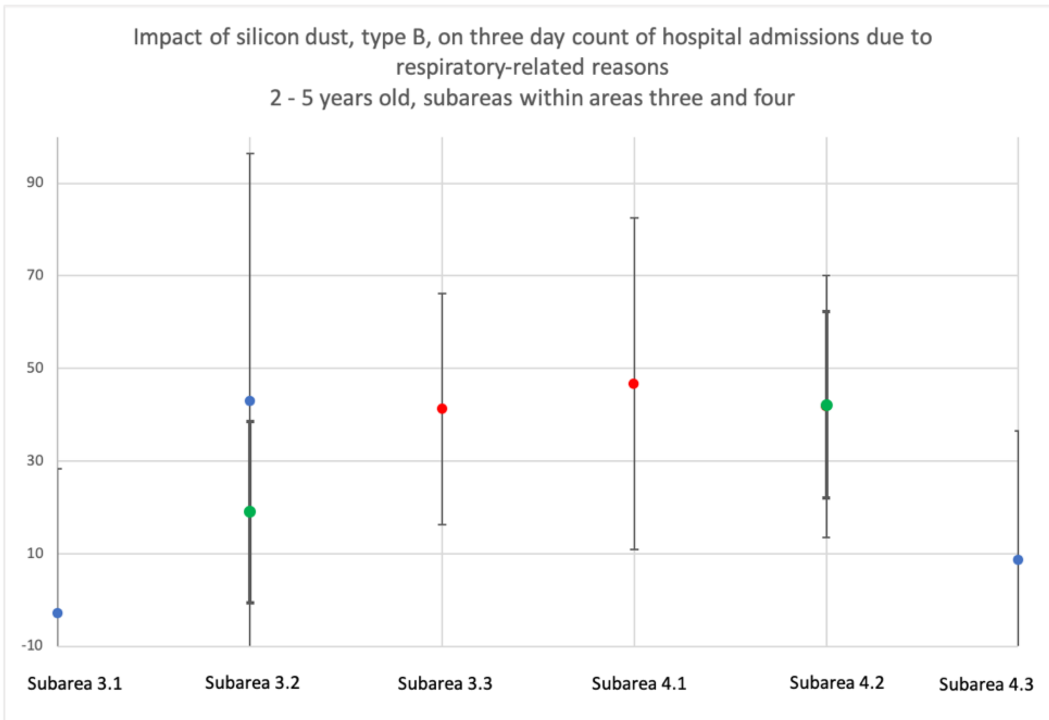


Figure 11: Subareas of the areas three and four of the city of Fokino. Impact of 1 mg/m^3 increase in three-day average inhaled concentration of type B silicon dust on three-day count of hospital admission due to respiratory-related reasons among children between 2 and 5 years old per subarea of areas three and four. The red dots are significant estimates, the blue dots are not significant. The green dots represent the average estimates for areas three and four as a whole. The bars represent 95% confidence intervals.