Vog: Using Volcanic Eruptions to Estimate the Health Costs of Particulates

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Abstract

The negative consequences of long-term exposure to particulate pollution are well-established

In this paper, we use volcanic emissions to document the effect of particulate pollution on hospital admissions and charges. Industrial and other types of anthropogenic pollution generally induce high correlation among various pollutants, possibly complicating the attribution of quantifiable effects to several different pollutants. Our pollution source, on the other hand, leads to relatively independent variation in pollutants. This variation allows us to more precisely measure the effect of particulate matter on various public health outcomes and costs in a context where pollution levels are well below Environmental Protection Agency (EPA) ambient air quality standards.

Kīlauea is the most active of the five volcanoes that form the island of Hawai`i. Emissions from Kīlauea produce what is known as "vog" (volcanic smog) pollution. Vog is essentially small particulate matter (sulfate aerosols) suspended in the air, akin to smog pollution in many cities. Vog represents one of the truly exogenous sources of air pollution in the United States. Based on local weather conditions (and whether or not the volcano is emitting), air quality conditions in the state of Hawai`i can change from dark, polluted skies to near pristine conditions in a matter of hours.

We adopt two main approaches to estimate the health impact of the pollution produced by Kīlauea. Both use high frequency data on air quality and emergency room (ER) admissions and estimate linear models. The first method estimates a parsimonious model with regional and seasonal fixed effects via Ordinary Least Squares (OLS). The second method exploits variations in wind patterns in the island chain in conjunction with information on emissions levels near Kīlauea to construct an instrumental variables (IV) estimator.

The OLS estimator can be justified on the grounds that the variation in air quality is unrelated to human activities. The two main omitted variables that could impact our analysis are traffic congestion and avoidance behaviour (*e.g.*, people avoiding the outdoors on "voggy" days). We see no compelling reason to believe that the former is systematically correlated with volcanic pollution. In addition, adjusting for a flexible pattern in seasonality will control for much of the variation in traffic congestion. The latter, avoidance behaviour, is thornier and has bedevilled much of the research in this area. We are unable to control for this omitted variable and our estimates of the effects of pollution on health care utilization should be viewed as being inclusive of this adjustment margin (we nevertheless see no effect of pollution on fractures which may be indicative of limited avoidance behaviour). In addition, a large degree of measurement error in our pollution variables should bias our estimates downwards. Error in pollution exposure measurement may arise through imprecision in measurement instruments and misalignment between measurement and exposure locations. As such, one can reasonably view our OLS estimates as lower bounds of the true impact of vog on emergency medical care utilization (as in much of the literature).[1] Finally, but importantly, a unique feature of our design is that we have a source of particulate pollution that is much less related to many other industrial pollutants than in other regions of the US. Consequently, we provide an estimate of the health cost of a specific type of particulate pollution that is more credible than much of the extant literature.

To address the measurement error bias as well as any lingering omitted variables biases from industrial pollution or traffic congestion, we also employ an instrumental variables (IV) estimator. Our strategy employs emissions measurements from the south of Hawai`i island (where Kīlauea is located) in conjunction with wind direction data collected at Honolulu International Airport to instrument for particulate levels on the south shore of O`ahu (a different island with high population density). Kīlauea is located on the southeast part of the island of Hawai`i which can be seen in the map in Figure 1. The basic idea is that when winds come from the northeast there is very little particulate pollution on O`ahu, which as shown in Figure 2 is to the northwest of the island of Hawai`i, because all of the emissions from Kīlauea are blown out to sea. Figure 3 is a satellite image showing sulphur dioxide concentrations during typical northeast wind conditions: the plume of emissions coming from the volcano is blown to the southwest, away from the Hawaiian islands. On the other hand, when volcanic emissions levels are high and when the winds come from the south, particulate levels on O`ahu are high.

Little is known about the health impacts of volcanic emissions, although a few recent studies have focused on modern eruptions.[2] In a study of Miyakejima island in Japan, Ishigami et al.

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[1] For example, Künzli and Tager (1997) explain how simple OLS designs tend to underestimate the effect of air pollution on health. Sheppard et al. (2012) and Goldman et al. (2011) both suggest that the usual estimators may suffer from severe attenuation bias due to measurement error.

[2] In terms of historical eruptions, Durand and Grattan (2001) use health records from 1783 to document a correlation between pulmonary ailments and vog in Europe caused by the eruption of Laki volcano in Iceland.

Figure 1: Topographical Map of the Island of Hawai`i

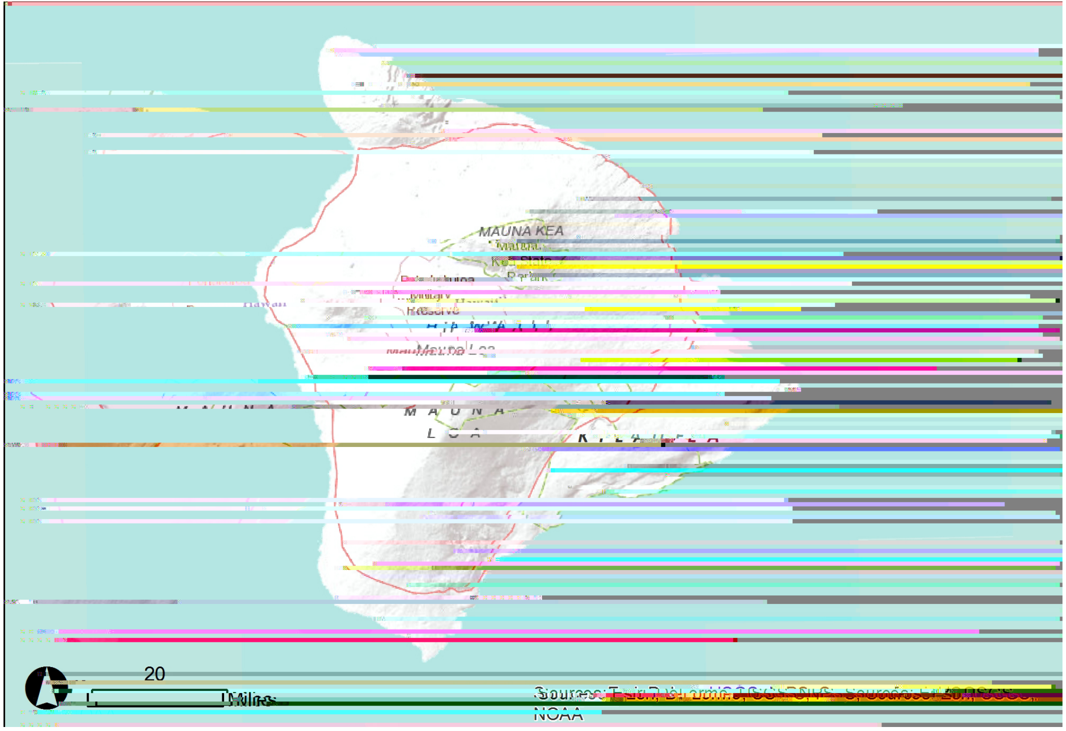
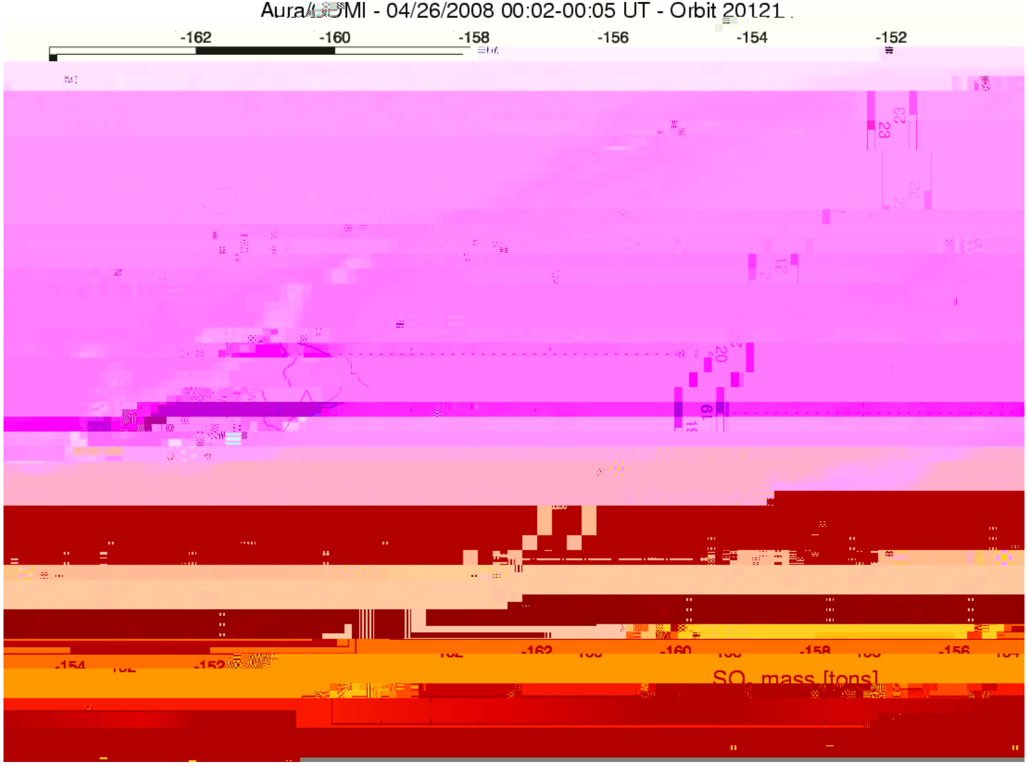


Figure 2: Map of the Hawaiian Islands

Figure 3: Satellite Image of Sulphur Dioxide Mass



Source: NASA Earth Observatory

(2008) found a strong correlation between sulphur dioxide (SO_2) concentrations and self-reported pulmonary effects (cough, sore throat, and breathlessness). Kīlauea itself has been the focus of a number of recent epidemiological studies. Prior to the 2008 escalation in emissions, nearby residents self-reported increased pulmonary, eye, and nasal problems relative to residents in areas unaffected by vog (Longo et al. (2008); Longo (2009)). A strong correlation between vog and outpatient visits for pulmonary problems and headaches was found by Longo et al. (2010). Longo (2013) uses a combination of self-reported ailments and in-person measurements (blood pressure and blood oxygen saturation) to document strong statistical correlations with exposure to vog. Half of the are causing health problems. In particular, selection bias (for example, respondents volunteered to answer surveys and the socio-economic characteristics of individuals who choose to live close to the volcano are quite different to the rest of the state) and self-reporting errors make it difficult to infer causal evidence from previous epidemiological studies on Kīlauea.[3]

There is, of course, a much broader literature that attempts to estimate a causal relationship between industrial sources of pollutants and human health. Within economics, there has been an attempt to find "natural" or quasi-random sources of pollution variation in order to eliminate many of the biases present in epidemiological studies based on purely correlative evidence. Chay et al. (2003) use variation induced by the Clean Air Act in the 1970s to test for a link between particulate matter and adult mortality. Chay and Greenstone (2003) use the 1981-82 recession as a quasi-random source of variation in particulate matter to test for an impact on infant mortality. Neidell (2004) uses seasonal pollution variation within California to test for a link between air pollution and children's asthma hospitalizations. Lleras-Muney (2010) uses forced changes in location due to military transfers to study the impact of pollution on children. Moretti and Neidell (2011) use boat traffic in Los Angeles; Schlenker and Walker (2016) use airport traffic in California; Knittel et al. (2016) use road traffic; and Currie and Walker (2011) use the introduction of toll roads as sources of quasi-exogenous pollution variation. Arceo-Gomez et al. (2016) use thermal inversions to measure the effect of CO and PM_{10} on infant mortality in Mexico.

There is also a corresponding medical literature on the health effects of pollution. The studies that most closely align with our own investigate the effects of particulates on respiratory hospital admissions and mortality. An early and influential study exploited the intermittent closure of a steel mill in Utah Valley to demonstrate a causal link between PM_{10} pollution and respiratory hospital admissions, particularly among pre-school age children Pope III (1991). This study used monthly hospital admissions. A follow-up study in the same area found a significant correlation between 5-day moving average PM_{10} pollution and non-accidental mortality Pope III et al. (1992).

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[3] The leading scholar in this literature notes that her "cross-sectional epidemiologic design was susceptible to selection bias, misclassification, and measured associations, not causality" Longo (2013, p. 9). In particular, the cross-sectional nature of previous studies may not eliminate unobserved confounding factors. Because we exploit variation in pollution from the volcano over time within a region, our research design does a more thorough job of eliminating these confounds.

Dockery et al. (1993), Pope et al. (1995), Pope III et al. (2002) and Pope III et al. (2009) all investigate the effects of long-term exposure to particulates and observe strong correlations with mortality in the US.

The contributions of this study to the existing literature are as follows. First, the vast majority of the studies in the economics literature exploit sources of pollution that are the result of human activity (*e.g.*, from cars, airplanes, factories, or starting fires to clear forest).[4] Second, we use more accurate data on the costs of hospitalization than much of the other literature and, particularly, is associated with 2% additional ER charges when we use our OLS estimates. Our IV estimates imply a much larger effect, between 23 and 36%. We find strong effects among the very young. We do not find any effects of particulate pollution on cardiovascular-related or fracture-related admissions, of which the latter is our placebo.

The balance of this paper is organized as follows. In the next section, we give some further background on the volcano and describe our data. Following that, we discuss the relationship between volcanic emissions and pollution. We then describe our methods. After that, we summarize our results. Finally, we conclude.

1 Background and Data

Kīlauea's current eruption period began in 1983 and occasionally disrupts life on the island of Hawai`i and across the state. Lava flows displaced some residents in 1990 and a small number again in late 2014. Other than these minor impacts, the lava flows serve mainly as a tourist attraction. The primary impact of the volcano on human activity has been intermittent but severe deteriorations in air quality. Kīlauea primarily emits water vapour, carbon dioxide, and sulphur dioxide (these gases comprise 99% of total emissions), along with other minor trace gases (hydrogen, hydrogen chloride, hydrogen fluoride, and carbon monoxide (CO); totalling 1% of emissions).[6] SO_2 poses a serious threat to human health and is also a common industrial pollutant. Moreover, SO_2 turns into particulate matter which is also another harmful pollutant and the main pollution problem caused by the volcano.

There are currently two main sources of air pollution on Kīlauea: the summit itself and a hole (volcanic cone) in the \East Rift Zone" on the side of the volcano. Since March 12, 2008, there has been a dramatic increase in emissions from Kīlauea: a new vent opened inside the summit, emissions fluctuate on a daily basis between 500 and 1,500 tons of SO_2 per day. As a reference point, the Environmental Protection Agency's safety standard for industrial pollution is 0.25 tons of SO_2 per day from a single source (Gibson (2001)). Kīlauea is, not surprisingly, the largest stationary source of SO_2 pollution in the United States of America. Depending on volcanic activity, rainfall, and prevailing wind conditions, there can be vast daily differences in the actual amount of SO_2 present near the summit and surrounding areas, ranging from near pristine air quality to levels that far exceed guidelines set by the EPA.

Volcanic pollution, or vog, is composed of different gases and aerosols, and the composition typically depends on proximity to the volcano. Near Kīlauea's active vents, vog consists mostly of SO_2 gas. Over time, SO_2 gas oxidizes to sulfate particles through various chemical and atmospheric processes, producing hazy conditions (particulate pollution). Thus, farther away from the volcano (along the Kona coast on the west side of Hawai`i Island and on the other Hawaiian islands), vog is essentially small particulate matter (sulphuric acid and other sulfate compounds) and no longer contains high levels of SO_2. Because this species of particulates is high in sulphuric acid, the results of this study may be more pertinent to other particulate sources that are also high in sulfate aerosols such as coal-fired power plants. In summary, the volcano has the potential to produce high levels of SO_2 pollution near the volcano and high levels of a particular species of particulate pollution anywhere in the state of Hawai`i.

We employ data from two primary sources. First, we obtained data on ER admissions and charges in Hawai`i from the Hawai`i Health Information Corporation (HHIC). Second, we obtained data from the Hawai`i Department of Health (DOH) on air quality from thirteen monitoring stations in the state.

The ER data include admissions information for all cardiovascular and pulmonary diagnosis-related groups, as well as all admissions for fractures and dislocations of bones other than the pelvis, femur, or back. Fractures are designed to serve as a placebo, as they should be unaffected by air pollution. The data span the period January 1, 2000 to December 31, 2012. These data include information on the date and cause of admission as well as the total amount charged for patient care. In addition, we know the age and gender of the patient. We also have information on a broadly defined location of residence. In particular, HHIC reports the residence of location as an \SES community," which is a collection of several ZIP codes. We show the SES communities on the islands of O`ahu, Hawai`i, Maui, Lana`i, Moloka`i and Kaua`i in Figure A1 in the appendix.

To put the data in a format suitable for regression analysis, we collapsed the data by day, cause of admission, and SES community to obtain the total number of admissions and total ER charges on a given day, in a given location, and for a given cause (*i.e.*, pulmonary, cardiovascular, or fractures). Once again, it is important to note that the location information corresponds to the patient's residence and not the location of the ER to which he or she was admitted. We did this because we believed that it would give us a more precise measure of exposure once we merged in the pollution data.

We use measurements of the following pollutants: particulates 2.5 and 10 micrometres in diameter ($PM_{2:5}$ and PM_{10}) and SO_2.[7] All measurements for SO_2 are in parts per billion (ppb), and particulates are measured in micrograms per cubic meter (μg/m^3). For particulates, two measures were available: an hourly and a 24-hour average computed by the DOH.[8] Using the hourly measures, we computed our own 24-hour averages, which were arithmetic averages taken over 24 hourly measures. Most of the time, either the one hour or the 24-hour measure was available, but rarely were both available on the same day. When they were, we averaged the two. For our empirical results, we spliced the two time series of particulates (*e.g.* the 24 hour averages provided by the DOH and taken from our own calculations) together and took averages when appropriate so we could have as large of a sample as possible for our regression analysis. The measurements of SO_2 were taken on an hourly basis; to compute summary measures for a given day, we computed means for that day.

To merge the air quality data into the ER admissions data, we used the following process. First, means for all the monitoring stations on a given day in a given SES community. Table A1 in the appendix displays the mapping between the monitoring stations and the SES communities. We did not use data from SES communities that had no monitoring stations. In total, we used data from nine SES communities.

Unfortunately, we do not have complete time series for pollutants for all nine SES communities. By far, we have the most comprehensive information for $PM_{2:5}$ and, to a lesser extent, SO_2. We report summary statistics for the pollutants in Table 1.[9]

In Figures 4 through 6, we present graphs of the time series for each of the pollutants that we

Figure 4: PM$_{2.5}$ by SES Community

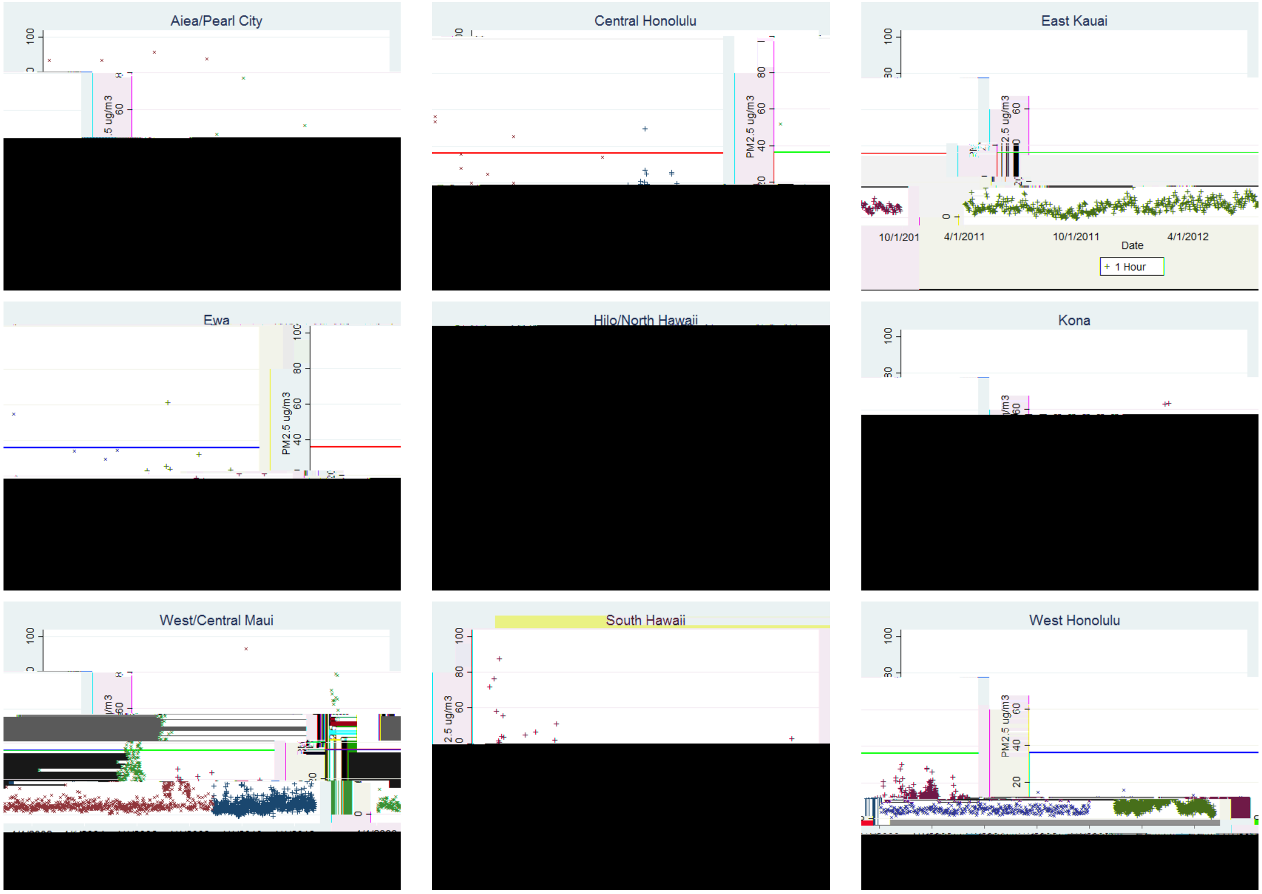


Figure 5: PM$_{10}$ by SES Community

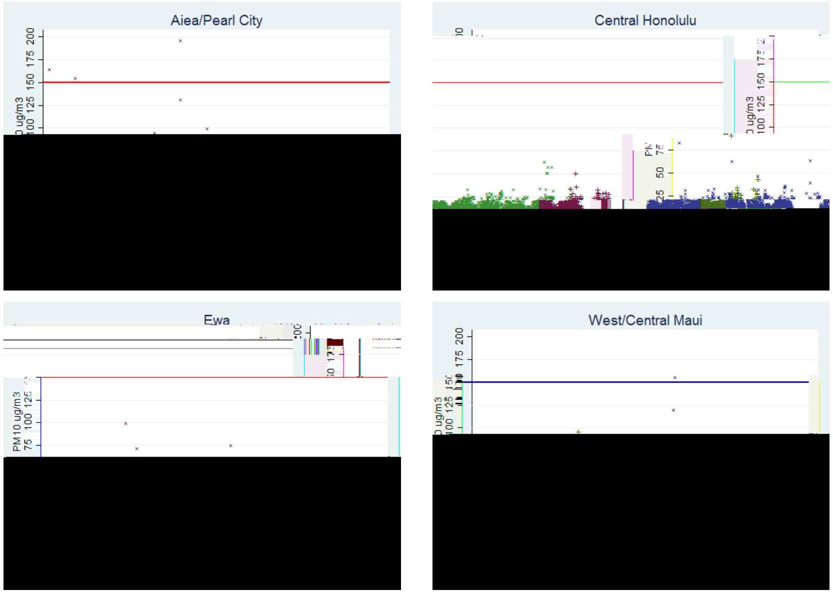
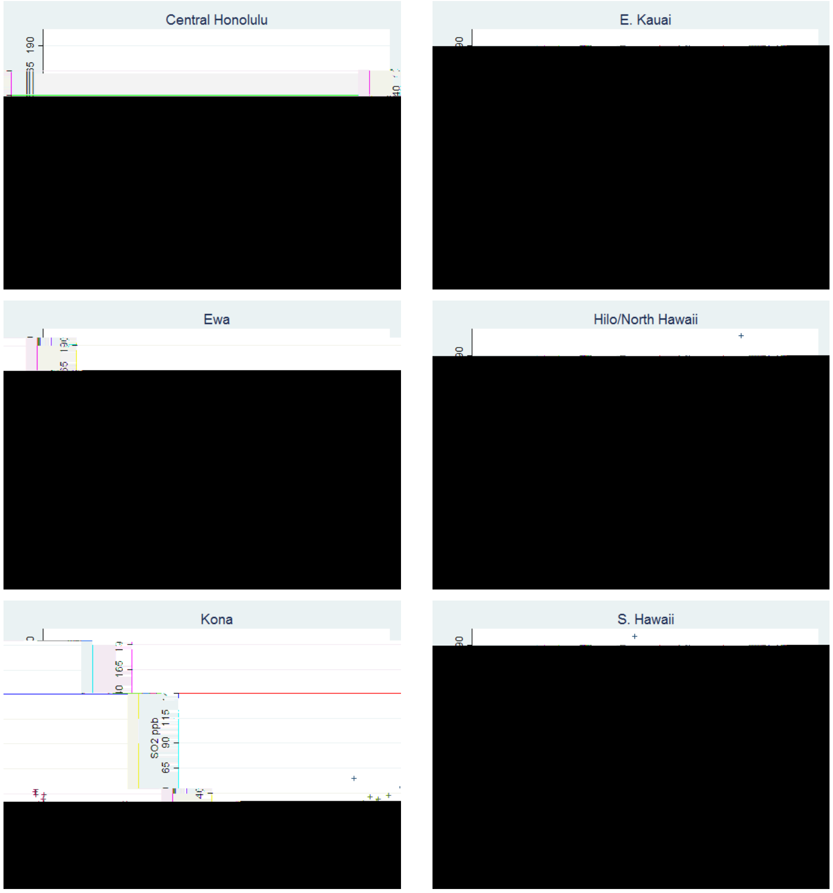
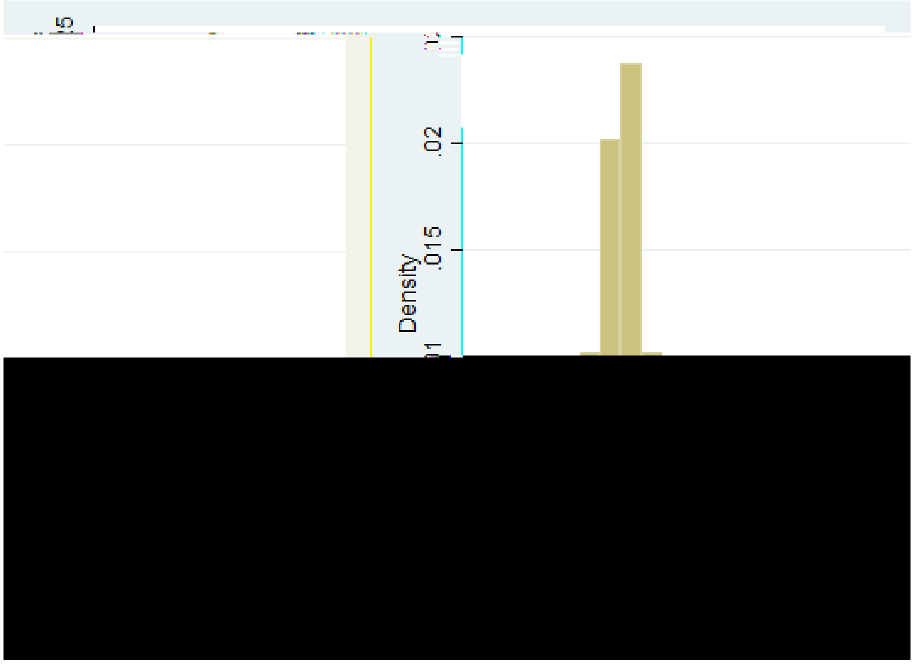


Figure 6: SO$_2$ by SES Community



tional Oceanic and Atmospheric Association from their weather station at Honolulu International Airport. These data are reported in degrees (rounded to the nearest ten) with zero corresponding to the winds coming from due north. We summarize these data in the histogram in Figure 7. As can be seen, the winds primarily come from the northeast. In fact, the mean wind direction is 92.3 degrees and the median is 70 degrees. However, we do see a cluster of data between 120 and 180 which reflects that occasionally the winds do come to O`ahu from the south. When this happens, the volcanic emissions from Kīlauea are blown to the island of O`ahu, not out to sea. Travel time from Kīlauea to O`ahu depends on wind strength, exact direction, and the location of the plume offshore. According to Tofte et al. (2017): \The straight-line distance from the vents to Honolulu is about 350 km. A typical wind speed between 4 and 10 m/s would give the vog plume 10 to 24 h to reach Honolulu." This travel time could be shorter if the plume is sitting offshore directly south of O`ahu due to recent northeast winds (as depicted in Figure 3).

Figure 7: Histogram for Wind Direction Data



We conclude this section by reporting summary statistics from the HHIC data for all the SES Communities for which we have air quality information in Table 1. An observation is an SES community/day. For all the SES communities we consider, we see that, on an average day, there were 4.01 admissions for cardiovascular reasons, 5.00 admissions for pulmonary reasons, and 1.98

admissions for fractures in a given region. Total charges for cardiovascular-related admissions are $5159.18 per day, whereas pulmonary-related admissions cost a total of $4204.16. Finally, note that these amounts correspond to what the provider charged, not what it received, which, attempt to construct a sensible denominator for each of these days. Second, regional fixed effects will accll and, reg.90341o7yon(a)-340(se4l19034ill)-3541(th)1541(th)sech

We would argue that SO_2 levels in South Hawai`i are unrelated to most causes of particulate pollution on O`ahu other than, of course, vog. It is also important to say that, in unreported results, we found no direct effects of SO_2 on pulmonary outcomes and, so, it appears as if using SO_2 levels from South Hawai`i as an IV does not violate any exclusion restrictions. In addition, we exploit the fact that most of the time trade winds from the northeast blow the volcanic emissions out to sea and so, on days with trade winds there is very little vog. However, on occasion, the winds reverse direction and come from the south and this blows the vog towards the island of O`ahu.

We restrict the IV estimations to the island of O`ahu since one of the aims of this work is the estimate the health consequences of particulate pollution without being contaminated by other pollutants. Using $SO_2$ pollution from the island of Hawai`i (in conjunction with wind direction) as an instrument for particulate pollution on O`ahu provides us with a clean way of doing this. Inclusion of regions on Maui or Hawai`i in the estimations may have compromised this because these regions may have had higher SO_2 concentrations due to their proximity to the volcanic eruptions.

Accordingly, our IV approach works as follows. The first stage is

$$p_{tr} = {}_r + {}_1 SO2_t + {}_2 NE_t + {}_3 SO2_t \quad NE_t + e_{tr} \qquad (2)$$

where p_{tr} is the particulate level (either PM_{10} or $PM_{2:5}$) in any of the regions on O`ahu at time $t$, $SO2_t$ is the $SO_2$ level at time $t$ in South Hawai`i, NE_t is a dummy variable indicating that the winds at Honolulu International Airport are coming from the northeast (*i.e.* the wind direction measurements take on values between 10 and 360 degrees: NE_t is a dummy variable for wind directions between 10 and 90 degrees), and ${}_r$ is a regional fixed effect. We do not include any seasonality controls since there are no systematic seasonal patterns in volcanic emissions that are also correlated with ER utilization and inclusion of these would greatly weaken the explanatory power of the instruments. In the second stage, we then estimate

$$outcome_{tr} = \hat{p}_{tr} + {}_r + ''_{tr} \qquad (3)$$

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little to no rain).

using only ER utilization data from O`ahu.

There is an important caveat to our results, which is that our OLS and IV estimates include

table, we see a significant relationship between air quality and emissions in both periods. In fact, the estimated coefficients are almost identical (0.00059 compared to 0.00055). This is reassuring given that the level of emissions from the ERZ has been relatively constant over the two time periods. It is only the summit source of emissions that has experienced the very large increase since 2008.

Turning to $PM_{2.5}$ in the final four columns, we still see significant effects of volcanic emissions on air quality in all four columns. Comparing emissions from the summit in 2000-2007 and 2008-2010 the correlation coefficient between CO and $PM_{2:5}$ is 0.85 (see Mar et al. (2000)). In our sample, it is 0.0118. As evidence that SO_2, PM corresponding number for PM

effects of $PM_{2:5}$ in column 5, we see that the point estimate is 0.553, whereas the analogous OLS estimate was 0.030, which is about 18 times larger. Accordingly, a one standard deviation increase in PM_{10} results in 2.6 additional hospitalizations per day; the corresponding number for $PM_{2:5}$ is 1.82. Finally, looking at the impacts on the log of admissions in columns 3 and 7, we see that a one $g=m^3$ increase in PM_{10} and $PM_{2:5}$ is associated with a 5.7% and a 7.0% increase in admissions, respectively. If we scale these numbers up by the respective standard deviations in PM_{10} and $PM_{2:5}$

admissions are contaminated by SO_2 that has migrated from the island of Hawai`i to O`ahu.

In Table 9, we estimate a version of the first stage in equation (2) except that in lieu of either $PM_{2.5}$ or PM_{10}, we use SO_2 levels on O`ahu as the dependent variable. Whereas the estimation of the first stage in Table 7 demonstrates the degree to which volcanic emissions creates particulate pollution on O`ahu, Table 9 indicates the degree to which the volcanic emission on the island of Hawai`i (as proxied by $SO_2$ levels on south Hawai`i) are associated with SO_2 levels on O`ahu. The basic idea of this exercise is to test if it really is volcanic emission of $SO_2$ on the island of Hawai`i that get converted to particulates on O`ahu that is driving our results.

We estimate all four specifications from Table 9 and we do not find evidence that the volcanic emissions from Kīlauea are raising SO_2 levels on O`ahu. The coefficient on $SO_2$ is never significant and always has the incorrect sign. In contrast, the coefficient estimates on $SO_2$ in Table 7 are all positive and highly significant indicating a strong relationship between volcanic emissions from Kīlauea and particulate levels on O`ahu. Next, the interactions between wind direction and SO_2

such as the very young and the very old. Because the different bins contain different numbers of ages, these estimates will vary, in part, for purely mechanical reasons. So, to gain a better idea of whether the effects of pollution are higher for a given group, we report

(Effect)

that we are aware of that allow us to directly compare our results.[21] Those that do exist tend to find smaller effects. Ghosh and Mukherji (2014) explore the impact of air pollution on children in urban India. Their pollution measures vary fortnightly and they do not use a quasi-experimental source of pollution variation; their identification strategy relies on using month and city fixed effects along with other controls. Ghosh and Mukherji (2014) find that a one standard deviation increase in $PM_{2:5}$ is associated with a 6.01 probability points increase in the likelihood of a cough, and a 1 standard deviation increase in PM_{10} is associated with a 14.74 probability points increase in the probability of a cough. The study closest to our own is probably Ward (2015), which finds strong evidence for the detrimental effect of particulate pollution for the respiratory health of children in Ontario, Canada. Ward (2015) finds that a one standard deviation change in particulate pollution is correlated with a 4% increase in respiratory admissions. This occurs in an area where particulate lev4451 0fewb-27(ero)278w eU.S.-3486aEPA-3486atandard etc." Thus, one of the reasons we may be one of the few studies to observe both statistically and economically significant effects of particulates is that we have an instrument that affects only one pollutant. Kīlauea volcano does not emit carbon monoxide or nitrogen dioxide (which creates ozone in the presence of sunlight).

Within the context of our finding a causal link between short-term variation in particulate pollution and ER hospitalizations, it is interesting to note that of the six main "criteria" pollutants regulated by the EPA (carbon monoxide, nitrogen dioxide, ozone, sulphur dioxide, lead, and particulate pollution), particulate pollution and lead are the only pollutants without hourly air quality standards. In terms of temporal frequency, the standards for particulate pollution are the least

5 Conclusions

We have used variation in air quality induced by volcanic eruptions to test for the impact of SO_2

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Table 1: Summary Statistics for Pollutant and Hospitalization Data

	PM_{10} in $g{=}m^3$	$PM_{2:5}$ in $g{=}m^3$	SO_2 in *ppb*	Cardiovascular		Pulmonary		Fractures	
				Admissions	Charges	Admissions	Charges	Admissions	Charges
Aiea/Pearl City	16.53	4.37	{	4.41	5005.89	5.00	3932.30	2.25	1608.22
	(5.61)	(2.41)		(2.35)	(3733.90)	(2.90)	(3020.09)	(1.56)	(1374.24)
Central Honolulu	13.85	4.25	0.62	4.75	6334.18	5.42	5043.31	2.40	1952.71
	(4.71)	(2.32)	(0.75)	(2.51)	(4354.10)	(2.92)	(3624.98)	(1.61)	(1561.85)
East Kauai	{	5.84	2.77	2.57	4548.77	3.10	3041.77	1.16	902.77
	{	(2.94)	(4.10)	(1.61)	(3253.94)	(1.85)	(2233.14)	(1.11)	(951.47)
Ewa	15.19	4.94	0.70	5.36	7218.27	7.67	6378.39	2.66	1900.35
	(5.70)	(2.99)	(0.64)	(2.68)	(4750.31)	(3.56)	(3954.93)	(1.69)	(1496.38)
Hilo/North Hawai`i	11.60	5.19	2.87	4.13	5124.33	4.55	3599.80	1.66	1128.62
	(3.55)	(4.15)	(5.92)	(2.27)	(3584.68)	(2.52)	(2793.71)	(1.33)	(1183.50)
Kona	{	15.98	4.96	3.08	4366.75	4.11	3743.41	1.94	1600.16
		(5.88)	(4.61)	(1.90)	(3264.70)	(2.39)	(2671.91)	(1.43)	(1413.31)
South Hawai`i	{	9.12	11.28	2.48	3078.78	2.96	2379.53	1.16	840.45
		(4.84)	(13.33)	(1.81)	(2836.40)	(2.04)	(2249.64)	(1.10)	(1046.95)
West/Central Maui	20.41	6.41	{	3.11	3992.91	3.26	2482.01	1.73	1494.84
	(7.54)	(5.19)		(2.01)	(3445.52)	(2.22)	(2235.51)	(1.41)	(1432.09)
West Honolulu	{	7.36	{	4.74	6125.65	7.27	6362.04	2.21	1736.69
		(3.70)		(2.37)	(4084.08)	(3.45)	(3973.84)	(1.51)	(1442.21)
All	16.04	6.52	3.29	4.01	5159.18	5.00	4204.16	1.98	1512.00
	(6.24)	(3.30)	(6.96)	(2.45)	(4018.47)	(3.23)	(3460.13)	(1.53)	(1417.32)

Notes: Reports means and standard deviations in parentheses.

Table 2: Effects of Volcanic Emissions of SO_2 (tons/day) on Particulate Pollution

Table 4: Pollution Correlation Matrix

	PM$_{2:5}$	PM$_{10}$	SO$_2$	CO	NO$_2$
PM$_{2:5}$	1				
PM$_{10}$	0.5247	1			
SO$_2$	0.4047	0.0937	1		
CO	0.0118	0.0081	0.0560	1	
NO$_2$	0.0798	0.0267	0.2032	-0.0346	1

Table 5: Effects of Particulates on Pulmonary Outcomes

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	PM$_{10}$ (in levels)				PM$_{2:5}$ (in levels)			
	Levels		Logs		Levels		Logs	
	Admissions							
t	0.015	0.012	0.0006	0.0002	0.030	0.025	0.0036	0.0038
	(0.004)	(0.005)	(0.0007)	(0.0009)	(0.006)	(0.007)	(0.0010)	(0.0013)
$t-1$		0.009		0.0008		0.007		0.0000
		(0.005)		(0.0008)		(0.007)		(0.0013)
F-Test		[0.000]		[0.2205]		[0.000]		[0.0043]
NT	13902	12933	13902	12933	17831	14844	17831	14844
	Charges							
t	13.67	11.89	-0.0045	-0.0058	43.61	28.11	0.0052	0.0040
	(4.03)	(4.74)	(0.0025)	(0.0032)	(6.40)	(8.13)	(0.0026)	(0.0037)
$t-1$		6.34		0.0014		13.68		0.0002
		(4.62)		(0.0030)		(8.08)		(0.0036)
F-Test		[0.000]		[0.1187]		[0.000]		[0.2072]
NT	13869	12899	13869	12899	17745	14751	17745	14751

significant at the 10% level; significant at the 5% level; significant at the 1% level

Notes: All estimations include region, day, month, and year dummies. Newey-West standard errors are reported in parentheses. The F-test is a test that the sum of the contemporaneous and lagged pollution variable sum to zero and its p-value is reported in brackets. The dependent variable is ER admissions or charges either in levels or logs.

Table 6: Placebo Tests: Effects of Particulates on Admissions for Fractures

	(1)	(2)	(3)	(4)
	PM_{10}		$PM_{2:5}$	
t	0.003	0.001	0.002	0.000
	(0.002)	(0.003)	(0.003)	(0.004)
t 1		0.003		0.003
		(0.003)		(0.004)
F-Test		[0.435]		[0.677]
NT	14004	13036	17965	14982

Notes: Per Table 5.

Table 7: IV Results: First Stages

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	PM_{10}				$PM_{2:5}$			
NE (Northeasterly winds)	-1.23	-1.21	-0.12	-0.12	-1.02	-1.02	-0.46	-0.58
	(0.30)	(0.29)	(0.28)	(0.27)	(0.20)	(0.20)	(0.20)	(0.19)
SO_2	0.06	0.06	0.06	0.05	0.04	0.04	0.04	0.03
	(0.02)	(0.02)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
SO_2 NE	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03
	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
Day of Week Dummies	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Month Dummies	No	No	Yes	Yes	No	No	Yes	Yes
Year Dummies	No	No	No	Yes	No	No	No	Yes
F-Test	18.46	17.76	8.99	4.28	29.54	28.87	13.16	14.64
NT	6814	6814	6814	6814	6195	6195	6195	6195

significant at the 10% level; significant at the 5% level; significant at the 1% level

Notes: All estimations include region dummies. Newey-West standard errors are reported in parentheses. The *F*-Test is a test of the joint significance of the excluded exogenous variables.

Table 8: IV Results: The Impact of Particulates on Pulmonary Outcomes

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Admissions	Charges	Admissions	Charges	Admissions	Charges	Admissions	Charges
	Levels		Logs		Levels		Logs	
PM_{10}	0.418	331.38	0.057	0.082	-	-	-	-
	(0.073)	(72.53)	(0.010)	(0.015)				
$PM_{2:5}$	-	-	-	-	0.553	337.01	0.070	0.067
					(0.087)	(77.25)	(0.011)	(0.015)
F-Test	18.46				29.54			
NT	6814	6779	6814	6779	6195	6115	6195	6115

significant at the 10% level; significant at the 5% level; significant at the 1% level

Notes: All estimations include region dummies. Newey-West standard errors are reported in parentheses. The *F*-Test is a test of the joint significance of the excluded exogenous variables. We only report the *F*-statistics from the first stages using admissions; the *F*-statistics from the regressions using charges are similar.

Table 9: OLS Estimates of the Effects of SO_2 from the Island of Hawai`i on $SO_2$ on O`ahu

	(1)	(2)	(3)	(4)
NE (Northeasterly winds)	-0.305	-0.304	-0.243	-0.260
	(0.047)	(0.047)	(0.048)	(0.046)
SO_2	-0.002	-0.002	-0.002	-0.002
	(0.002)	(0.002)	(0.002)	(0.002)
SO_2 NE	0.004	0.004	0.003	0.003
	(0.002)	(0.002)	(0.002)	(0.002)
Day of Week Dummies	No	Yes	Yes	Yes
Month Dummies	No	No	Yes	Yes
Year Dummies	No	No	No	Yes
F-Test	1.62	1.61	1.11	1.01
	[0.1989]	[0.1997]	[0.3298]	[0.3655]
NT	4633	4633	4633	4633

significant at the 10% level; significant at the 5% level; significant at the 1% level

Notes: All estimations include region dummies. Newey-West standard errors are reported in parentheses. The *F*-Test is a test of the joint significance of SO_2 and its interaction with the wind variable. Its *p*-value is reported in brackets.