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Volcanic air pollution over the Island of Hawai'i: Emissions, dispersal, and composition. Association with respiratory symptoms and lung function in Hawai'i Island school children

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ABSTRACT

Background: Kilauea Volcano on the Island of Hawai'i has erupted continuously since 1983, releasing approximately 300–12000 metric tons per day of sulfur dioxide (SO_2). SO_2 interacts with water vapor to produce an acidic haze known locally as "vog". The combination of wind speed and direction, inversion layer height, and local terrain lead to heterogeneous and variable distribution of vog over the island, allowing study of respiratory effects associated with chronic vog exposure.
Objectives: We characterized the distribution and composition of vog over the Island of Hawai'i, and tested the hypotheses that chronic vog exposure (SO_2 and acid) is associated with increased asthma prevalence, respiratory symptoms, and reduced pulmonary function in Hawai'i Island schoolchildren.
Methods: We compiled data of volcanic emissions, wind speed, and wind direction over Hawai'i Island since 1992. Community-based researchers then measured 2- to 4-week integrated concentrations of SO_2 and fine particulate mass and acidity in 4 exposure zones, from 2002 to 2005, when volcanic SO_2 emissions averaged 1600 metric tons per day. Concurrently, community researchers recruited schoolchildren in the 4th and 5th grades of 25 schools in the 4 vog exposure zones, to assess determinants of lung health, respiratory symptoms, and asthma prevalence.
Results: Environmental data suggested 4 different vog exposure zones with SO_2, PM2.5, and particulate acid concentrations (mean ± s.d.) as follows: 1) Low (0.3 ± 0.2 ppb, 2.5 ± 1.2 μg/m^3, 0.6 ± 1.1 nmol H+/m^3), 2) Intermittent (1.6 ± 1.8 ppb, 2.8 ± 1.5 μg/m^3, 4.0 ± 6.6 nmol H+/m^3), 3) Frequent (10.1 ± 5.2 ppb, 4.8 ± 1.9 μg/m^3, 4.3 ± 6.7 nmol H+/m^3), and 4) Acid (1.2 ± 0.4 ppb, 7.2 ± 2.3 μg/m^3, 25.3 ± 17.9 nmol H+/m^3). Participants (1957) in the 4 zones differed in race, prematurity, maternal smoking during pregnancy, environmental tobacco smoke exposure, presence of mold in the home, and physician-diagnosed asthma. Multivariable analysis showed an association between Acid vog exposure and cough and strongly suggested an association with FEV1/FVC <0.8, but not with diagnosis of asthma, or chronic persistent wheeze or bronchitis in the last 12 months. Conclusions: Hawai'i Island's volcanic air pollution can be very acidic, but contains few co-contaminants originating from anthropogenic sources of air pollution. Chronic exposure to acid vog is associated with increased cough and possibly with reduced FEV1/FVC, but not with asthma or bronchitis. Further study is needed to better understand how volcanic air pollution interacts with host and environmental factors to affect respiratory symptoms, lung function, and lung growth, and to determine acute effects of episodes of increased emissions.

1. Introduction

Kilauea is one of 3 active volcanoes on the Island of Hawai'i and one of the most active volcanoes on Earth (Holcomb et al., 1987). Since the onset of eruption in 1983, it has released at least 300 metric tons of sulfur dioxide (SO_2) per day and as much as 30,000 tons per day during

Abbreviations: EPA, Environmental Protection Agency; $PM_{2.5}$, particulate matter ≤2.5 μm in diameter; SO_2, sulfur dioxide gas; SO_4, sulfate; FEV_1, Forced Expiratory Volume in 1 s; FVC, Forced Vital Capacity.

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vigorous eruptive activity, from Pu'u O'o vent on the east rift zone on the volcano's flank and Halema'uma'u Crater at the volcano's summit (Elias and Sutton, 1998). Even during non-eruptive periods prior to 1983, Kilauea's SO_2 emissions of 50,000–100,000 tons per year were 1000 times greater than the United States Environmental Protection Agency's (EPA's) definition of a major pollution source. During active eruption, Kilauea's output can exceed 2 million metric tons (2 Tg) per year.

In the presence of sunlight, SO_2 and other volcanic gases react chemically with oxygen, water vapor, and dust to yield fine, respirable particles comprised mainly of sulfuric acid and other sulfate species (SO_x). The conversion proceeds with a half-life of approximately 6 h, resulting in a haze of SO_2, acid, and other particles known locally as vog (Clarke and Porter, 1991). Vog is trapped under an inversion layer that is usually 1500–2000 m high and is carried from its source by prevailing trade winds from the northeast, around the 4169-m summit of Mauna Loa and into the seaside towns in the lee of the mountain (Fig. 1) (Chen and Nash, 1994). Here, volcanic air pollution may linger. At night, vog moves toward the ocean as cool air descends from the mountains (Fig. 1A), but is drawn back onshore during the day as air over the coast heats and rises more quickly than the air over the adjacent ocean (Fig. 1B).

During periods of low wind speed, vog can accumulate in communities near the volcanic vents. During periods of sustained winds from the south and southwest, vog may be carried to communities on the north and east sides of the island. Thus, because of local topography, Hawai'i Island communities are exposed to different concentrations and composition of volcanic air pollution, depending on the amount of volcanic emissions, the speed and direction of the wind, humidity and precipitation, and the height of the inversion layer.

Studies of the health effects of Hawai'i's volcanic air pollution are of interest not only to other communities near active volcanoes worldwide, but can also provide insights into the specific effects of individual components, such as SO_2 and SO_4, in anthropogenic air pollution produced by fossil fuel and biomass combustion. Such air pollution is a complex mixture that includes other gases, organic compounds, oxidants, and heavy metals. To date, Hawai'i Island has relatively few traffic or industrial sources of air pollution that might confound studies of health effects of vog, SO_2, and SO_4. In contrast to large-scale studies of the association between anthropogenic air pollution and respiratory symptoms and lung function (Ware et al., 1986; Dockery et al., 1996; Gauderman et al., 2004; Dimakopoulou et al., 2014), studies of health effects of volcanic air pollution have sometimes been limited by sample size and selection, or lack of concurrent measures of air quality and quantitative measures of respiratory health (Michaud, 2000; Longo and Yang, 2008; Longo et al., 2008, 2010; Chow et al., 2010; Iwasawa et al., 2015).

The unique stationary source of outdoor air pollution, and the varying distribution of vog across the island's communities allowed for performance of a large cross-sectional study that applies the design and methodology of the Children's Health and Twenty-four Cities Studies (Ware et al., 1986; Dockery et al., 1996; Gauderman et al., 2004). We present the findings of a multidisciplinary, community-based participatory research effort to investigate association between vog and respiratory symptoms, diagnosed asthma or bronchitis, and reduced lung function.

2. Materials and methods

To delineate different zones of air pollution, we compiled Kilauea Volcano SO_2 emission rates data collected by the U.S. Geological Survey (USGS, 1992–2010), and wind speed and direction at an offshore point northeast of Hawai'i Island that determines wind patterns over the island. Community-based researchers then directly measured concentrations of SO_2, fine particulate matter ($PM_{2.5}$), and fine particle acidity between 2002 and 2005 in Hawai'i Island communities within the putative vog exposure zones. Concurrently, community researchers assessed other environmental factors and the respiratory symptoms and lung function of children who attended schools in each of the zones.

2.1. SO_2 gas emissions

SO_2 gas emissions were measured regularly by vehicle-based correlation spectroscopy (COSPEC) at the summit of Kilauea between 1979 and 2003 and from Pu'u 'O'o and Kilauea's east rift zone between 1992 and 2003. This technique uses the strong absorbance of ultraviolet sunlight energy by SO_2 gas, and a cross-correlation signal processing technique, to measure the abundance of SO_2 in a pollution plume (Milan, 2008). In late 2003, USGS began to augment the traditional COSPEC measurements with data from one of the new generation of miniature spectrometer systems. These measurements are also based on the absorption of ultraviolet energy by SO_2 gas, but use the Differential Optical Absorption Spectroscopy (DOAS) method for calculating the amount of SO_2 in the volcanic plume. Because of increased emissions from the summit of Kilauea beginning in 2008, the USGS modified the analysis technique to include evaluation of ultraviolet spectra at longer

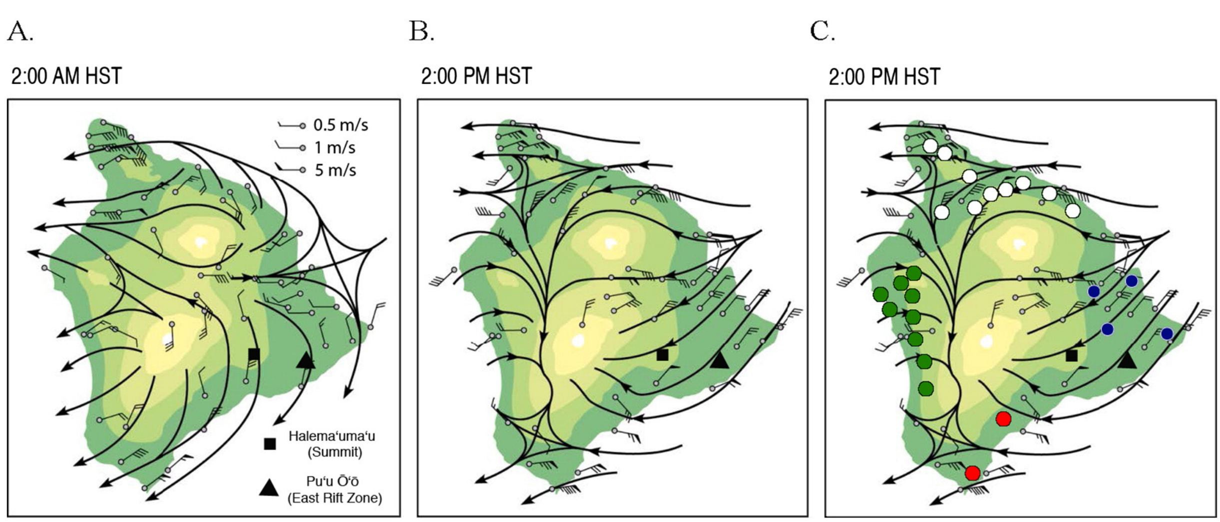

Fig. 1. Halema'uma'u (Summit) and Pu'u 'O'o (East Rift Zone) vents, trade wind pattern, July–August 1990. Colors change with every 1000 m elevation. A. Wind speed and direction during northeast winds, 2 a.m. B. Wind speed and direction during northeast winds, 2 p.m. C. Participating schools in vog exposure zones, 2002–2005: Low (white), Intermittent (blue), Frequent (red), Acid (green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)