DANIEL K. INOUYE ASIA PACIFIC CENTER FOR SECURITY STUDIES

OCCASIONAL PAPER, AUGUST 2017

Effects of Climate Change on Volcanic Emissions and Health Security in Hawaii by 2050

Canyon DV, Campbell JR

Abstract

While it is commonly understood that climate change will modify the weather, it is also predicted to influence volcanic emissions directly. It will thus have a significant effect on the geophysical properties of the planet, as well as the exposure of humans to emissions of ash, dust and aerosols. Because of local topography, communities in the Hawaiian Islands are exposed to different concentrations and compositions of volcanic air pollution, depending on the volume of volcanic emissions, the speed and direction of the wind, humidity and precipitation, and the height of the inversion layer. Health effects from vog exposure vary greatly among individuals. People with pre-existing respiratory conditions such as asthma, emphysema and bronchitis are more prone to experience the adverse effects of vog. In Hawaii, there has been an increase in the prevalence of asthma since at least 2000 that has been anecdotally attributed to vog. Investigating possible alternative causes, researchers found significant increases in sensitivity of adults to indoor aeroallergens, particularly those originating from dust mites, cockroaches, cats and dogs. Climate change may actually play an indirect causal role by encouraging human behavior that exposes people to irritating indoor environmental influences, which subjects may then speciously associate with vog exposure.

Key words
Vog, volcanic emissions, health security, climate change

Volcanic Emissions in Hawaii

Volcanic vents and fissures emit a range of materials derived from magma, gases and water (USGS 2016). Emissions may occur during violent eruptions, pyroclastic flows, and more discretely over time as ash, dust and aerosols. The consequent effects on humans range from immediate and dramatic contact to passive exposure at great distances. While it is commonly understood that climate change will modify the weather, it is also predicted to influence volcanic emissions directly (Compton et al 2015). It will thus have a significant effect on the geophysical properties of the planet and exposure of all organisms to emissions of ash, dust and aerosols.

Volcanic gas emissions are mainly composed of water vapor (H_2O, 37.1%), carbon dioxide (CO_2, 48.9%), sulfur dioxide (SO_2, 11.8%) and fine particulate matter ($PM_{2.5}$) (Symonds et al 1994; Sutton et al 1997) (Table 1). Other gases released by volcanoes include carbon monoxide (CO), hydrogen sulfide (H_2S), carbonyl sulfide (COS), carbon disulfide (CS_2), hydrogen chloride (HCl), hydrogen (H_2), methane (CH_4), hydrogen fluoride (HF), boron, hydrogen bromide (HBr), mercury (Hg) vapor, hydrogen (H), helium (He), nitrogen dioxide (NO_2), carbon disulfide (CS_2), methane, ammonia, radon, other organic compounds, and even gold (Cadle 1980; Weinstein et al 2013).

Mt Kilauea, located on Hawaii Island, is one of the most active volcanoes on Earth (Holcomb et al., 1987). Since recent eruption began in 1983, the Pu'u O'o vent on the east rift zone of the volcano and Halema'uma'u Crater at the volcano's summit have released over 300 mt of SO_2 daily rising to over 30,000 mt per day during vigorous activity (Elias et al 1998). Even during non-eruptive periods prior to 1983, Kilauea's SO_2 emissions ranged from 50,000 to 100,000 mt annually, which was a thousand times greater than the United States Environmental Protection Agency's (EPA's) definition of a major pollution source. Kilauea also emits about 270 tons of mercury annually and is a source of mercury on Oahu, 320 km away (Siegel and Siegel, 1987).

Table 1: Typical composition of volcanic gases at vents (Cadle 1980; Symonds et al 1988, 1994; Chin and Davis 1993)

SPECIES	%/VOL	TG/YEAR
H_2O	50-90	n/a
CO_2	1-40	75
SO_2	1-25	1.5-50
H_2S	1-10	1-2.8
COS	10^{-4}-10^{-2}	0.006-0.1
CS_2	10^{-4}-10^{-2}	0.007-0.096
HCL	1-10	0.4-11
HBR	n/a	0.008-0.1
HF	$<10^{-3}$	0.06-6

Four categories of gaseous substances are produced by volcanic activity (Kizer 1984):

1. Gases and vapors: The gaseous state of elements that normally exist as liquids or solids
2. Aerosols: Droplets or particles suspended in a gaseous medium
3. Fumes: Volatile aerosols from molten materials (<0.1 μm)
4. Smoke: Combusted volatile gases and particles (<0.5 μm)

Vog is a familiar term used in Hawaii to describe the hazy conditions caused by volcanic emissions (Watanabe 2011). The word 'vog' was coined in the middle to late 20th Century and derives from the words, 'volcanic' and 'smog'. Vog refers to the mixture of volcanic gases and aerosols, and very small particles, primarily sulfur compounds, that are emitted into the air where they react with water vapor to form a haze. When vog from the Kilauea volcano is trapped in the boundary layer in the atmosphere beneath the trade wind inversion, humans are exposed and adverse health effects have been observed for local populations (Sutton et al 1997; Longo 2013). Vog dispersion is primarily affected by local wind patterns and vog concentration is a function of the volcanic gas emission rate.

Sulfur dioxide gas is a severe irritant of the eyes, mucous membranes and skin (CDC 1978) and the SO_2 concentration in vog is highest near the volcano vents and fissures (e.g. Halema'uma'u and Pu'u 'O'o). SO_2 levels reduce at greater distances from the source due to atmospheric dilution. For example, although vog haze may be heavy on the western side of the island of Hawaii, the SO_2 levels are typically very low due to the distance away from the source at Kīlauea. Consequently, impacts of small acidic particulates, to which SO_2 has bonded, are of greater concern than SO_2 gas in western Hawaii. In communities nearer to Kilauea, SO_2 vog emissions may be a greater concern than particulates.

Wind patterns

Over the Hawaiian Islands, northeasterly trade winds occur approximately eighty percent of the year and are most persistent during the summer months when they blow 85 -95% of the days (Kodama and Businger 1998). Trade winds cause vog dispersion patterns to drift southwesterly from the Kilauea vent onto the south Kona region and along the Kona coast (Porter and Businger 2000). During the day, onshore sea breezes carry vog into the topographic saddle between Mauna Loa and Hualalai, and at night, offshore sea breezes carry vog back down the coast (Sutton et al 1997). This diurnal sea breeze pattern causes the vog to accumulate on the west-southwestern region of the island. In contrast, when Kona winds (southwesterly) are present, the majority of the vog is concentrated on the east side of Hawaii Island (USGS 1997). During the winter, as cold fronts approach, western Kona winds typically blow the vog back over the Hawaiian Islands, and cause vog conditions to persist over all the islands for days (Porter and Businger 2000). On Oʻahu, more than 300 km northwest of the Island of Hawaiʻi, Kona winds were commonly described as bringing rain and hazy conditions (Lyons 1899).

Normally, communities downwind from the volcano vents experience twice as much exposure to vog as compared to other communities, due to their geographic location relative to the volcanic vent and the island's wind patterns (Longo 2013). Ambient air SO_2 concentration data from 1987-1992 revealed that SO_2 concentrations are highest under very mild winds (0-2 m/s) whether the prevailing wind is blowing from the east or southwest (Kona winds) (Sutton et al 1994).

More recent studies have shown that over the past 37 years (1973-2009), northeasterly trade winds have been decreasing in both frequency and intensity, while easterly trade winds have been increasing in frequency and intensity, suggesting a shifting of prevailing winds over the Hawaiian Islands (Garza et al 2012). Hawaii's prevailing trade winds are governed by the subtropical ridge, a component of the global air-circulation patterns, which is in turn is a function of the difference in temperature gradients between the earth's equator and poles (Hazlett 2011).

SO_2 emissions

SO_2 emission rates from Kilauea Volcano have been measured on a regular basis since 1979 (Elias and Sutton 2012). Measurements at the Hawaii Volcanoes National Park often reveal average SO_2 concentrations exceeding 290 ppb in a single day and concentrations up to 1300 ppb in a single hour, far exceeding the Environmental Protection Act accepted health standard of 44 ppb (125μg/m^3) of ambient SO_2 over a 24-hour period (Hollingshead et al 2002; EPA 2008). In early 2008, when Kilauea's activity increased due to an additional eruption vent at the volcano's summit crater, SO_2 exposure in downwind communities increased threefold and averaged 75 ppb/day

(Longo 2013). Another study revealed a long-term increasing trend in the annual mean sulfate ion concentration in Hawaii between 2000-2010 (Hand et al 2012).

Effects of Vog on Health Security

Because of local topography, communities in the Hawaiian Islands are exposed to different concentrations and compositions of volcanic air pollution, depending on the volume of volcanic emissions, the speed and direction of the wind, humidity and precipitation, and the height of the inversion layer.

Although all Hawaiian Islands occasionally see vog in the air, especially during westerly Kona Winds, the Hawaii State Department of Health believes that residents of islands other than Hawaii Island are not at risk for exposure to harmful SO^2 levels from Kilauea volcano emissions because the vog is diluted as it moves across the ocean channels (HSDH 2008).

Health effects from vog exposure vary greatly among individuals. People with pre-existing respiratory conditions such as asthma, emphysema and bronchitis are more prone to experience the adverse effects of vog. These include: headaches, breathing difficulties, increased susceptibility to respiratory ailments, watery eyes, and sore throat (HSDH 2008).

People with asthma who are physically active outdoors are most likely to experience the health effects of SO_2. The main effect, even with a short exposure, is a narrowing of the airways (called bronchoconstriction). This may cause wheezing, chest tightness, and shortness of breath.

SO_2 is a colorless gas that can affect the respiratory system and irritate the eyes and skin. Inhalation of SO_2 causes inflammation of the respiratory tract resulting in coughing, mucus secretion, exacerbation of asthma and chronic bronchitis, and can make people more prone to infections of the respiratory tract (Longo 2013). The World Health Organization recommends an exposure to concentrations of no greater than 7.6 ppb (20µg/m^3) over 24-hour mean (WHO 2014). A concentration of 6-12 ppm, 20 ppm, and 10,000 ppm can cause immediate irritation of the nose and throat, eye irritation, and irritation on moist skin, respectively (USGS 2016). Studies on animal models show prolonged exposure to concentrations in excess of 10 ppm can cause damage to the epithelium of the airways, similar to those seen in patients with chronic bronchitis (WHO 2005). Exposures to high concentrations (300 ppm) demonstrate slowing of ciliary transport of mucus, an important mechanism in preventing pulmonary infections.

The Kilauea Volcano adult health study revealed significant associations of exposure to vog and adverse health effects including increased self-reported cough, phlegm, rhinorrhea, sore or dry throat, sinus congestion, wheezing, eye irritation, and sinus congestion (Longo et al 2009). Exposure to vog was also associated with increased mean pulse rate, increased mean systolic blood pressure, and increased respiratory rate. Daily SO_2 exposure during the 2004 survey averaged 25 ppb.

A subsequent Kilauea Volcano adult health study in 2012, conducted when the average SO_2 daily exposure was 49 ppb, revealed an increased prevalence of eye irritation, respiratory symptoms (daily cough, phlegm, dry cough, and shortness of breath without exertion), hypertension and a new finding on decreased oxygen saturation (likely related to exposure to $PM_{2.5}$) and skin irritation compared to the initial 2004 survey (Longo 2013). Furthermore, several vog-sensitive populations were identified including asthmatic individuals, respiratory and cardiac compromised individuals, children and adolescents, and SO_2-sensitive individuals, revealing a higher burden of vog-related disease in such vulnerable populations (Longo et al 2010).

At high concentrations, the acute systemic effects of SO_2 include: upper airway irritation, pneumonitis, pulmonary edema (fluid in the lungs), and acute respiratory distress syndrome (ARDS) (Weinstein et al 2013). Acute symptoms increase as SO_2 levels and/or breathing rates increase and lung function typically returns to normal within an hour post exposure. Chronic or recurrent systemic effects include recurrent or prolonged exacerbation of respiratory disease, bronchiolitis obliterans, which causes irreversible narrowing of bronchi and lung fibrosis. Hydrogen sulfide (H_2S) causes cough, shortness of breath and pulmonary edema.

At high frequency inhalation, the acute systemic effects of fluoride and chlorine gases include coughing, laryngeal spasm, bronchitis, pneumonitis, pulmonary edema, and ARDS (Weinstein et al 2013). Long-term exposure results in permanent lung injury. Acute carbon monoxide symptoms include headache, impaired dexterity, asphyxia, collapse and coma. Long term exposure causes permanent neurological impairment. Acute mercury vapor symptoms include bronchitis, pneumonitis, pulmonary edema, mercury intoxication and neurotoxicity. Overexposure to any of these gases may cause death.

Small particulate matter with diameters of less than 2.5μm ($PM_{2.5}$) are small enough to penetrate the respiratory system causing respiratory and cardiovascular morbidity. This impedes the lung's ability to respond against bacterial infections, increases the risk of stroke and myocardial infarction, vascular dysfunction, progression of atherosclerosis and developing lung cancer (WHO 2005). It is estimated that approximately 3% of cardiopulmonary and 5% of lung cancer deaths are attributable to particulates globally. The guideline for $PM_{2.5}$ is $<25\mu/m^3$ over a 24-hour period (WHO 2014). The coexistence of PM and SO_2 exacerbates health risks when SO_2 gets adsorbed onto the PM's surface forming sulfuric acid, which then can be delivered to the distal portion of lung causing damage to the cell lining of the lung (WHO 2005).

A recent study on volcanic emissions and respiratory symptoms in school children on Hawaii Island produced contrary results (Tam et al 2016). Four exposure zones were created: low, intermittent, frequent and acid. When physician diagnosed asthma and persistent wheeze were examined over a 12-month period, people in the intermittent zone had more illness than those in low zones, but those in frequent and acid zones had the lowest illness. The authors attributed the acid result to unknown protective factors, but it is more likely that less susceptible people chose to live in areas worst affected by volcanic emissions. It was concluded that chronic exposure to strongly acid particulates was associated with cough and a trend to reduced lung function, but not with diagnosis of asthma or persistent wheeze or bronchitis.

Effects of Forecasted Climate Changes on Vog

Anthropogenic effects on global warming are expected to lead to various changes in the climate including changes in temperature, winds, and rainfall. The General Circulation Model (GCM) is often used to project global climate change (IPCC 2013). While extensive climate projections have been made for several Pacific Island countries based on downscaling from an ensemble of models (ABoM and CSIRO 2011), the direct application of GCM to Hawaii may be reduced due to the relatively small size and unique topography of the Hawaiian Island chain.

Changes in temperature

In general, mean surface temperature and sea surface temperature are expected to rise in Hawaii. The mean global surface temperature is projected to increase between 0.4 and 2.7°C by 2045-2065 and increase between 0.3-4.8°C by 2081-2100 (IPCC 2014).

Hawaii experiences unique region-specific climate change effects, including an accelerated decrease in the difference between daily daytime high and nighttime low temperatures, resulting in a warmer environment overall (Eversole and Andrews 2012). The rate of increasing mean surface temperature has risen to over 0.17°C per decade in the last 40 years and is projected to continue warming, with a net increase of 0.83-1.11°C by the year 2035 and an increase of 2.50-2.78°C by the year 2085 (Safeeq et al 2013; Keener et al 2012). Sea-surface temperatures are also projected to increase between 0.6°C and 0.72°C by 2030, and 1.3°C and 2.7°C in the Pacific by 2100 (ABoM and CSIRO 2011).

Increased concentration of vog over the island may in turn increase trade wind inversion frequency and strength. An inversion is a layer in the atmosphere in which temperature increases with elevation. In Hawaii, this commonly occurs at 1800 to 2400 m. Increased temperature is consistent with increased frequency of trade wind inversion days from less than 80% to around 90% since the 1990s and a decrease in trade wind frequency since the late 1970s (NOAA 2013). SO_2 condenses rapidly in the stratosphere and forms sulfate aerosols that increase the reflection of radiation from the Sun back into space. This slightly cools the Earth's lower atmosphere while warming the stratosphere. The increasing difference in temperature above and below the inversion layer can strengthen temperature inversions, making it even more difficult for trade winds to penetrate the inversion layer. The presence of the trade wind inversion influences Hawaiian climate by limiting cloud height and causing flat cloud decks to form, limiting the amount of rainfall, reducing relative humidity, and producing dry air and clear skies at the highest elevations.

If the height or frequency of the inversion changes due to warming, significant hydrological and ecological changes can be expected (Loope and Giambelluca 1998; Taylor and Kumar 2016). Rising temperatures may result in lower trade wind inversion base height and an increase in trade wind inversion days causing vog to be trapped closer to the ground for longer durations resulting in higher concentration of vog over the island. Historically in Hawaii, both upward and downward trends in base height have been observed and the results are weak and inconsistent (Cao et al 2007).

It was recently confirmed that the worldwide redeployment of water due to global warming and melting of glaciers changes the distribution of pressure on continents, which reduces or increases pressure on the ocean floor crust and can produce significant geophysical responses in the form of earthquakes and volcanic eruptions (Compton et al 2015). Melting of the ice caps may thus increase volcanic eruptions in Hawaii with subsequent effects on volcanic gas emission rates. However, models of the Pacific Ocean suggest that Hawaiʻi will experience minimal sea level rise by 2050 with the bulk of the average 12 inch rise being experienced in the western Pacific (SOEST 2008).

Changes in wind

Northeast trade winds are expected to decrease in frequency and intensity, while east trade winds are expected to increase in both frequency and intensity. Average wind speed in Hawaii is expected to decrease. Garza et al (2012) observed that changes in frequency and intensity of prevailing wind in the Hawaiian Islands within the past 30 years (1973-2009) had resulted in decreasing northeast trade wind frequency and increased east trade wind frequency.

Weakening northeast trade winds are thought to be caused by the reduction of the strength of mean tropical atmospheric circulation, which is driven by the convective overturning of air across the Pacific Ocean where air convection occurs to the west and subsides to the east. This is known as the Walker circulation and climate models predict it to weaken in response to sea surface air warming (Vecchi et al 2006). As the sea surface air warms, water vapor concentration increases near the sea surface, but the rate of precipitation governed by convection increases at a slower rate. As the atmosphere absorbs moisture faster than it can precipitate, air circulation slows down to remain energetically balanced and slower trade winds result. Winds across the tropical Pacific have weakened by 3.5% since 1860 and Vecchi et al expect them to continue to weaken a further 10% by 2100. Mean wind speed in the Hawaiian Islands is expected to decrease by 0.25 to 0.50 m/s by 2035 in the high emission scenario (Storlazzi et al 2015) and weaker trade winds are associated with lower inversion base heights (Grindinger 1992).

While the rate of vog production in Hawaii is natural, unavoidable and unmodifiable, weather-related climate changes do impact on vog distribution. Decreasing trade winds have already been reported and further decreases are forecasted (Chu and Chen 2005). When the trade winds are light or absent or when winds blow from the south, much of the vog stays on the eastern side of the Hawaii Island, where it sometimes moves into the city of Hilo (Sutton et al 1997). Reduced trade wind frequency and speed is expected to result in the accumulation of vog over Hawaii Island. The observed shift of prevailing winds from northeast to east may result in changes to the distribution of vog exposure.

Changes in Precipitation

Rainfall in Hawaii varies depending on the geographic location due to island topography. The numerous deep valleys and steep ridges contribute to orographic precipitation driven by trade winds and present a challenge to the accurate projection of rainfall. A general downward trend in annual precipitation has been documented over the past century in the Hawaiian Islands (Eversole and Andrews 2014). Rainfall in Hawaii has decreased about 15% over the past 20 years and is projected to decrease a further 5-10% in the wet season, but increase 5% in the dry season by the end of the 21st Century (Timm and Diaz 2009). This decrease in rainfall is consistent with an increase in trade wind inversion days, which decrease convective rain (Hamilton 2014). In contrast, rain intensity and downpours increased by approximately 12% in Hawaii between 1958 and 2007 and are projected to increase in frequency through 2040 (Fletcher 2010; Norton et al 2011). Furthermore, vog plumes mixing with clouds can cause an overabundance of vog particles resulting in water droplets that are too small to fall as rain thus decreasing rainfall even further (Giambelluca et al 2013).

Changes in Health Security

In Hawaii, there has been an increase in the prevalence of asthma since at least 2000 that has been anecdotally attributed to vog. Baker and Horiuchi (2014) investigated and found that the increase from 8.9% to 14.1% was limited to adults. Children did not experience the same increase. Since this did not suggest a link to vog which would presumably affect all populations equally, Min et al (2014) investigated possible alternative causes. They found significant increases in sensitivity to indoor aeroallergens in adults, but no commensurate increase in allergies caused by grasses, weeds and molds. This change was attributed to an increase in sensitivity to household aeroallergens originating from dust mites, cockroaches, cats and dogs.

In developed nations, warm humid regions like Hawaii can experience acute effects of rising temperatures resulting from global climate change, which encourages people to work and live more in closed, air-conditioned environments. In addition, daily television and radio weather reports in Hawaii alert viewers to recurring vog conditions, which are then typically followed by recommendations for people to remain inside their homes and minimize outdoor activities. On vog-alert days, if people experience asthmatic symptoms, they may attribute them logically and causally to elevated vog exposure. However a confounding factor is that by remaining indoors, people may experience increased exposure to indoor allergen sources such as mold and cockroaches. Both of these allergen sources are common in warm, humid climates like Hawaii and both can induce severe, acute symptomology. This in turn could lead to specious perceived associations of asthma symptoms with vog concentrations, viewed as causality by lay populations. However correlation is not causality, a fact that complicates similar assessments by environmental health professionals in "sick-building syndrome" (Joshi, 2008). Allergic responses to indoor allergens could also be exacerbated in atopic individuals in Hawaii who were made more susceptible according to the “Hygiene Theory” of allergy development. (Strachan, 2000).

Airborne volcanic gases and fine particulates in Hawaii can be high and by 2050, an overall mild increase in vog exposure due changing wind patterns, temperature and precipitation is probable. However, localized effects are likely to be more noticeable. In some areas already exposed, the changes may further exacerbate current detrimental health effects, such as eye irritation, respiratory symptoms, hypertension, decreased oxygen saturation and skin irritation. Other exposed areas may be spared and experience relief. It is unlikely that the distribution of vog will change to the extent that the entire state will be affected.

Kauahikaua and Tilling (2014) report that historically, reports of volcanic-gas health effects away from Kīlauea have been infrequent. However, during heavy volcanic activity at Mauna Loa, reports of gasses were common across all Hawaiian Islands. This was thought to be due to massive volumes of gas being released in short bursts by discrete eruptions from vents above the inversion layer. Such high altitude gas emissions would be blown to the northeast until falling below the inversion layer when they would be blown back to the islands by the trade winds. A shift to more easterly trade winds may thus distribute such high altitude eruption emissions more effectively over the island chain with subsequent increases in vog exposure.

As the study by Tam et al (2016) indicated, vog exposure and its effects on the health of populations will be moderated by the migration of vulnerable subpopulations, such as asthmatic individuals, respiratory and cardiac compromised individuals and SO_2-sensitive individuals, to other areas with less exposure. Also, in critically assessing causality in perceptions of vog-related asthma symptoms, published reports comparing children and adults have produced counter-intuitive findings, raising the possibility of unidentified confounding variables. Climate change may actually play an indirect causal role by encouraging human behavior that exposes people to irritating indoor environmental influences, which subjects may then speciously associate with vog exposure.

The mild increase in vog forecasted over the next few decades should thus not be an issue that would be of especially high concern to policy makers and the public. It may be more effective to focus attention on reducing indoor allergens and improving building safety to address changes in behavior and increasing indoor lifestyles due to a warming climate. Policy makers should provide adequate health promotion information and educate the public so that they can make well-informed decisions to mitigate downstream health effects due to vog.

The views expressed in this article are those of the authors and do not necessarily reflect the official policy or position of the Daniel K. Inouye Asia Pacific Center for Security Studies, the Department of Defense, or the U.S. Government.

References

1. ABoM and CSIRO. 2011. Climate Change in the Pacific: Scientific Assessment and New Research. Australian Bureau of Meteorology and Commonwealth Scientific and Industrial Research Organisation, Vol 1: Regional Overview and Vol 2: Country Reports, http://www.cawcr.gov.au/projects/PCCSP/, accessed Jul 2016.
2. Baker K, Horiuchi BY. Baseline estimates chronic disease Hawaii health survey, HHS mortality 2011-2013 selected ICD10 codes. Hawaii Asthma Institute, Honolulu.
3. Cadle RD. A comparison of volcanic with other fluxes of atmospheric trace gas constituents: Reviews of Geophysics and Space Physics, 1980;18:746-752.
4. Cao G, Giambelluca TW, Stevens DE, Schroeder TA. Inversion variability in the Hawaiian trade wind regime. Journal of Climate, 2007;20:1145-1160.
5. CDC. Occupational health guidelines for sulfur dioxide. U.S. Department of Health and Human Services, 1978, http://www.cdc.gov/niosh/docs/81-123/pdfs/0575.pdf, accessed Jul 2016.

6. Chin M, Davis DD. Global sources and sinks of COS and CS_2 and their distributions. Global Biochem. Cycles, 1993;7(2):321–337.
7. Chu P-S, Chen H. Interannual and interdecadal rainfall variations in the Hawaiian Islands. J Clim. 2005;18:4796–813.
8. Compton K, Bennett RA, Hreinsdottir S. Climate-driven vertical acceleration of Icelandic crust measured by continuous GPS geodesy. Geophysical Research Letters 2015;42(3):743-750.
9. Elias T, Sutton AJ, Stokes JB, Casadevall TJ. Sulfur dioxide emission rates of Kīlauea Volcano, Hawaii, 1979-1997: U.S. Geological Survey Open-File Report, 1998;98-462.
10. . Elias T, Sutton AJ. Sulfur dioxide emission rates from Kilauea Volcano, Hawaii, 2007–2010: U.S. Geological Survey Open-File Report, 2012;2012–1107.
11. EPA. Air quality standards, 2008. http://www.epa.ie/air/quality/standards/#.VOVWnPnF-So, accessed Jul 2016.
12. Eversole D, Andrews A. Climate change impacts in Hawaii: a summary of climate change and its impacts to Hawaii's ecosystems and communities. University of Hawaii at Mänoa Sea Grant College Program, UNIHI-SEAGRANT-TT-12-04, 2014.
13. Fletcher CH. Hawaii's Changing Climate. Honolulu: Center for Island Climate Adaptation and Policy. University of Hawaii Sea Grant College Program, 2010.
14. Garza J, Chu P, Norton C, Schroeder T. Changes of the prevailing trade winds over the islands of Hawaii and the North Pacific. Journal of Geophysical Research, 2012.
15. Giambelluca TW, Chen Q, Frazier AG, Price JP, Chen Y-L, Chu P-S, Eischeid JK, Delparte DM. Online rainfall atlas of Hawaii. Bull. Amer. Meteor. Soc. 2013;94,313-316.
16. Grindinger CM. Temporal variability of the trade wind inversion: Measured with a boundary layer vertical profiler. M.S. thesis, Dept. of Meteorology, University of Hawaii at Manoa, 1992.
17. Hamilton K. Projecting Climate change in Hawaii. IPRC Climate 2014;14(1):3-11.
18. Hand J, Schichtel B, Malm W, Pitchford M. Particulate sulfate ion concentration and SO2 emission trends in the United States from the early 1990s through 2010. Atmospheric Chemistry and Physics Discussions, 2012;19311-19347.
19. Hazlett M, Climate Change Could Have Major Impacts on Wind Resources, N. AM. Windpower, Jan. 4, 2011, http://www.nawindpower.com/print.php?plugin:content.7130.
20. Holcomb RT. 1987. Eruptive history and long-term behavior of Kilauea Volcano. Volcanism in Hawaii, (eds) RW Decker, TL Wright, PH Stauffer. US Geol. Surv. Prof. Pap. 1987;1(1350):261-350.
21. Hollingshead A, Businger S, Draxler R, Porter J, Stevens D. Dispersion modeling of the Kilauea plume. Bound-Layer Meteor, 2002;108(1):121-144.
22. HSDH. Frequently Asked Questions and Answers on Vog and Volcanic Emissions from Kilauea. Hawaii State Department of Health, Honolulu, 2008.
23. IPCC. Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, RK Pachauri, LA Meyer (eds.). IPCC, Geneva, Switzerland, 2014.
24. IPCC. General circulation model. http://www.ipcc-data.org/guidelines/pages/gcm_guide.html, accessed Jul 2016.

25. Joshi, S. (2008) The Sick Building Syndrome, Indian J Occup Environ Med. 12(2): 61–64.
26. Kauahikaua J, Tilling R. Natural hazards and risk reduction in Hawaii. Characteristics of Hawaiian volcanoes. U.S. Geological Survey Professional Paper 2014;1801.
27. Keener VW, Marra JJ, Finucane ML, Spooner D, Smith MH. Climate change and Pacific Islands: indicators and impacts. Report for The 2012 Pacific Islands Regional Climate Assessment. Washington, DC: Island Press, 2012.
28. Kizer KW Toxic inhalations. Emer Med Clin North Am, 1984;2:649-666.
29. Kodama KR, Businger S. Weather and forecasting challenges in the Pacific region of the National Weather Service. Weather and Forecasting, 1998;13:523-546.
30. Longo B, Yang W, Green J, Longo A, Harris M, Bibilone R. An indoor air quality assessment for vulnerable populations exposed to volcanic vog from Kilauea Volcano. Family & Community Health, 2010;33(1): 21-31.
31. Longo B. Adverse health effects associated with increased activity at Kīlauea Volcano: a repeated population-based survey. ISRN Public Health, 2013;ID475962:1-10.
32. Longo B. The Kilauea Volcano adult health study. Nursing Research, 2009;23-31.
33. Loope LL, Giambelluca TW. Vulnerability of island tropical montane cloud forests to climate change, with special reference to East Maui, Hawaii. Climate Change 1998;39:503–517.
34. Lyons CJ. Volcanic eruptions in Hawaii: Monthly Weather Review, 1899;27(July 29):298–299.
35. Min K, Yoshida M, Miike R, Tam E. Aeroallergen sensitivity in Hawaii: association with asthma and increased prevalence of sensitivity to indoor allergens since 1966. Hawaii Journal of Medicine & Public Health 2014;73(9, Sup. 1):9-12.
36. NOAA. Regional Climate Change and Scenarios for the U.S. National Climate Assessment. NOAA Technical Report NESDIS, 2013;142-148.
37. Norton CW, Chu P-S, Schroeder TA. Projecting changes in future heavy rainfall events for Oahu, Hawaii: a statistical downscaling approach. J. Geophys. Res. 2011;116:D17110.
38. Porter J, Businger S. Studies of the Hawaii volcano plume from satellite and models. Geoscience and Remote Sensing Symposium. 2000;4:1649-1651.
39. Safeeq M, Mair A, Fares A. Temporal and spatial trends in air temperature on the Island of Oahu, Hawaii. International Journal of Climatology, 2013;33(13):2816-2835.
40. Siegel BZ, Siegel SM. Hawaiian volcanoes and the biogeology of mercury. Volcanism in Hawaii, Vol. 1, R Decker, T Wright, P Stauffer (eds), U.S. Geological Survey, U.S. Gov't. Printing Office, 1987;1350:822–839.
41. SOEST. Sea level rise in Hawaiʻi: Hawaiʻi's changing climate, School of Ocean and Earth Science and Technology, University of Hawaiʻi, 2008. http://www.soest.hawaii.edu/coasts/sealevel accessed Aug 2017.
42. Storlazzi CD, Shope JB, Erikson LH, Hegermiller CA, Barnard PL. Future wave and wind projections for United States and United States-affiliated Pacific Islands: U.S. Geological Survey Open-File Report 2015;2015–1001.
43. Strachan, D. (2000) Family size, infection and atopy: the first decade of the hygiene hypothesis, Thorax, Suppl 1, S2-10.

44. Sutton AJ, Elias T, Hendley JW II, Stauffer PH. Volcanic air pollution -- A hazard in Hawai`i, U.S. Geological Survey Fact Sheet 1997;FS169-97.
45. Sutton AJ, Elias T, Navarette R. Volcanic gas emissions and their effects on ambient air character at Kilauea Volcano, Hawaii: U.S. Geological Survey Open-File 1994;94-569.
46. Symonds RB, Rose WI, Bluth GJS, Gerlach TM. Volcanic-gas studies: methods, results, and applications. Volatiles in magmas: reviews in mineralogy, MR Carroll, JR Holloway (eds), 1994;30:1-66.
47. Symonds RB, Rose WI, Reed MH. Contribution of Cl- and F-bearing gases to the atmosphere by volcanoes. Nature, 1988;334:415-418.
48. Tam E, Miike R, Labrenz S, Sutton AJ, Elias T, Davis J, Chen YL, Tantisira K, Dockery D, Avol E. Volcanic air pollution over the Island of Hawaii: Emissions, dispersal, and composition. Association with respiratory symptoms and lung function in Hawaii Island school children. Environmental International 2016;92-93:543-552.
49. Taylor S, Kumar L. Global climate change impacts on Pacific Islands terrestrial biodiversity: a review. Tropical Conservation Science 2016;9(1):203-223.
50. Timm O, Diaz H. Synoptic-statistical approach to regional downscaling of IPCC twenty-first Century climate projections: seasonal rainfall over the Hawaiian Islands. Journal of Climate, 2009;22(16):4261-4280.
51. USGS. Increases in vog may not mean increases in volcanic activity. Jan 1, 1997. http://hvo.wr.usgs.gov/volcanowatch/archive/1997/97_06_27.html, accessed Jul 2016.
52. USGS. Volcanic gases and their effects, 2016. http://volcanoes.usgs.gov/hazards/gas/index.php, accessed Jul 2016.
53. Vecchi G, Soden B, Wittenberg A, Held I, Leetmaa A, Harrison M. Weakening of tropical pacific atmospheric circulation due to anthropogenic forcing. Nature 2006;73-76.
54. Watanabe J. Old newspaper clipping puts birth of term 'vog' in the 1960s: Honolulu Star-Advertiser, June 1, 2011. http://www.staradvertiser.com/hawaii-news/old-newspaper-clipping-puts-birth-of-term-vog-in-the-1960s/ accessed Jul 2016.
55. Weinstein P, Horwell CJ, Cook A. Volcanic emissions and health, Essentials of Medical Geology, Springer Netherlands, 2013, 217-238.
56. WHO. Air quality guideline: global update 2005. Particulate matter, ozone, nitrogen dioxide, and sulfur dioxide. http://www.euro.who.int/__data/assets/pdf_file/0005/78638/E90038.pdf?ua=1, accessed Jul 2016.
57. WHO. Ambient (outdoor) air quality and health. Jan 1, 2014. http://www.who.int/mediacentre/factsheets/fs313/en/, accessed Jul 2016.