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Perceptions of volcanic air pollution and exposure reduction practices on the Island of Hawaiʻi: Working towards socially relevant risk communication

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ABSTRACT

Kīlauea volcano, on the Island of Hawaiʻi, is one of the most active volcanoes in the world. Over the past four decades it has released large amounts of volcanic gases and aerosols which form volcanic air pollution known as ʻvogʼ. Communities downwind of Kīlauea have been chronically or episodically exposed to this potentially harmful air pollution and have raised concerns about the hazards of vog exposure. Public health and civil protection agencies have offered a range of advice, information, and mitigation strategies for living with vog. In this mixed-methods social study, we investigate the translation of official advice into practice in Island of Hawaiʻi communities and assess how risk communication could be improved by considering public input, preferences, and community relevance. Given the paucity of information on the long-term effects of chronic vog exposure, assessing the effectiveness of public health and risk communication is vital.

In 2015, through questionnaire surveys (n = 143), four focus groups and several stakeholder meetings, we assessed whether, and how, residents accessed intervention advice, if it was relevant and useful, how they acted on it and how they would like to receive advice and urgent exposure warnings in the future. We also investigated local knowledge and self-developed interventions and documented the perceived risks of vog exposure, including symptoms that people attribute to vog.

Most participants (83%) perceived that vog caused health symptoms such as exacerbation of asthma, itchy eyes, and blocked nose and 62% thought it was harmful to their long-term health. A third of participants had considered relocating to avoid the vog yet, despite this, most people took no action to reduce vog exposure. Participants reported that the official advice was difficult to follow given their living situation or lifestyle. Some participants viewed the agency advice as inconsistent, irrelevant, or out of date. Participants preferred to receive advice and air quality alerts via a variety of media, depending on factors such as their access to internet, cell phone, and radio reception.

The study findings led to a collaboration with federal and state health, land management, educational, science, and civil protection agencies to improve and standardize health advisory messaging, to make it more relevant to Island of Hawaiʻi communities and environment. New print-

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able and web-based communication products were developed, which included local knowledge of effective protective actions/symptom reduction strategies. An interagency 'Vog Dashboard' was also introduced to consolidate vog knowledge, including sources of air quality data, vog forecasts, and advice on vog environmental, agricultural, and health impacts. This dashboard was recommended as a primary site for advice by international media outlets in 2018 and was heavily used during the 2018 Kīlauea and 2022 Mauna Loa eruption crises.

1. Introduction

Human exposure to particulate matter (PM) and gaseous pollutants can cause adverse health effects. Acute and chronic exposure to PM < 2.5 μm diameter ($PM_{2.5}$) increases both pulmonary and cardiovascular mortality and morbidity [1]. Asthmatics are particularly sensitive to sulfur dioxide (SO_2) gas, with exposure to even low concentrations causing airway constriction and exacerbation of asthmatic symptoms [2]. Globally, most exposures to volcanic particles and gases are acute, lasting days to months. However, on the Island of Hawai'i, emissions of SO_2 from the active vents at Kīlauea Volcano have impacted downwind communities for several decades.

Prior to 1983, when an era of continuous volcanic activity at Kīlauea began, written observations of volcanic air pollution or haze, known as 'vog', were uncommon, and public complaints were rare [3] although vog was a problem during the 1969–74 eruption of the Maunaulu vent [4]. However, since 1983, populations downwind of the eruption have been chronically or episodically exposed to airborne volcanic gases (mainly SO_2) and sulfate aerosol. Vog exposure has resulted in reports of headaches, lung irritation, and breathing difficulty (e.g., Refs. [5,6]); the long-term effects of vog exposure are still being investigated. Over the years, public health and civil protection agencies have offered a range of advice and resources to the public to help mitigate the effects of living with vog.

The public understanding of volcanic hazards, and their potential impact to health, will inform how and whether people take actions to reduce their risk. However, their interpretation of the risk will also be based on their own experiences, values, and cultural influences [7]. Best practice in public health and crisis risk communication includes involving the beneficiaries of the advice in its development, ensuring that their opinions are listened to, and that cultural complexities are considered [8]. Consistent messaging amongst agencies is also important, because it can enhance trust in the advice-givers, due to improved credibility and accountability, thereby increasing uptake of the protective measures (e.g., Ref. [9]).

In this mixed-methods social study, we investigated the translation of official advice on vog exposure reduction into practice in Island of Hawai'i communities. We assessed whether, and how, residents accessed intervention advice, if it was relevant and useful, how they acted on it, and how they would like to receive advice and urgent exposure warnings in the future. We also investigated local knowledge and self-developed interventions and documented the perceived risks of vog exposure, including symptoms that people attribute to vog. Using the observed knowledge and behaviours, we worked in collaboration with local health and civil protection agencies to improve health advisory messaging and make it more relevant to Island of Hawai'i communities and environment.

Our research adopted an exploratory approach to enable us to learn more about this under-researched and poorly understood topic. An exploratory rather than confirmatory hypothesis testing approach lends itself to the emergence of new ideas and understandings of the phenomena under study [10].

2. Background

2.1. Eruption history and gas release

The amount of SO_2 gas released during a Hawaiian eruption scales with the eruption size/volume [11]. An era of nearly continuous activity began at Kīlauea in 1983, with the onset of the Pu'u'ō'ō middle East Rift Zone eruption (MERZ) [12]. From 2008 to 2018, in addition to the ERZ activity, the summit of the volcano was also in continuous eruption, adding to the already substantial gas release from the volcano. From January 1983–May 2018, Kīlauea emitted between 500 and >10,000 tonnes of SO_2 per day (t/d) [13–15]. The summit 2008–2017 long term average SO_2 emission rate was ~5000 t/d [13,14].

The addition of the summit degassing source in 2008, at Halema'uma'u vent, not only increased the amount of SO_2 released by several fold but, because of the vent location, the impact of the emissions also increased. The summit plume hugged the flank of Mauna Loa Volcano as it travelled overland directly toward downwind communities (Fig. 1), whereas the Pu'u'ō'ō (MERZ) plume mainly travelled along the coast as it wrapped around the island [16].

In 2008, when gas emissions were extremely high, the Hawaii County Civil Defense Agency advised evacuation of impacted communities near the summit of Kīlauea [17], but public response, the short duration, and rapidly changing location of high concentrations of SO_2 led to a change to 'shelter-in-place' recommendations. Closure and mandatory evacuations of Hawai'i Volcanoes National Park occurred in April 2008, with subsequent intermittent park closures during periods of poor air quality.

In 2018, a new flank eruption began on the volcano's lower East Rift Zone (LERZ) in the Puna district, bringing an end to the ongoing summit and MERZ vent activity. This was the most destructive volcanic event in the past 200 years in Hawai'i, with over 700 structures destroyed [18] and 35.5 km^2 of land covered by lava [19]. During the 4-month LERZ event, emissions increased to as much as 200,000 t/d through June and early July 2018 [18].

The MERZ and LERZ flank eruptions had frequent lava flows that entered the ocean. These flows reacted with seawater to create large steam plumes laden with hydrochloric acid, volcanic glass, and metal particles that created a significant local hazard [15,20–22].

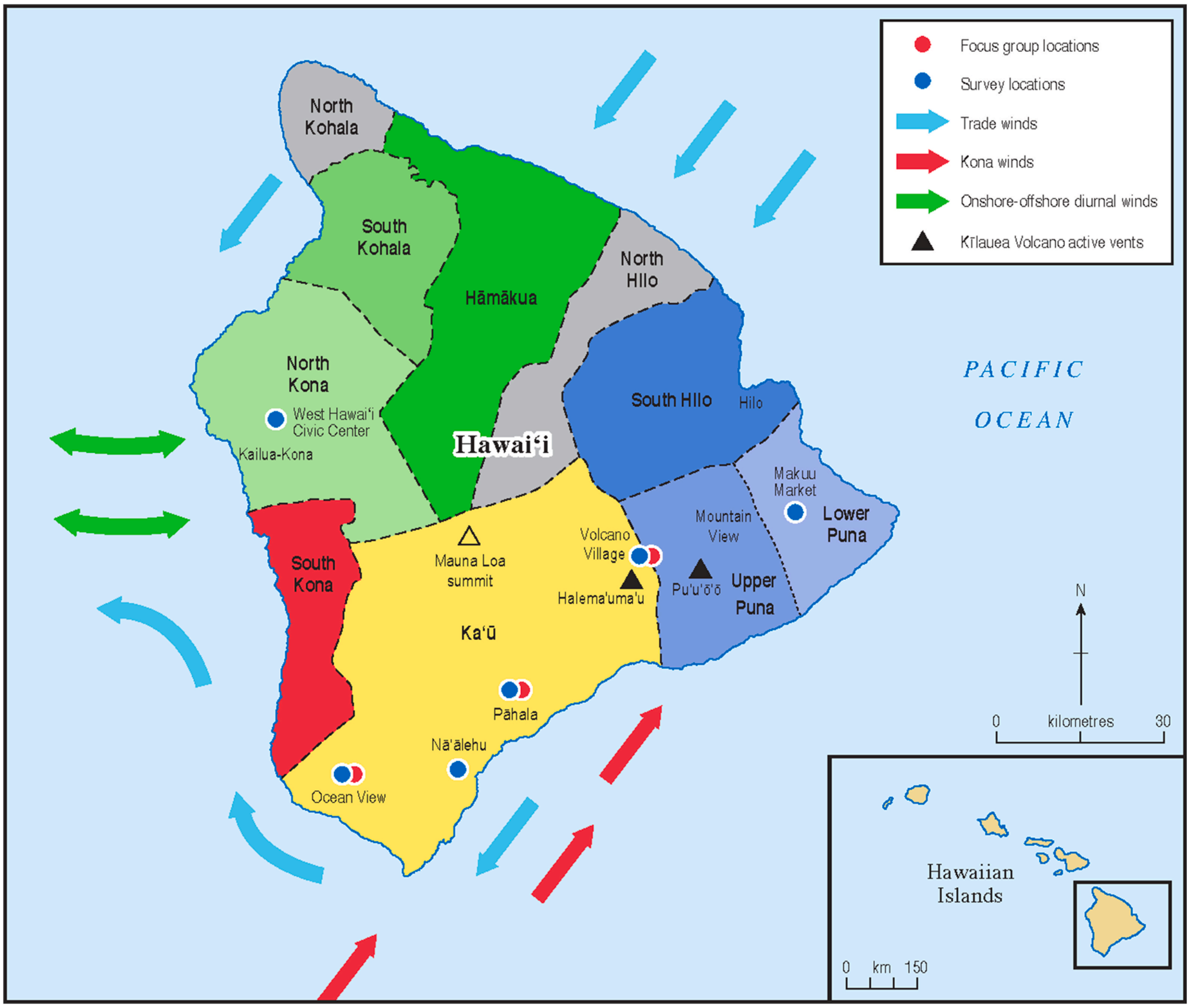

Fig. 1. Geographical divisions, focus group and survey locations for this study, and generalized wind conditions. Active vent locations refer to the time of the survey in 2015.

2.2. *Vog formation, composition, concentration, and dispersion*

The gases released from Kīlauea's vents are primarily water (H_2O), carbon dioxide (CO_2), and SO_2, along with smaller amounts of other gases including hydrogen chloride and hydrogen fluoride. Small amounts of toxic metals including selenium, mercury, and lead have also been documented in the Kīlauea plumes [20,23]. Water and CO_2 are key constituents of the atmosphere and do not pose a hazard at Kīlauea. CO_2 is quickly diluted in the open atmosphere and, in the current eruption era, only poses a hazard when it concentrates in near source confined spaces or underground lava tubes [15,22]. On the other hand, SO_2 can affect the human body at relatively low concentrations. Communities downwind of the emission sources during prevailing trade winds are frequently impacted by the volcanic plume, while communities in east Hawai'i and other areas of the island are intermittently affected during trade wind disruptions [24]. Over the years, communities have voiced concerns about the impact that the vog may be having on their health [16,25,26].

Air quality monitoring data collected by the Hawai'i State Department of Health (HDOH) and the National Park Service (NPS) show that SO_2 concentrations exceed U.S. Environmental Protection Agency (EPA) health standards on a regular basis. From 2010 to 2018, various Island of Hawai'i communities (Pāhala, Hawaiian Ocean View Estates (HOVE), Volcano National Park, Mountain View, and Hilo) experienced SO_2 concentrations which exceeded the EPA 1-h health standard [27] of 75 parts per billion (ppb) [28–31].

As SO_2 is transported in the atmosphere, it reacts with oxidants (e.g., oxygen), moisture, and dust in the presence of sunlight to form acidic sulfate aerosol (H_2SO_4; a type of particulate matter), and other sulfate compounds. This chemical process occurs over periods of minutes to days and forms the hazy mixture of gases and aerosols known as vog. Particulate matter (PM) concentrations in downwind communities (Kona, HOVE, and Pāhala) have exceeded the EPA $PM_{2.5}$ health standard repeatedly [28,30,32]. Since the composition of vog depends on how much time the volcanic plume has had to react in the atmosphere, in communities far from

Kīlauea's active vents, aerosols are the main component of vog; however, closer to the volcano, vog contains both aerosols and unreacted SO_2 gas [33,34].

From May to September, northeast trade winds generally blow 85–95% of the time [35] and the gaseous emissions from erupting vents are blown to the southwest of the Island of Hawai'i (Fig. 1). Offshore, near South Point, an atmospheric eddy caused by Mauna Loa Volcano forces the plume northwards and the vog becomes trapped along the Kona (west) coast by diurnal sea breezes. During winter months, trade winds are frequently absent [35] and east Hawai'i, the entire island, or even the entire State of Hawaii can be affected by vog [36]. Changes in the prevailing trade winds have been documented over the past decades [37,38], suggesting that northeast trade wind interruptions may become more common with climate change. During this study (January–March 2015), there were over 60 days with periods of interrupted trade winds at the summit of Kīlauea when winds had a southerly component (Kona winds) or were light and variable [39].

2.3. Geography and population demographics

In 2020, the population of the Island of Hawai'i was 200,629 people [40]. Over the generations, the Island of Hawai'i has attracted a diverse population, with 34.3% White, 13.0% Native Hawaiian/Pacific Islanders, 20.1% Asian, and 13.8% Hispanics/Latinos in 2020, with similar data in 2010 [40,41]. According to the 2020 census, 31.2% of people identify themselves as being from two or more races [40]. Some villages or sub-divisions tend to attract specific groups depending on their heritage (e.g., sugar cane growing areas) or modern occupations (e.g., some areas attract U.S. mainland retirees, military, scientists, or artist communities).

The majority of the population of the Island of Hawai'i lives in low to mid elevation areas, but some communities stretch up the slopes of the volcanoes to over 4000 ft/1.2 km ASL. On the east side of the island, residents of Volcano Village and the surrounding housing subdivisions live within 10 km of Kīlauea's degassing summit crater, and communities along the Hawai'i Belt Road are within 10 km of the decades long degassing sources on the MERZ. Many communities, housing subdivisions, and census-designated places were within 10 km of the degassing fissures during the intense 2018 LERZ eruption; however, based on HDOH data during the LERZ eruption, the vog was most severe in communities in the south and west of the island [28,32].

Communities living at elevation (e.g., Volcano Village) experience temperatures in winter which fall to < 10 °C/50 °F overnight and rise to 15–25 °C/59–77 °F during the day. Those in coastal areas experience more stable temperatures year-round, with highs generally 25–30 °C/77–86 °F, and lows rarely below 16 °C/60 °F. The Island of Hawai'i's rainfall pattern is extremely diverse; the east side of the island is much wetter than the west side, with annual rainfall amounts as low as 200 mm on the leeward side of the island, and as high as 10,000 mm on the windward side. Mist and fog are common in mountainous areas, including in Volcano Village up to the 4000 ft summit of Kīlauea, west of which is much drier. The Island of Hawai'i is typically split into nine districts which host towns, villages, and housing subdivisions [42]. For this study, we divided the island into ten districts (Fig. 1), splitting Upper and Lower Puna due to the substantial change in elevation between the residential areas close to the active vents and those located closer to sea level.

2.4. Existing advice

At the time of this study (2015–16), local communities and visitors to the Island or State of Hawai'i had a range of mainly online options if they wished to receive advice on protecting themselves from vog exposure. The primary advice was provided by the HDOH, which had a vog fact sheet on their main webpage. Frequently Asked Questions addressed key concerns about vog and volcanic gas composition, whether these volcanic products are harmful and how to protect oneself from exposures. One branch of the HDOH (Clean Air) also had a webpage about volcanic air pollutants, which gave general recommendations for protection based on advice from the American Lung Association (ALA), which had a section on vog on its website. HDOH also offered informal advice by telephone, including information on air cleaners and respiratory protection. A vog phone helpline operated from 2008 to 2012, which provided pre-recorded daily vog levels based on monitoring data from an air quality station in South Kona. The helpline also linked to the Rocky Mountain Poison Control 24-h call center, which provided information to the public regarding vog.

Other agencies and organizations, such as U.S. Geological Survey Hawaiian Volcano Observatory (USGS HVO), the Hawai'i State Governor, Hawai'i County Civil Defense (HCCD), and the County of Hawai'i (CH) also provided advice on their websites, based on the wording and information from HDOH and ALA. The University of Hawai'i at Hilo (UH Hilo) also offered online information which included both standard and novel advice.

Table 1 summarises the advice that was given by the different agencies/organizations prior to this study. Most agencies/organizations recommended staying indoors, using an air conditioner, closing doors/windows, limiting physical exertion, drinking liquids, and, for those that have existing medical conditions, contacting a doctor, if necessary, and keeping medication on hand. Some agencies advised potentially leaving the area, using a cloth or mask over the face, not smoking, and avoiding cigarette smoke. UH Hilo showed how to manufacture an inexpensive vog filtration system [43], and students at the Hawai'i Academy of Arts and Sciences, an Island of Hawai'i charter school, developed a similar DIY 'vog scrubber' that was marketed locally [44]. The order and content of the advice depended on the agency (and even within the same agency's advice on different pages), highlighting the fact that, at the time, a wide variety of advice was available, which may potentially have led to confusion or even reduced trust in the agencies and the advice itself. Additionally, all of the advice was 'generic,' i.e., applicable to anywhere in the world, and was not specific to the lifestyles and environment of the Island of Hawai'i.

The diversity of housing, climates, and available resources suggests that generic advice may not be applicable across island communities. Those at high altitudes are likely to have better constructed housing, to protect against the cooler winters, whereas those at low elevations may have open housing, which is not designed to be sealed. If the indoor environment is not easily differentiated from the outdoor environment, then advice to go indoors, close windows and doors, and turn on air conditioning may be seen as inappro-

Table 1
Vog protection advice from agencies and organizations. Numbers indicate the order that the advice is given. Stars indicate that the advice is not given as part of a list (so no order discernible). UH Hilo had two webpages with advice so is represented in two columns.

Advice	HDOH	HDOH (Clean Air Branch)	ALA	USGS HVO	HCCD/CH	Governor	UH Hilo 1	UH Hilo 2
Stay indoors	2	1	2	1	1	2	1	*
Use air conditioner	3 re-circ. setting	1 if available	2 if poss.	1 if poss.	1 if available	2 re-circ. setting	2 if available	* if available
Close doors/windows	2			2	2	2 at night	1	*
Avoid/limit outdoor physical exertion	4	3	7	3, 4	3 esp. if sensitive	2		* esp. if fatigued
Contact doctor if resp. symptoms	6	6	4	5	4	4		
Keep meds on hand	1	5	3	6	5	4	*	
Drink plenty of liquids	5	4 esp. warm liquid	6	7	6 esp. warm liquid	3		* bottled
Heed advisories from Civil Defense	7			*				
Use daily meds	1		3			4		
Consider leaving the area	7					4	*	
Use damp cloth/dust mask etc.	8		8		9 for ash	5		* if work outdoors
Do not smoke/avoid 2nd hand smoke		2	1					
Monitor wind/air conditions			5			1		
Use air cleaner/purifier					7		2 if available	* if available
Make cheap filtration system							3	*

Empty cells indicate that the agency does not mention that item of advice. Please see main text for acronyms for agencies. Agency websites where the advice was taken from (note that these have now been updated or replaced so not given as hyperlinks): HDOH; HDOH Clean Air; ALA; HVO; HCCD/CH: ; ; Governor; UH Hilo

priate, unhelpful, or frustrating. Advice that does not address communities' needs or lifestyles may be counterproductive. One objective of this study was to use community feedback to improve the content, availability, and uptake of information for mitigating vog impacts on Hawai‘i communities.

3. Methods

This study took an exploratory, mixed-methods qualitative/quantitative approach by utilizing 1) Focus groups with community members; 2) Focus groups with representatives from the official advice-giving agencies and organizations; 3) a questionnaire-based survey of community members (see Supplementary Material 1). Ethical approval for the research was given by Durham University (ESE20141202CH), and questionnaire-based surveys were conducted only by authors from Durham University. In addition, public input to a social media group called ‘Vog Talk,’ provided information on local knowledge and practices relating to vog protection strategies. This forum, moderated by the authors, became a venue for answering questions, directing users to resources, and discussing symptoms, anxieties and official advice related to vog exposure. This platform also provided an opportunity for sharing photographs of current vog conditions. As of 2023, it had over 1100 members.

3.1. Community focus groups

Three small community focus groups were conducted; one each in the Ocean View, Volcano Village/Mountain View, and Pāhala communities, which covered a range of distances from the volcano (from 5 to 80 km). While Ocean View and Pāhala are downwind during prevailing trade wind conditions, the Volcano Village/Mountain View area experiences vog only during non-trade wind conditions. Each was organised with the help of local community leaders who invited members of their communities whom they thought might like to contribute to a discussion on protection strategies related to vog exposure. The community organisers were asked to invite 8-10 adults (over 17 years) with a range of genders, ages, and backgrounds. Each focus group took place in a community setting (community center, local café, and library, respectively). The aim of the focus groups was to gain specific information on the communities' knowledge related to vog and how to protect themselves, whether they knew about and followed existing advice, and whether they had developed their own strategies for protection. Each focus group meeting was between 1 and 1.5 h long. The final composition of the groups is given in Table 2.

Written consent was acquired from all participants after the purpose of the focus groups had been explained. The participants were informed that they could leave the discussion at any time. The discussions were conducted by the research team and consisted of formal and informal discussion. The formal discussion was based around the following pre-defined questions:

o Tell me about the vog. Do you notice it? How often? Where is it worst? (A map was provided for people to draw on or add post-it notes).

Table 2
Demographics of the community focus groups.

Area	Ocean View	Volcano	Pāhala
Focus group location	Community center	Village café	Public library
Number of participants	6	7	7
Female:Male	3:3	6:1	5:2
Age range	38–68	57-70 +	17-70 +
Participants' address	Ocean View	Volcano + 2 Mountain View residents	Pāhala/Wood Valley + 1 Volcano resident employed in Pāhala
Employment	3 employed, 3 retired	4 employed, 3 retired	1 student, 4 employed, 2 retired

o What are your concerns/worries about vog? How does it affect your life?
o Do you protect yourselves from the vog? Tell me about the different things that you do, or that you've heard that others do. Do these actions work?
o Are you aware of and do you act on official advice? If not, why not? If yes, which aspects? Is the advice useful? How would you like to receive advice?

The aim of the informal discussion was to obtain community input on how best to conduct the questionnaire survey. It was critical to gain understanding of appropriate local phrasing, best locations, and methods to conduct the survey but also to ensure that the survey was asking questions which were relevant to the communities' concerns. Informal discussions were held at Ocean View and Volcano Village as the survey was already in progress when the Pāhala focus group was held. In this discussion, people were presented with the pilot survey and asked:

o What do you think of the questionnaire? Is it worded appropriately? Does it ask the right questions?
o Where do you think the survey should be conducted within the communities?
o A key aim is to ensure that the findings of this study are useful for the whole community. What do you think are the best ways to share the findings?
o If the formal advice were updated to reflect local knowledge, would that be useful?

During the focus groups, a note taker was used to record the discussions, which were also captured via digital audio recording. Following the focus groups, the discussions were anonymously documented using the transcribed audio recordings, and the hand-written notes. From the report generated by this process, the following themes were identified: symptoms; interventions; advice accessibility and relevance; and general observations. Discussion relevant to those themes was then highlighted in the documented focus group discussions. These themes and discussion findings were then used to write a summary of each focus group, which was then sent to the participants, for their information.

3.2. Focus groups and meetings with agencies/professionals

Prior to starting the study, focus groups/meetings were conducted with a number of local agencies and professional groups in order to gain background information relevant to the study. The meetings included representatives from health, land management, emergency response, county/federal government, and academic groups.

The Ka'ū Rural Health Community Association, Inc. (KRHCAI) is a non-profit organization which was formalized in 1998 and promotes a healthy community through supporting health, education, research, and economic sustainability opportunities. The research team met with KRHCAI's Executive Director in January 2015 to inform them of the study and to ask advice on how best to conduct such a study in the Ka'ū district. The executive director was clear that such a study was welcome but voiced strong concern that, in the past, several other academic studies had been conducted in Ka'ū communities, requiring time and commitment from community members, but that study findings had not been adequately disseminated to the community, and there had been no positive impact as a result of the studies. KRHCAI suggested edits for the questionnaire survey and provided advice on suitable locations to conduct the surveys.

The team also met with a group of HDOH public health nurses at a district health center in South Kona. The group spoke of their personal experiences of vog exposure, and of their professional experiences with the public and then gave advice on suitable locations for conducting the questionnaire survey in the South Kona area.

A formal focus group with advice-giving agencies and organizations was held at the HDOH Environmental Health Services office in Hilo in February 2015. The aim of the meeting was to gain insight into how the agencies perceived the advice that is given and its relevance and usefulness in its current form. The meeting was attended by 11 representatives from HDOH, HCCD, NPS, USGS HVO, UH Hilo and CH. Written consent was acquired from all participants after the purpose of conducting the focus groups had been explained. The meeting was around 1.5 h long. The focus group consisted of a formal and informal discussion. The formal discussion was based around the following pre-defined questions:

o Do you experience vog yourselves? In what way? How often? What do you do about it?
o What do you think communities in different areas do to protect themselves from vog? (use map)
o Who is the current advice aimed at? In what forms is it available?
o Do you think people find the current advice useful and relevant? To which communities is it most relevant?
o How else could the advice be disseminated (other than internet)?

o What do the agencies think of a multi-agency approach to consistent wording and advice with a more community-relevant approach to the wording?

The information gained from this discussion is presented in Section 2.4 and Section 6.

As with the community focus groups, the aim of the informal discussion was to obtain input on how the participants thought the authors should conduct the questionnaire survey. The discussions were based around the following questions:

o What do you think of the questionnaire? Is it worded appropriately? Does it ask the right questions?
o A key aim is to ensure that the findings of this study are useful for the whole community. What do you think are the best ways to share the findings?

The same process of transcribing and analysing the discussions was used as for the community focus groups. Again, a report was generated which was then disseminated to the participants.

3.3. The questionnaire survey

3.3.1. Questionnaire development

The first draft of the questionnaire was written by the co-authors at Durham University and was loosely based on themes from Protection Motivation Theory. This theory proposes that people's motivation to protect themselves depends upon their perceptions of threat and their ability to control the threat [45]. It has previously been used in volcanic environments to test the motivation for use of facemasks to reduce exposures to volcanic ash [46–49].

The face and content validity of the questionnaire was established using a range of methods designed to check that the items were adequate and sufficient for measuring the constructs of interest and respondents understood the question in the way intended by the researchers. This included input provided by colleagues at the USGS Hawaiian Volcano Observatory, who were more familiar with public perceptions of vog and local community sensibilities that might influence the phrasing of the questionnaire. And, as discussed above, the draft questionnaire was then shown to participants in the community and professional focus groups at meetings in January 2015, and comments incorporated. The questionnaire was then piloted in February 2015, using five participants drawn from the Volcano Village community. Based on the pilot, it was shortened and wording refined to ensure that it was appropriate for the various communities on the Island of Hawai'i.

3.3.2. Questionnaire content

Consent for the questionnaire was obtained verbally after participants were read a participation information document. Verbal consent was chosen as it is estimated that 13% of adults over 16 years in the County of Hawai'i do not have basic literacy skills [50], and focus group participants also advised that people would hesitate to participate if they had to 'waste time' signing a document.

The full survey is provided in the Supplementary Material (SM1), but a summary is given below:

The survey starts by asking participants what their address/area or elevation is. In piloting, it was clear that some communities would not be comfortable with divulging a higher degree of detail than their sub-division and, in some cases, elevation. In Ocean View, for example, people prefer to define their address by their home's elevation above sea level rather than by a house name/number and road. In the survey, only sub-division was recorded, and elevation where appropriate (i.e., Ocean View). Gender, number of home occupants, age, and ethnicity were recorded.

Participants were asked if they smoke or have a diagnosed respiratory disease. These questions were drawn from epidemiological questionnaires previously used with Hawai'i participants in surveys to determine the health impact of vog on children [24].

A subset of questions then investigated whether people notice the vog and how often, whether it is worse at certain times of day, and how they recognise that there is vog. These questions help understand how people's perceptions of the presence of vog tie into actual values measured by local air quality monitors and through vog forecast models generated by University of Hawai'i at Manoa (UHM).

The following questions explored whether people perceive a change in their health when there is vog, whether they think symptoms have changed over time and whether the vog might be harmful to their long-term health. Severity of impact was also explored through a question at the end of the survey which asked if they would consider moving house, to avoid the vog.

The next section of the survey investigated the actions that people take to protect themselves when there is vog. The participants were given a list of actions, taken from the official advice (Table 1) and asked whether they undertake these actions never, occasionally, usually or always. They were also given the opportunity to describe other actions, or self-developed interventions, which were not part of the list.

The participants were then asked whether someone had advised them to take these actions and, if so, whether the advice received was helpful and consistent. They were then asked how they would like to receive advice on coping with vog in the future. The participants were also asked whether they are aware of air quality advisories (urgent messages or warnings), whether and how they access these and how they would like to access these in the future.

As much of the official advice relates to protection by retreating indoors, closing doors and windows and turning on air conditioning, the next section of the survey explored if people thought their homes were well-sealed, the sorts of windows they have (if any), whether they have air conditioners or purifiers and, if they do, whether they think they make a difference. Perceived barriers to taking action were explored through the participant's answers to the questions on actions that they took (notes were made on comments whilst completing that section).

Finally, participants were asked if they were employed, how much of their time was spent working outdoors and whether they protect themselves at work, when there is vog.

3.3.3. Administering the survey

Feedback from the focus groups gave a clear steer that surveys should be conducted in public settings, where a 'good cross-section of society' would likely be present. Farmers' markets were chosen as an ideal location as these attract a wide range of social groups and are weekly community events. Four markets were chosen: Volcano Village, Maku'u (both on Sundays), Ocean View (Saturday), and Nāʻālehu (Wednesday). The farmers' markets in the North Kona district were perceived as primarily tourist destinations and not a good place to attract a good cross-section of residents, so, for Kona, the West Hawaiʻi Civic Center was chosen where people from the district and surrounding areas converge to have their driving licenses renewed. The aim was not to recruit a representative sample of the local populations but to recruit a good mix of resident individuals exposed to vog. The chosen locations (Fig. 1) covered all areas substantially affected by vog (depending on wind direction). The aim was to achieve 25 participants from each location, making this survey pilot scale (i.e., potentially too few to draw results of statistical significance) but sufficient to be able to draw conclusions on use of protective interventions to give to the advice-giving agencies.

During the interviews at Nāʻālehu market, the participants' answers indicated that there was an unusual atmospheric/topographic condition, which meant that people living immediately to the southwest of Nāʻālehu received little vog, whereas those to the north-east, especially in Pāhala, were exposed to higher concentrations. Given that most of the participants at that market happened to be from Discovery Harbour and other settlements to the southwest, we decided to visit Pāhala separately. As there is no farmers market in Pāhala, the authors interviewed a group of older participants attending a community center, and administrative staff and teachers at the local school.

At the end of the survey period, the participants originated from more districts than had been anticipated as people had travelled to distant farmers' markets and the West Hawaiʻi Civic Center. This resulted in fewer participants from the districts of original interest, and the target of 25 participants per locale was not always achieved. Therefore, a number of additional surveys were also completed by volunteers: i) who were members of the 'Vog Talk''social media group; ii) who were recommended by the Public Health nurses in Kona; iii) or who lived in the Hilo area (invited by local colleagues).

All surveys were conducted by the lead author except for 13 surveys conducted by a Durham University research assistant, because of the high interest in the survey in Volcano Village. The demand was anticipated, and the colleague trained in advance. The locations and dates that surveys would be conducted were advertised through the 'Vog Talk' social media group and through a press release which was publicized by various media groups including prime-time television and radio news programmes. However, most of the participants were not previously aware of the project.

4. Questionnaire results

The results of the qualitative research (focus group response) are incorporated into the discussion of the questionnaire data in Section 5. It should be noted that the conditions at this time may have influenced people's perceptions of vog, particularly in east Hawaiʻi, where the interruption in trade winds led to more frequent vog exposures.

A total of 146 questionnaires were completed. Three questionnaires, from participants living in South Kohala and Hamakua districts, were excluded from the analysis as these locations were not part of the target study area. Additionally, there were no participants from North Hilo or North Kohala districts, which were also not targeted areas in the study (Fig. 1).

The data were analysed using IBM SPSS 22. Frequencies and percentages were obtained for responses obtained from nominal scales (e.g., participants indicated whether or not they had noticed vog, whether or not they thought vog was worst in the morning, whether or not they noticed various signs of vog such as smell and taste, whether or not they noticed a change in household health when there was vog, and whether or not they reporting specific symptoms such as a runny nose when there was vog). The association between these categorical responses and other categorical variables (i.e., district, age-group, gender) was determined using the non-parametric Chi-square test of independence. Binary logistic regressions were used to examine nominal (e.g., gender), ordinal (e.g., age-group), and/or continuous variables (e.g., distance that the participant lived from the vent in kilometers) as predictors of 'yes' responses (e.g., responded 'yes' to vog being harmful to their health). Coefficients are reported as odds-ratios (OR) which can be interpreted as the change in the odds of a 'yes' response for a one-unit increase in the value of the predictor.

Means were computed for data obtained on ordinal scales (e.g., ratings of frequency of noticing vog, ratings of frequency of actions taken when there is vog) and the non-parametric Kruskall-Wallis test was used to establish whether ratings were significantly different across the districts. If the Kruskall-Wallis test was significant (i.e., $p < .05$), Bonferroni corrections were applied to post-hoc tests to correct the family-wise error rate for multiple comparisons. Ordinal logistic regressions were used to examine nominal (e.g., gender), ordinal (e.g., age-group), and/or continuous variables (e.g., distance that the participant lived from the vent in kilometers) as predictors of ratings of the frequency of actions taken when there is vog. Coefficients are reported as odds-ratios (OR), which can be interpreted as the change in the odds of the rating being one level higher for a one-unit increase in the value of the predictor.

Means were computed for data obtained on ratio scales (e.g., number of symptoms reported when there is vog) and the parametric one-way ANOVA test was used to establish whether the number of symptoms reported was significantly different across the districts. Because the assumption of homogeneity of variances was violated, Welch's test was conducted and the Games-Howell post-hoc test was used for multiple comparisons.

For the analysis, the studied area was grouped into four districts with some reference to the County of Hawaiʻi zone maps [42] (Fig. 1). The districts and their main communities are described in Table 3. The grouping of districts relates to the local vog composi-

Table 3
District divisions by wind conditions, vent proximity and mean elevation.

District	Main surveyed communities	Wind conditions for vog	Mean (& range) distance from Halemaʻumaʻu vent based on participants' addresses[1]	Mean (& range) distance from Puʻuʻōʻō vent based on participants' addresses[1]	Mean (& range) elevation above sea level for each district
South Hilo & Lower Puna	Hilo, Pahoa and Kalapana	Interrupted trade winds (Kona or variable winds)	36.6 (30–43) km	25.9 (12–38) km	149.7 (3–350) m
Upper Puna	Volcano, Mountain View	Interrupted trade winds (Kona or variable winds)	8.5 (4–25) km	13.8 (9–19) km	1045.6 (440–1225) m
Kaʻū	Pāhala, Nāʻālehu, Discovery Harbour, South Point and Ocean View	Trade winds	81.7 (30–110) km	108.5 (55–140) km	602.8 (200–1372) m
South & North Kona	Captain Cook, Kealakekua, Kailua-Kona	Trade winds	166.1 (150–220) km	199.6 (180–220) km	289.2 (13–762) m

[1] Data based on Google map distance calculations for South Hilo, Lower Puna, and Upper Puna, where the winds travel linearly, and by estimation for Kaʻū, South Kona and North Kona, where the winds travel around the island topography as shown in Fig. 1. Data were not available for one person in Upper Puna, who did not give their address data.

tion, concentrations, and dispersion [20,22,24,32,51]. Windward (east) Hawaiʻi – represented in this study by South Hilo, and Lower & Upper Puna – usually experience intermittent vog exposures during Kona and interrupted trade wind conditions. These areas receive a mixture of SO_2 and sulfate aerosol, with locations closest to the active vents (i.e., Upper Puna) experiencing the highest amounts of SO_2 gas. Kaʻū district experiences chronic vog exposure during the dominant trade wind conditions, with the communities receiving a mixture of SO_2 and sulfate aerosol. South & North Kona also experience chronic vog during trade wind conditions but mostly receive sulfate aerosol [24,32]. It should be noted, however, that the entire island (and state) can experience vog during prolonged periods of interrupted trade winds.

To take plume chemistry into account for the data analysis [24], mean distance from each vent for each district was calculated, based on participants' addresses (Table 3). The distances to the Halemaʻumaʻu and Puʻuʻōʻō vents are highly correlated ($r = 0.979$, $p < .01$), suggesting that either measure can be used in the analysis, so only distance to Halemaʻumaʻu was used. Mean elevation above sea level correlates with temperature [52], so may influence residents' behaviour and house construction. Thus, mean elevation was also calculated for each district based on participants' address data (Table 3).

For each district, or group of districts (see Table 3), at least 23 participants were recruited. Overall, as shown in Table 4, two thirds of the participants were female (compared to 50.4% for the County (island) in the 2020 census [42]), but a Chi-Square (χ^2) test showed there was no significant differences in the percentages of males and female participants among the districts ($\chi^2(3) = 1.10$, $p = .776$). The age of the participants was skewed towards older people with 51% being over 60 years. A Chi-square test showed that there was no significant difference in the proportions in the older age-group across the four districts ($\chi^2(3) = 3.31$, $p = .346$). The County of Hawaiʻi has the highest percentage of +65 years population across Hawaii State, but this only accounts for 22.7% of the island's population [40] indicating that our participants were not representative of the population demographics.

Over half the sample was white (alone), which is not reflective of the census data presented in Section 2.3 (34.3%). Mixed ethnicity participants made up about a fifth of the sample (and included all participants who identified as Hispanic/Latino or Other Asian), and Hawaiian/Pacific Islanders about a tenth (Table 4). The proportion of white participants was significantly different across the four districts ($\chi^2(3) = 10.63$, $p = .014$), and there was a significantly higher proportion of white participants in Upper Puna compared to the other three districts ($ps < .05$).

Related to employment, 18 participants chose not provide information about their employment/occupation. Admin/clerical workers made up the biggest proportion across the four districts (34.3%) followed by retirees (22.4%) (Table 4). A Chi-square test, to check whether there were significant differences among districts, was not possible due to low numbers of responses in some categories.

The number of adults and children in the households of the participants was pooled and is represented as a mean (by district) in Table 4. Household numbers are noticeably low (overall mean of 2.4), reflecting the skewed age of participants. South Hilo & Lower Puna and North & South Kona had slightly more people per household than Upper Puna or Kaʻū. A Kruskal-Wallis test confirmed that there are significant differences between groups ($\chi^2(3) = 11.99$, $p = .007$). Post-hoc tests with a Bonferroni correction showed that none of the pairwise comparisons were significantly different from one another, although the differences between South Hilo & Lower Puna and Kaʻū ($p = .056$) and South Hilo & Lower Puna and Upper Puna ($p = .051$) were marginal. Overall, about a quarter of participants have children in the household. A Chi-square test found that the proportion of children in households significantly differed across districts ($\chi^2(3) = 10.81$, $p = .013$) with children being more common in South Hilo & Lower Puna and North & South Kona compared to Kaʻū, which agrees with overall household size. Around 25% of the households had smokers and there were no significant differences amongst the districts ($\chi^2(3) = 1.82$, $p = .611$).

We also asked the participants to report if they or anyone in the household had a diagnosed respiratory disease. Just under a quarter of participants (23.1%) reported they had a respiratory disease and although the proportion was slightly higher in participants under 60 (24.3% compared to 21.9% in over 60s), the difference between these two age-groups was not significant ($\chi^2(1) = 0.113$, $p = .737$). The reported incidence of respiratory disease in the household was slightly higher at around 34% (Table 4) with no signifi-

Table 4
Demographic data for the participants and information on their households, by district.

Demographic data	South Hilo & Lower Puna	Upper Puna	Ka'ū	South & North Kona	Full sample
Total N(%) in each district	34 (23.8%)	37 (25.9%)	49 (34.3%)	23 (16.1%)	143 (100%)
Gender					
Male	35.3%	40.5%	30.6%	30.4%	34.3%
Female	64.7%	59.5%	69.4%	69.6%	65.7%
Age-group					
19-39	26.5%	10.8%	12.2%	17.4%	16.1%
40-59	23.5%	35.1%	30.6%	47.8%	32.9%
Over 60	50.0%	54.1%	57.1%	34.8%	51.0%
Ethnicity					
Caucasian	41.2%	78.4%	59.2%	52.2%	58.7%
Mixed ethnicity	35.3%	16.2%	14.3%	13.0%	19.6%
Hawaiian/Pacific Islander	8.8%	0.0%	12.2%	21.7%	9.8%
Japanese	8.8%	5.4%	4.1%	8.7%	6.3%
Filipino	0.0%	0.0%	8.2%	0.0%	2.8%
Native American	2.9%	0.0%	2.0%	4.3%	2.1%
African American	2.9%	0.0%	0.0%	0.0%	0.7%
Employment					
Admin/clerical	29.4%	37.8%	20.4%	65.2%	34.3%
Retired	23.5%	16.2%	34.7%	4.3%	22.4%
Self employed	14.7%	18.9%	16.3%	8.7%	15.4%
Manual	8.8%	5.4%	4.1%	13.0%	7.0%
Agricultural/farm	2.9%	8.1%	4.1%	0.0%	4.2%
Care/nursing	2.9%	2.7%	0.0%	4.3%	2.1%
Other	2.9%	2.7%	2.0%	0.0%	2.1%
No data	14.7%	8.1%	18.4%	4.3%	12.6%
Household size (mean)	3.0	2.0	2.0	3.2	2.4
Children in household (% yes)	35.3%	24.3%	8.2%	34.8%	23.1%
Smokers in household (% yes)	17.6%	24.3%	30.6%	26.1%	25.2%
Respiratory disease in household (% yes)	29.4%	27.0%	36.7%	43.5%	33.6%

cant differences amongst the districts ($\chi^2(3) = 2.21$, $p = .531$). Asthma was the main disease reported for adults; 15% of the participants, themselves, reported having asthma and they said that 5.5% of other adults in their households had diagnosed asthma. For their children, asthma was the only reported disease (7.0%) with 93.0% of children in households not having any reported respiratory diseases. This compares to 7.8% prevalence of asthma nationally in the U.S. and 5.8% for children [53].

4.1. Perceiving vog

The survey asked the participants if, when and how, they notice vog. We present the data according to district because geographic location in relation to the active vents is most likely to affect vog exposure. In all four districts, over 90% of people noticed vog with 100% in South & North Kona saying they did (Table 5). The mean ratings of frequency ranged from 2.27 in Upper Puna (2 = few times/month) to 3.00 in South & North Kona (3 = few times/week) and a Kruskal-Wallis test confirmed that there were significant differences between districts ($\chi^2(3) = 10.28$, $p = .013$). However, post-hoc tests with Bonferroni's correction for multiple comparisons showed that none of the pairwise contrasts were significantly different from each other although the South Hilo & Lower Puna ($M = 2.88$) versus Upper Puna ($M = 2.27$) difference was marginal ($p = .051$).

The participants were asked if there was a time of day when they thought air quality was worst. Of those that responded (136) just over half identified a time of day (55.1%) with 14.0% being undecided. Vog was perceived to be worse in the morning by around two-thirds of the participants (62.4% in the overall sample; Table 5) and in the afternoon by about a quarter (28.2% overall). There were also significant differences in the proportions across districts perceiving vog as worst in the morning ($\chi^2(3) = 18.56$, $p < .001$) or afternoon ($\chi^2(3) = 20.29$, $p < .001$); people living in South & North Kona, which are the districts farthest from the Halema'uma'u vent (see Table 3) were the least likely to perceive morning vog as the worst (23.1%) and most likely to report afternoon vog as the worst (84.6%). This observation was supported by binary logistic regression analyses which showed that the odds of identifying morning vog as the worst was significantly lower (odds ratio (OR) = 0.98, $p < .001$) and the odds of identifying afternoon vog as the worst was significantly higher (OR = 1.02, $p = .001$) for participants who lived farthest from the vent. Elevation of residence above sea level, on the other hand, did not change the odds of either morning vog or afternoon vog (ORs = 1.00, ps > .42).

It was also important to understand how people recognised vog as there are other sources of airborne particles/gas which can also form hazes, such as sea mist. Most people recognised the vog by seeing a visible haze (92.9% overall) and/or noticing health symptoms (85.6% overall). Sulfur smell and taste were noticed less often (55.1 and 38.6% overall) although the proportions were significantly different across districts (sulfur smell $\chi^2(3) = 24.38$, $p < .001$; taste $\chi^2(3) = 19.56$, $p < .001$). These sensory signs were most likely to be identified by people living in Upper Puna (81.1%, 59.5%) and South Hilo & Lower Puna (65.6%, 53.1%), which are the regions closest to the vent, and have the highest concentrations of SO_2 gas.

Binary logistic regressions confirmed that participants were more likely to say that they noticed haze (OR = 1.03, $p = .025$) and less likely to say that they noticed a sulfur smell (OR = 0.986, $p < .001$) or taste (OR = 0.99, $p < .001$) if they were farther from

Table 5
Factors associated with perceiving vog, by district.

	South Hilo & Lower Puna	Upper Puna	Kaʻū	South & North Kona	Full sample	Chi-square (χ^2)
Do you ever notice that the air quality is poor due to vog? (%yes)	94.1%	94.6%	95.6%	100.0%	95.8%	n/a[a]
How often do you notice vog? (mean rating[b])	2.88	2.27	2.55	3.00	2.63	10.28
From your experience, is there a time of day when the air quality is worst? [c]						
Morning[d]	78.9%[i]	60.0%[i, ii]	73.9%[i]	23.1%[ii]	62.4%	18.56***
Afternoon[d]	21.1%[i]	16.7%[i]	17.4%[i]	84.6%[ii]	28.2%	20.29***
Evening	26.3%	15.0%	8.7%	7.7%	14.7%	n/a[a]
Night	5.3%	5.0%	26.1%	0.0%	10.7%	n/a[a]
Don't know/depends	9.4%	20.0%	10.9%	17.4%	14.0%	n/a[a]
How do you recognise when it is voggy? [e], [f]						
Visible haze	93.8%	78.4%	97.8%	100.0%	92.0%	n/a[a]
Sulfur smell[d]	65.6%[i ii]	81.1%[ii]	43.5%[i iii]	21.7%[iii]	55.1%	24.38***
Taste[d]	53.1%[i]	59.5%[i]	21.7%[ii]	17.4%[ii]	38.4%	19.56***
Health symptoms	87.9%	86.5%	80.4%	91.3%	85.6%	n/a[a]
Other	3.1%	2.7%	2.2%	0.0%	2.2%	n/a[a]

*p < .05, **p < .01, ***p < .001.
[a] Chi-square test not appropriate because one or more cells have an expected count less than 5.
[b] Rated frequency on an ordinal scale from 0 = never, 1 = few times/year, 2 = few times/month, 3 = few times/week, 4 = daily.
[c] Participants selected one or more times of day when they perceived air quality was worst.
[d] When Chi-square was significant (p < .05) post-hoc analyses were conducted to determine which of the districts were significantly different from each other based on pairwise comparisons. Each superscript number denotes subsets of districts whose proportions do not differ significantly from each other at the .05 level.
[e] Participants selected one or more signs from the options provided.
[f] Two (or three, for health symptoms) participants answered this question despite saying they never noticed vog in the air.

the Halemaʻumaʻu vent, which is consistent with the measured low SO_2 concentrations in leeward Hawaiʻi [32]. Notably, distance of residence from the vent did not significantly predict the odds of noticing health symptoms during vog events (OR = 1.00, p = .61). This is consistent with observation that both SO_2 gas and sulfate aerosol have well-documented health impacts [1].

Elevation of residence was also predictive of people noticing haze and sulfur smell. At high elevations, the odds of noticing haze were significantly lower (OR = 0.997, p = .004) but the odds of noticing a sulfur smell were significantly higher at higher elevation (OR = 1.001, p = .010). Elevation was not predictive of either noticing taste (OR = 1.00, p = .20) or health symptoms (OR = 1.00, p = .27).

Participants were asked if they, or anyone they live with, had noticed a change in their health when there was vog (Table 6). Overall, 83.2% said yes, ranging from 91.3% of participants in the Kona districts perceiving a change in health compared to 75.5% in Kaʻū district. When analysed according to gender, females were more likely to notice a change in health ($\chi^2(1) = 7.833$, p = .005). No significant differences were found across age groups ($\chi^2(2) = 2.658$, p = .265) or between those with and without diagnosed respiratory disease (Table 4) but this effect was marginal ($\chi^2(1) = 2.901$, p = .089).

Of those that perceived changes in household health due to vog, 81.5% identified two or more symptoms (Table 6). A one-way Welch's ANOVA (homogeneity of variances could not be assumed) found a significant difference in the mean number of symptoms reported between districts (Welch (3, 65.475) = 3.94, p = .012, $\eta^2 = 0.092$). Games-Howell post-hoc tests showed that significantly more vog symptoms were reported in South Hilo & Lower Puna compared to Kaʻū (mean difference 2.41, p = .019).

The symptoms identified in those who had noticed changes in household health when there is vog are listed in Table 7. Sixty percent of participants reported eye irritation and ~50% experienced headache/migraine and/or cough. More than 40% of participants perceived that vog exposure made them tired or gave them a stuffy nose. Around a third of participants experienced shortness of breath or wheeze, or a runny nose, due to vog exposures. Other symptoms such as phlegm, sore throat, and flu-like aches were less common. For the most part, there were no significant differences between districts (or the Chi-square tests could not be conducted; Table 7) but significant differences were found for stuffy nose ($\chi^2(3) = 8.55$, p = .036) and runny nose ($\chi^2(3) = 11.62$, p = .009); South Hilo & Lower Puna participants were more likely to experience runny nose than those in Kaʻū district and more likely to experience stuffy nose than those in Upper Puna.

Table 6
Perceptions of health symptoms related to vog exposure, by district.

	South Hilo & Lower Puna	Upper Puna	Kaʻū	South & North Kona	Full sample
Noticed change in household health when voggy (% yes)	85.3%	86.5%	75.5%	91.3%	83.2%
Number of symptoms identified					
One	13.8%	18.8%	24.3%	14.3%	18.5%
Two or more	86.2%	81.2%	75.7%	85.7%	81.5%
Mean number of symptoms identified[a]	4.94[i]	3.19[i ii]	2.53[ii]	4.04[i ii]	3.52

[a] When Chi-square was significant (p < .05), post-hoc analyses were conducted to determine which of the districts were significantly different from each other based on pairwise comparisons. Each superscript number denotes subsets of districts whose proportions do not differ significantly from each other at the .05 level.

Table 7
Perceptions of symptoms experienced, by district. All responses are percentage who answered yes to experiencing the symptom.

Symptoms[a]	South Hilo & Lower Puna	Upper Puna	Kaʻū	South & North Kona	Full sample	Chi-square (χ^2)
Eye irritation	75.9%	46.9%	59.5%	61.9%	60.5%	5.38
Headache/migraine	58.6%	50.0%	40.5%	61.9%	51.3%	3.30
Cough	51.7%	62.5%	40.5%	47.6%	50.4%	3.40
Tiredness	58.6%	40.6%	27.0%	52.4%	42.9%	7.57
Stuffy nose[b]	55.2%[i]	21.9%[ii]	37.8%[i ii]	52.4%[i ii]	40.3%	8.55*
Shortness of breath/wheeze	31.0%	37.5%	40.5%	33.3%	36.1%	0.735
Runny nose[b]	55.2%[i]	25.0%[i ii]	18.9%[ii]	23.8%[i ii]	30.3%	11.62**
Phlegm	37.9%	25.0%	16.2%	33.3%	26.9%	4.44
Sore throat	27.6%	12.5%	16.2%	19.0%	18.5%	n/a[c]
Achy/flu-like symptoms	20.7%	12.5%	5.4%	19.0%	13.4%	n/a[c]
Skin irritation	24.1%	9.4%	5.4%	9.5%	11.8%	n/a[c]
Sinus problems	17.2%	0.0%	13.5%	14.3%	10.9%	n/a[c]
Irritability	20.7%	9.4%	0.0%	4.8%	8.4%	n/a[c]
Dizziness	13.8%	3.1%	0.0%	0.0%	4.2%	n/a[c]
Other symptoms[d]	31.0%	12.5%	13.5%	9.5%	16.8%	n/a[c]

*p < .05, **p < .01, ***p < .001.
[a] Participants could choose any number of symptoms.
[b] When Chi-square was significant (p < .05) post-hoc analyses were conducted to determine which of the districts were significantly different from each other based on pairwise comparisons. Each superscript number denotes subsets of districts whose proportions do not differ significantly from each other at the .05 level.
[c] Chi-square test not appropriate because one or more cells have an expected count less than 5.
[d] Other symptoms included allergies, chest congestion, sleeplessness, nausea, anxiety, chest pain, and dry mouth.

We also asked if people perceived that they had always had these symptoms when exposed to vog. This was an open-ended question, so the results are qualitative. Of those that answered (4 out of the 118 people who had at least one symptom did not provide an answer to this question), the majority said that they had always had symptoms when there is vog. Forty-six people volunteered the information that they thought their symptoms had got worse over time (with greater exposure) and five people thought they had got better (related to wind conditions).

In response to the question ‘Do you think vog might be harmful to your long-term health?', 61.5% said yes, 16.1% said probably and 5.5% said maybe, and 14.0% said they did not think it was harmful (2.8% were not sure). We recoded these variables into yes/probably (1) and maybe/no/not sure (0) to compare perceptions of harm by district, distance of residence from the Halemaʻumaʻu vent, elevation from sea level, age, gender, and existing respiratory disease. There were no significant differences across districts (although the effect was borderline $\chi^2(3) = 6.951$, $p = .073$), and responses were not predicted by distance from the vent (OR = 1.008, p = .062), elevation from sea level (OR = 0.999, p = .234), or gender (OR = 1.43, p = .39). However, the participants were more likely to rate the vog as definitely or probably harmful to their long-term health if they were younger (OR = 0.533, p = .039), or had existing respiratory disease (OR = 3.58, p = .047).

For those that answered positively to the question on whether vog may be harmful to long-term health (yes, probably, maybe; 83%), when asked in what way people perceived that harm might occur, 75.6% thought that long-term exposure to vog would cause respiratory damage, 10.1% thought it would cause general poisoning of the body, and 14.3% thought it would cause other types of harm. Again, this was an open-ended question which was then coded to themes of responses.

4.2. Actions taken when there is vog

The next part of the questionnaire addressed how people’s behaviours map onto the recommended actions for exposure reduction from vog. A list of the recommended actions from various agencies was given, and the participants rated how often they took these actions, when the vog was bad. These were rated using an ordinal scale (0 = never, 1 = occasionally, 2 = usually, 3 = always) and means calculated, by district (Table 8). The highest mean scores were for doing nothing (occasionally to usually across all districts), closing windows and doors and going inside (occasionally to usually in all districts except Kaʻū, where participants never to occasionally did this), and stopping/limiting physical activity (in South Hilo & Lower Puna and Upper Puna occasionally to usually). Across all districts, the participants said they drank lots of water (occasionally to usually) but, from additional verbal responses noted while administering the questionnaire, some found it hard to separate this vog mitigation action from their normal drinking habits.

As shown in Table 8, Kruskal-Wallis tests showed significant differences across districts for checking warnings ($\chi^2(3) = 8.91$, $p = .030$), stopping/limiting activity ($\chi^2(3) = 23.14$, $p < .001$), staying indoors ($\chi^2(3) = 14.10$, $p = .003$), closing windows and doors ($\chi^2(3) = 13.57$, $p = .004$), and relocating ($\chi^2(3) = 13.63$, $p = .003$). Post-hoc contrasts (with Bonferroni correction for multiple comparisons) showed that the frequency of taking such actions was significantly higher in Upper Puna compared to Kaʻū and South & North Kona. Upper Puna has the highest concentrations of SO_2 gas [32] so this likely relates to the greater uptake of protective actions.

We also analysed these data according to a number of geographical, demographic, and perception variables including distance from Halemaʻumaʻu vent, elevation above sea level, age, gender, whether they have children in the household, whether anyone in the household has a respiratory disease, whether they had noticed any change in household health when there was vog, and their ratings of perceived harm.

Table 8
Mean ratings of frequency of recommended actions taken when there is vog, by district.

Mean rating[a]	South Hilo & Lower Puna	Upper Puna	Kaʻū	South & North Kona	Full sample	Kruskal-Wallis (χ^2)
Nothing different	1.29	1.00	1.71	1.74	1.43	7.69
Check for warnings/advice[b]	0.91$^{i\ ii}$	1.08^{i}	0.45^{ii}	0.39$^{i\ ii}$	0.71	8.91*
Stop/limit physical activity[b]	1.09$^{i\ ii}$	1.59^{i}	0.73^{ii}	0.52^{ii}	1.01	23.14***
Go/stay indoors[b]	1.09$^{i\ ii}$	1.65^{i}	1.00^{ii}	0.52^{ii}	1.11	14.10**
Close windows and doors[b]	1.18$^{i\ iii}$	1.81^{ii}	1.10^{iii}	0.35$^{i\ iii}$	1.18	13.57
Turn on air conditioner	0.24	0.00	0.04	0.26	0.11	n/a[c]
Turn on dehumidifier	0.18	0.27	0.06	0.09	0.15	n/a[c]
Turn on air purifier	0.44	0.19	0.04	0.30	0.22	n/a[c]
Drink lots of water	1.82	1.58	1.55	1.04	1.54	6.56
Use respiratory protection	0.12	0.38	0.08	0.04	0.16	n/a[c]
Take medication	0.79	0.35	0.51	0.35	0.51	1.40
Contact a doctor	0.12	0.08	0.06	0.17	0.10	n/a[c]
Temporary relocation	0.24	0.73	0.27	0.22	0.37	13.63**

*p < .05, **p < .01, ***p < 001.
[a] Actions rated on a 0–3 scale: 0 = never, 1 = occasionally, 2 = usually, 3 = always;
[b] When the Kruskal-Wallis test was significant (p < .05) post-hoc analyses were conducted to determine which of the districts were significantly different from each other based on pairwise comparisons. Each superscript number denotes subsets of districts whose proportions do not differ significantly from each other at the .05 level.
[c] Chi-square test not appropriate because one or more cells have an expected count less than 5.

As shown in Table 9, when the data were correlated with distance from Halemaʻumaʻu vent those who lived farther from the vent (in Kaʻū and South & North Kona) were more likely to do nothing different, and were less likely to check warnings, stop/limit physical activity, stay indoors, close doors and windows, use respiratory protection and relocate. When the data were correlated with address elevation, those living at higher elevation were more likely to stop activity, stay indoors, close doors and windows, and to relocate when there was vog. But those living at higher elevation were less likely to turn on air conditioning (but note that only 9 people in the whole sample had air conditioning).

The correlations with gender show that males were more likely than females to say they would do nothing different and less likely to do many of the actions, such as check for warnings and advice, stop/limit physical activity, go indoors, close windows and doors, and drink lots of water. If someone in the household had a respiratory disease, the participants were more likely to take medication but less likely to relocate. Also, if the participant perceived that they had health problems due to the vog, they were more likely to take many of the recommended actions. Taking action was, however, unrelated to whether or not the vog was perceived as definitely or probably harmful.

However, it is worth noting that there is shared variance between some of these variables, and their effects on taking actions when there is vog may not be unique (i.e., locations farther from the Halemaʻumaʻu vent tend to be at lower elevation (r_s = −0.374, p < .001); people living at high elevation and older participants are less likely to have children (r_s = −0.168, p = .046; r_s = −0.418, p < .001); older people are less likely to rate the vog as harmful (r_s = −0.174, p = .037); females and people with respiratory disease are more likely to notice health problems with vog (r_s = 0.188, p = .024; r_s = 0.200, p = .016). Multiple ordinal logistic regression models were therefore conducted, and the significant explanatory variables are shown in Table 9. The results of the multiple regressions for some of the actions need to be treated with caution. For stop/limit physical activity, go/stay outdoors, and temporary relocation, the tests of parallel lines were significant which indicates that the slope coefficients are not the same across response categories. And, for turn on dehumidifier, turn on air purifier, use respiratory protection, and take medication, some of the parameters could not be estimated due to unexpected singularities in the Fisher information matrix. Despite these limitations, the results of the regression analyses are broadly consistent with the correlational data although they highlight that the positive relationships between elevation and stopping/limiting physical activity and closing windows and doors were not significant once distance from the Halemaʻumaʻu vent was controlled for.

The ability for people to take some of the recommended actions (e.g., closing doors and windows and staying indoors) depends on the structure of their dwelling and whether they own some of the suggested interventions (e.g., air conditioners). Participants living farther from the vent (likely at lower elevation) were less likely to say that their home was well sealed (OR = 0.994, p = .046). Participants in Upper Puna (high elevation, so lower annual temperatures) were significantly more likely to consider their home to be better sealed from the vog than those living in South & North Kona ($\chi^2(3)$ = 9.41, p = .024) as is also seen from the percentages in Table 10. However, elevation was not a significant predictor of being able to seal the home (OR = 1.001, p = .096). In Upper Puna, 94.6% of participants had glass panes in their windows, compared to 70.6–78.3% in the other districts (Table 10), and this difference was significant for Upper Puna versus South Hilo & Lower Puna and Kaʻū ($\chi^2(3)$ = 8.34, p = .039). The proportion of participants with louvre/slatted windows was not significantly different across districts. And for screen only, the percentages ranged from 2.7% in Upper Puna compared to 8.2–14.7% in the other districts (Chi-square test was not appropriate). Homes at high elevation were more likely to have glass panes (OR 1.002, p = .003) and less likely to have louvre windows (OR = 0.999, p = .029).

Overall, only 25.9% of participants had any sort of air purifying device, with only 6.3% having an air conditioner, 14.0% having a dehumidifier and 11.9% having an air purifier (Table 10). Participants in South & North Kona were significantly more likely to have an air conditioner than participants in Kaʻū ($\chi^2(3)$ = 9.46, p = .024). Of those that did have an air purifier 75.7% said that they used

Table 9
Spearman's correlations (r_s) and logistic regressions of recommended actions taken when there is vog with geographic, sociodemographic, and perceptual factors.

	Distance from Halema'uma'u vent (km)	Elevation (m)	Gender[b]	Age[a]	Children in household	Existing respiratory disease	Notice health problems with vog	Perceived Harm[c]	Significant predictors (OR)
Nothing different	.244**	−.139	−.213*	.035	−.030	−.009	−.396***	−.056	Distance from HMM vent (1.01), Gender (0.465), Notice health problems with vog (0.049)
Check for warnings/ advice	−.196*	.089	.156	.027	−.013	−.044	.151	.033	Distance from HMM vent (0.991), Perceived harm (2.68)
Stop/limit physical activity	−.326***	.280**	.246**	−.035	−.042	.050	.329***	.055	Distance from HMM vent (0.988), Gender (2.69), Notice vog health problems (8.00)
Go/stay outdoors	−.366***	.166*	.286**	−.047	−.014	.109	.264**	−.024	Distance from HMM vent (0.99), Gender (3.32), Notice vog health problems (4.95)
Close windows and doors	−.372***	.242**	.228**	.064	−.047	.099	.192*	−.021	Distance from HMM vent (0.984), Gender (2.80)
Turn on air conditioning	.078	−.204*	.048	−.094	.009	.149	.109	.131	Elevation (0.996)
Turn on dehumidifier	−.157	.088	.048	.116	.027	.014	.130	.029	Notice health problems with vog[d]
Turn on air purifier	−.046	.017	.145	−.051	.095	−.034	.148	.072	Notice health problems with vog[d]
Drink lots of water	−.145	.036	.325**	−.114	.048	.161	.375***	.116	Distance from HMM vent (0.990), Gender (3.82), Notice vog health problems (12.1)
Use respiratory protection	−.238**	.083	.082	.042	−.046	.055	.165*	−.004	Distance from HMM vent (0.981), Notice health problems with vog[d]
Take medication	−.051	−.014	.107	.013	.048	.262**	.299***	.086	Existing respiratory disease (2.61), Notice vog health problems [d]
Contact a doctor	.134	−.097	.056	−.065	−.106	.156	.136	.162	
Temporary relocation	−.188*	.166*	−.035	−.078	−.056	−.195*	.162	−.019	Existing respiratory disease (0.307), Notice vog health problems (6.23)

*p < .05 (two-tailed), **p < .01 (two-tailed) ***p < .001 (two-tailed). HMM = Halema'uma'u.
[a] 0 = 19–39, 1 = 40–59, 2 = 60+.
[b] 0 = male, 1 = female.
[c] 0 = maybe/no/don't know, 1 = yes/probably,
[d] Parameter cannot be estimated due to unexpected singularities in the Fisher information matrix. There may be quasi-complete separation in the data and validity of the model fit is uncertain.

Table 10
Questions related to ability to enact interventions, by district.

	South Hilo & Lower Puna	Upper Puna	Ka'ū	South & North Kona	Full sample
Is your home well sealed from vog? (% yes)	35.3%	62.2%	38.8%	26.1%	42.0%
What sort of windows do you have[a]?					
Glass pane (% yes)	70.6%	94.6%	71.4%	78.3%	78.3%
Louvre/slatted (% yes)	32.4%	16.2%	24.5%	43.5%	27.3%
Screen only (% yes)	14.7%	2.7%	8.2%	8.7%	8.4%
Do you have an air purifying/dehumidifying device? [a]	26.5%	43.2%	14.3%	21.7%	25.9%
Air conditioner (% yes)	11.8%	0.0%	4.1%	13.0%	6.3%
Dehumidifier (% yes)	11.8%	32.4%	6.1%	8.7%	14.7%
Air purifier (% yes)	14.7%	18.9%	4.1%	13.0%	11.9%

[a] Participants could select more than one option, if needed.

it when there was vog and 70.3% thought it made a difference to their indoor air quality. Most of the participants with air purifiers had one with HEPA filter (58.8%) or HEPA and gas filters (11.8%); 29.4% didn't know what type of filter they had.

If the participants took actions which were not recommended by the agencies, they could also list these. There were 60 responses, showing that a substantial number of additional actions are taken (with some participants listing multiple actions). These can be categorised as taking actions to cool the body or surrounding environment (38.3%), drinking herbal teas and taking dietary measures (35.0%), symptom reduction using eye and nasal products (26.7%), various other approaches such as washing the face/skin, being in/near vegetation and taking vitamin supplements (21.7%), and rest/yoga/exercises (11.7%).

The participants were also asked an additional question on whether they would relocate (permanently) to avoid vog. The proportions considering moving were not significantly different across districts ($\chi^2(3) = 1.81$, $p = 9.46$, $p = .61$), ranging from 26.1% from South & North Kona to 41.2% in South Hilo & Lower Puna .

4.3. Advice on actions

Many of the respondents said that they had not been advised to take protective actions against vog (56.8% of the 118 who responded to this question) with many stating that the actions were just common sense. Of the 43.2% who had received advice, 29.4% received advice from HCCD, 29.4% from friends/family, 25.5% from the USGS HVO, 19.6% from the HDOH and 13.7% from the American Lung Association, UH (9.8%), radio (11.8%) and social media (3.9%). Of those that received advice, 79.2% said they found the advice helpful, 10.4% thought it was ‘fine’ and 10.4% said it was not helpful (out of 48 people who answered this question). When asked if the advice from different official sources was consistent, only 18.2% chose to answer this question, mainly because those that did not were unfamiliar with the official advice. Of those that did answer, 61.5% thought it was consistent.

When asked about the best ways to receive advice, of the 140 people who responded, by far the most popular answer (54.9%) was by website (Table 11), with radio being popular with a third (31.7%) of participants and social media, television, bulletin boards, and pamphlets being chosen by more than 20% of participants. No significant differences were seen among districts or for different age groups (or there were insufficient data for analysis), except for radio, where younger participants and those living in South Hilo & Lower Puna, and South & North Kona were more likely to prefer radio for advice than Kaʻū ($\chi^2(1) = 4.90$, $p = .027$; $\chi^2(3) = 14.54$, $p = .002$), and South Hilo & Lower Puna were also more likely to prefer social media for advice than Kaʻū ($\chi^2(3) = 10.71$, $p = .013$).

The participants were also asked if they were aware of air quality forecasts/advisories which, although not designed to provide information on protection, could be a route towards awareness of air quality issues, and behaviour change, which might lead to advice on protective measures being sought or taken. Eighty nine percent (88.8%) of the participants were aware of these alerts, with no significant difference with age ($\chi^2(1) = 0.008$, $p = .929$) or district ($\chi^2(3) = 1.81$, $p = .61$).

When asked what the best way was for receiving such alerts (the same choices were given as for receiving advice), of those that answered the question (140 participants), 42.1% chose text/SMS, 33.6% chose radio, 30.0% chose website (e.g., on news websites), and 25% wanted alerts via television (Table 11). No significant differences were seen for different age groups (or there were insufficient data for analysis), except for telephone message, where over 60s were more likely to want to receive alerts this way ($\chi^2(1) = 5.06$, $p = .024$), and for text/SMS where younger people (19–59) were more likely to want alerts via this medium ($\chi^2(1) = 11.5$, $p = .001$).

Table 11
Participants' preferred media for receiving advice on vog and receiving alerts. Percentage who said yes, by district and age.

Media (%yes)[a]	District				Age		
	South Hilo & Lower Puna	**Upper Puna**	**Kaʻū**	**South & North Kona**	**19–59**	**Over 60**	**Full sample**
Medium for advice							
Website	51.5%	59.5%	55.1%	52.2%	56.5%	53.4%	54.9%
Radio	48.5%	35.1%	12.2%	43.5%	40.6%	23.3%	31.7%
Television	36.4%	13.5%	20.4%	43.5%	27.5%	24.7%	26.1%
Social media	36.4%	29.7%	8.2%	30.4%	29.0%	19.2%	23.9%
Bulletin board	15.2%	16.2%	28.6%	30.4%	23.2%	21.9%	22.5%
Pamphlet	12.1%	21.6%	22.4%	26.1%	24.6%	16.4%	20.4%
Phonetree	12.1%	18.9%	6.1%	17.4%	14.5%	11.0%	12.7%
Community leaders	9.1%	2.7%	10.2%	17.4%	10.1%	8.2%	9.2%
Text/SMS	15.2%	10.8%	2.0%	8.7%	8.7%	8.2%	8.5%
Telephone message	15.2%	8.1%	6.1%	4.3%	4.3%	12.3%	8.5%
Digital sign	9.1%	10.8%	2.0%	13.0%	10.1%	5.5%	7.7%
Email	12.1%	0.0%	10.2%	8.7%	10.1%	5.5%	7.7%
Medium for alerts							
Website	23.5%	44.1%	24.5%	30.4%	29.0%	31.0%	30.0%
Radio	47.1%	32.4%	14.3%	56.5%	36.2%	31.0%	33.6%
Television	32.4%	17.6%	16.3%	43.5%	23.2%	26.8%	25.0%
Social media	35.3%	17.6%	0.0%	26.1%	20.3%	14.1%	17.1%
Bulletin board	2.9%	8.8%	14.3%	8.7%	5.8%	12.7%	9.3%
Pamphlet	2.9%	2.9%	0.0%	0.0%	1.4%	1.4%	1.4%
Phonetree	8.8%	5.9%	0.0%	8.7%	4.3%	5.6%	5.0%
Community leaders	2.9%	0.0%	4.1%	13.0%	4.3%	3.2%	4.3%
Text/SMS	47.1%	50.0%	26.5%	56.5%	56.5%	28.2%	42.1%
Telephone message	17.6%	11.8%	20.4%	8.7%	8.7%	22.5%	15.7%
Digital sign	5.9%	14.7%	4.1%	21.7%	11.6%	8.5%	10.0%
Email	8.8%	8.8%	14.3%	4.3%	8.7%	11.3%	10.0%

[a] Question allowed participants to select as many media as they wanted.

Those living in South & North Kona were more likely than those in Upper Puna and Ka'ū to prefer TV for alerts ($\chi^2(3) = 8.11$, $p = .044$), and social media was most preferred in South Hilo and Lower Puna and least preferred in Ka'ū ($\chi^2(3) = 19.3$, $p < .001$). People living in Ka'ū were also less likely to want to receive alerts through radio ($\chi^2(3) = 16.4$, $p = .001$) and text messaging ($\chi^2(3) = 8.05$, $p = .045$).

5. Discussion

Prior to this study, Island of Hawai'i residents were provided with advice on how to reduce risks from vog exposure during eruption crises and chronic degassing, by a number of health and civil protection agencies and associations. Table 1 highlights how this advice varied among the various organizations (including the order in which individual advice items were presented), potentially leading to confusion. Our study investigated how people experience and perceive vog, assessed whether and how residents accessed intervention advice, if they found it relevant and useful, how they acted on it (or developed their own interventions), and how they would like to receive advice and urgent exposure warnings in the future. The results of both the community focus group discussions and the questionnaire survey are discussed below.

5.1. Vog perceptions and symptoms

Previous research, conducted in 2001 in North and South Kona, found that participants considered vog to be the most likely natural or anthropogenic hazard to affect them within the following year [4]. This indicates that exposed communities have a high awareness of vog, and this finding is supported by the present study. The questionnaire survey confirmed that most participants noticed vog, although it was noticed by the highest number of participants, and most frequently, on the leeward side of the island (South & North Kona) and was most noticeable there in the afternoons. The prevalence of perceptions of vog in Kona is consistent with the chronic presence of vog on the leeward side of the island under prevailing trade winds. The diurnal wind regime blows the vog offshore at night and onshore through the day, where it is trapped against the flanks of the adjacent volcanoes [36] (Fig. 1). Most of the SO_2 gas has converted to sulfate aerosol by the time it reaches Kona, and this light scattering aerosol generates a highly visible haze against the mountains [33,34]. Closer to the vents, where SO_2 is more prevalent, participants more frequently reported smelling or tasting the gas. Some communities in Upper Puna can be impacted with even brief interruptions in trade winds, due to proximity to the vents.

A high percentage of participants (85.6%) noticed vog due to the onset of health symptoms, and this was similar to a separate question which asked if they perceived a change in their health when there was vog (83.2% said yes, with females more likely to experience symptoms) and 81.5% experienced two or more symptoms. Across the community focus groups, several adverse health effects and symptoms were also attributed to vog exposure. The contributors reported burning, itchy, and watery eyes (and 60.5% of questionnaire participants also reported eye symptoms). Some contributors had existing asthma and bronchitis (ranging from mild to severe and life-controlling), which they felt were exacerbated by the vog, and some had developed respiratory symptoms over time, which they thought were caused by the vog. Tam et al. (2016 [24] found that chronic exposure to vog aerosol on the leeward side of the island is associated with cough and a trend to reduced FEV1/FVC ratio (indicating an obstructive lung pattern) in children. Survey participants also reported blocked/running nose, cough, headaches, and colds with focus group participants describing lingering symptoms even after recovery. People also said that the symptoms from vog exposure were similar to having a cold/flu. Some people reported chest/lung pain and constriction, burning sensations, and breathing problems.

During high vog events, impacts to skin were also reported by focus group participants, including dry and/or itchy skin, rashes/red patches, and one person reported sunburn/windburn symptoms. People reported fatigue, 'fuzziness in the head,' and, through the Vog Talk group, dizziness. Some people felt the vog made them irritable and one participant described how he thought behaviour of children at the local school was adversely affected by the vog. Some people perceived that vog changes the flavour of food and drink.

Notably, there are a range of other environmental factors, such as the presence of mould and mildew (especially in high rainfall areas), second-hand smoke, pollen, or other allergens which may cause respiratory, skin, and eye symptoms attributed to vog exposure. There also may be times when volcanic air pollution interacts with a host of environmental irritants to exacerbate symptoms [6].

A few people in the focus groups felt they were completely unaffected by the vog but noted that they may have had symptoms which they had not previously attributed to vog, particularly related to skin issues. A number of people also reported that the vog initially did not affect them but that it does now (at the time of the survey), and this was also noted by several individuals in the questionnaire responses.

A substantial number of questionnaire participants (61.5%) perceived that vog exposure was harmful to their long-term (respiratory) health, with people with pre-existing respiratory disease being more likely to think this (72.7% of the 33 people with respiratory disease; 58.2% of the 110 people without respiratory disease). This high level of concern highlights the importance of advice-giving authorities providing information and updates of current medical knowledge, even during periods of relatively low volcanic activity and emissions.

The high level of awareness and experience of vog across the communities studied indicates that there is potential for high uptake of risk communication and public health information. Paton et al. (2001) [54] found that risk communication strategies were more likely to be successful when people had previously experienced a hazard themselves.

5.2. Protective actions taken to reduce vog exposure

The most effective intervention in protecting oneself from exposure to a pollutant is to remove oneself entirely from the affected area, and the participants in the community focus groups knew of several people who had moved away because of the vog, either to less affected parts of the island, to other Hawaiian Islands, or to the mainland U.S. Some people in the focus groups were considering doing so, themselves. In addition, one participant temporarily relocated to a vog-free part of the Island of Hawai‘i at least one weekend per month, on the advice of her doctor, with the objective of clearing her respiratory system through exposure to cleaner marine air and salt water. The questionnaire found that 32% of participants would consider relocating, which can be considered a marker of the severe impact that people perceive vog has on their lives. Yet, the fact that those interviewed/surveyed have not moved, implies that the economic and other costs of doing so outweigh the perceived benefits [7].

By far the most common response from the questionnaire participants was that they do not take action to reduce vog exposure. This contrasts with the focus group participants (who likely agreed to participate because of their interest and awareness of vog), who all took protective actions unless they perceived that vog did not harm them. As discussed in the following sections, inaction may be due to a range of factors, including not knowing about the risk or existing advice, perceptions of advice relevance or feasibility, feelings of not being able to control exposures and having to live with the pollution, or not being bothered by the impacts. Although most participants reported symptoms from vog exposure, and perceive that the vog will harm them in the long-term, their experience may not be sufficient to warrant action [55]. This may be especially true in Kona, where the particle ‘haze’ can be quite nebulous and easier to ignore than the presence of irritating SO_2 gas closer to the vent.

In relation to advice to go indoors and close doors and windows (which the questionnaire participants did occasionally to usually), focus group contributors reported that they do go indoors when there is bad vog, but many people’s houses are open to the environment, some just with screens and no glass in the windows, others with louvre/slatted windows. This was particularly the case for the participants in Ocean View and Pāhala (Ka‘ū district), whereas in Volcano Village (Upper Puna, which is at higher elevation and cooler temperatures), some people said that they do not go out at all when there is vog and considered their homes to be well-sealed. The focus group contributors also reported that modern houses were more efficiently sealed as many have fixed, double-glazed windows but that the older style houses tend to have louvred windows. They also noted the difference in house construction between those at sea level and those at higher (colder) elevations. The questionnaire survey results were consistent with the reported location-based differences in house construction.

As also seen in the questionnaire responses, few people in the focus groups had an air conditioner nor knew anyone who had one and there was the perception that air conditioners could introduce vog to the indoor environment. A few people had air cleaners/purifiers which, they perceived, really helped to improve indoor air quality. It is worth noting that the presence of air conditioners and purifiers in the homes may be linked to household income as well as temperature/elevation and house design. Districts in southeast and south Island of Hawai‘i have lower household income than west Hawai‘i [40].

Few people in the questionnaire survey used respiratory protection (‘never’ to ‘occasionally’). The focus group contributors also reported that they knew of a few (other) people who used respiratory protection (gas and particle masks) to prevent vog inhalation, but it wasn’t clear which types of mask were used. People also thought that baking soda and water applied to a disposable mask can work in reducing vog inhalation. This may link to the University of Hawai‘i at Hilo website (Table 1), which demonstrated this technique, although it was generally known before UH Hilo documented it.

In relation to self-developed interventions, people in the focus groups reported that sitting under a tree/in a vegetated area, or near dense native forest, offers some relief from vog exposure. There is evidence that certain types of vegetation can capture airborne pollutants, thereby effectively reducing local outdoor and indoor particulate concentrations (e.g., Refs. [56,57]).

In terms of managing symptoms, people reported that those with asthma take multiple medications to keep symptoms under control. Official advice recommends staying hydrated and many people in the focus groups agreed that this was useful as drinks ‘flush out’ phlegm from the throat. Some people felt that hot drinks and, especially, specific teas were particularly effective (there are herbal ‘vog remedies’ available in local food stores and pharmacies). The focus group contributors did not think that drinking plain water was particularly useful, which raises the question as to whether the questionnaire responses (‘occasionally’ to ‘usually’) were vog-specific.

Several people in the focus groups and questionnaire reported using over-the-counter, non-medicated saline nasal sprays or sinus rinses and eye gels/drops to manage rhinitis, congestion, and itchy eyes. Some had been prescribed medicated (steroidal or antihistamine) nasal sprays, eye drops or oral medications to reduce upper respiratory tract inflammation and irritation. Several people in the focus groups also reported washing their skin frequently when there is vog – the face and hands, in particular – which was perceived to help control respiratory and dermatological symptoms. One person reported that a warm cloth on the eyes helps with eye puffiness and irritation. Washing eyes with bottled water instead of catchment water (rainwater collected from roofs and stored in large tanks) was perceived to help, too. Catchment water may be acidic due to volcanic emissions and is commonly used as the sole water supply for much of the Island of Hawai‘i, as rural areas lack municipal water supply. People in the focus groups also reported the use of immune-boosting tablets or holistic/alternative medicine to promote overall health and resilience to the harmful effects of vog.

5.3. Use and relevance of advice

The questionnaire found that more than half of participants took action to reduce vog exposure, based on common sense or from information from friends or family, rather than as a result of receiving official advice. Those that had received advice identified Civil Defense, the USGS, or the HDOH as the advice source (totalling 45.3% of those who had received advice, with some of these participants receiving advice from multiple sources) with the majority stating that the advice was helpful (77.6%).

The focus group discussions were able to obtain deeper information on advice uptake. In general, the contributors thought that the official agency information, online, was not up to date and that the different agencies did not communicate well (based on inconsistent agency advice). Just over 40% of questionnaire respondents perceived the advice to be inconsistent; however, only 18.5% of the cohort responded to this question (those that said they used agency advice).

Participants from the Ocean View focus group felt strongly that the information was not relevant for them, particularly 'avoid physical exertion,' 'stay indoors,' 'use an air conditioner,' and 'close your house up tightly,' due to the structure of their homes and their outdoor lifestyles. Several people stated that, by the time you notice that the vog is an issue, it is already inside the home. The groups reported that going indoors was impractical for many people in these communities (but, particularly, retired Caucasians), who have chosen to have lifestyles where they are rarely in the house during the day. The point was also made that outdoor workers often cannot go inside. Focus group contributors in all locations found the advice to use air conditioning/purifiers irrelevant, as most did not have such devices in their houses.

5.4. Accessibility of advice and alerts

The mode of dissemination of public health protection advice is critical if communication is to be effective [58]. Online dissemination is currently the primary method of communication of vog protection strategies for all agencies involved. When gas emissions from Halemaʻumaʻu Crater first became extremely high in 2008–2010, Civil Defense issued alerts and advice via their website, radio, television, and optional cell phone text messaging (according to the agency focus group discussion).

The HDOH vog helpline provided a recorded daily update on vog level and 24-h medical information to callers. At the time of this study, the vog helpline was unavailable and no vog-related advice was provided on the HCCD website.

All focus group participants wanted the current advice on vog protection to be consistent on all websites offering advice, saying that it was annoying to have to go to multiple sites. They also suggested that it would be ideal to have one primary advice-giving agency such as Civil Defense.

The questionnaire survey found that the most popular way to receive advice was via website (54.9%). However, the residents in the Ocean View focus group were strongly against the prevalence of online advice and alerts, stating that many residents would be unaware of current websites because few people had computers (due to lifestyle choice or economic factors) and those that do have poor connection, with high-speed internet unavailable or unreliable in some rural areas. Those living at higher elevations in Ocean View also reported not having access to FM radio and having poor cellular reception. In 2015, much of Kaʻū had poor internet accessibility, and less radio reception than the rest of the county/state [59]. Those in remote Ocean View areas were keen to have a real-time warning system relevant to Ocean View conditions (there is already an HDOH regulatory air quality monitor installed at mid-elevation Ocean View); for example, a digital sign that tells people what the current vog concentrations are, perhaps as a 'traffic light' warning system at the entrance to the subdivision. Real-time warnings of gas concentrations have been used elsewhere in the world, such as following the eruption of Miyakejima, Japan [60]. Focus group participants in Pāhala and Volcano Village also wanted more real-time information. Funding and maintenance of such technology was discussed, and it was thought that this should be the responsibility of the primary advice-giving agency, but it was acknowledged that the costs were likely to be prohibitive.

In all focus groups, public service announcements were suggested; for example, a notice posted daily on a bulletin board by the local store or post office, with a vog forecast and advice. It was discussed how this could be provided by one of the agencies but posted perhaps by volunteers at the local Community Center, or another central location. All focus groups also suggested that regular information could be posted in the community newsletters or in county newspapers. They also reported that word of mouth was important, with people telephoning friends and family to warn them when the vog is bad, and how it would be good to have formal networks in place (although social media is taking this role already in some places).

In Volcano Village, which is close to the eruptive vents active in 2015, information on the current air quality at additional geographical locations was requested. Participants made suggestions for suitable locations for new monitors but concern was expressed about the lower accuracy of low-cost sensors as compared to EPA regulatory-grade air quality monitoring equipment such as that operated by the HDOH (although the high efficacy of certain types of low cost sensors for use in Hawaii has now been established; [32,61]. It was noted how difficult it would be to raise funds for the more accurate and expensive ones, and several potential funders were identified for supporting the cost of purchase, maintenance, and calibration. Ideally, people would like to be able to check the air quality in a particular location to influence their choices of whether to visit that place. One suggestion for achieving better local information was through 'citizen science' where residents report, perhaps through social media or an app, if the vog is bad in a particular location. The University of Hawaiʻi at Mānoa vog dispersion model (VMAP) uses modelled weather data with 900 m resolution to forecast the concentration and location of vog on the island [36]. Real-time local input could enhance and validate model information and help constrain uncertainties due to model resolution and island microclimate effects.

Volcano Village focus group participants were also keen that vog forecasts should be part of television weather reports (this does happen already, but the group wanted more detail and specific mention of vog rather than 'haze'). Other suggestions included: a rolling banner on the internet or television, or Civil Defense alerts on cell phones like they have for hurricanes, and frequent radio reports on areas currently affected by vog.

Finally, individuals in the Volcano Village group mentioned that, in general, people were not aware that there were ways to get air quality monitoring data, forecasts, or alerts about the vog (and one individual had even been told, in the past, that there was no information). Some contributors assumed that Civil Defense would put out a broadcast (of some kind) if the vog is bad, and, if this was not happening, then the group felt that people needed to know that a lack of broadcast does not mean that the air quality is fine. The focus groups were clear that people did not want to have to look for advice themselves (the 'self-serve' approach) but wanted information to be pushed to them by the agencies, which meant being kept regularly informed of conditions. Gregg et al. 2004 [4] found that, in their survey of Hawaiʻi residents, there was a similar expectation that officials would be responsible for community preparedness. Gregg et al. 2004 [4] inferred that this would lead to a low uptake of hazard information, less preparedness in the community to mitigate the effects of hazards, and that people would be less likely to react to warnings. Notably, a few participants did not feel the need for extra monitoring or forecasts as they knew when there was vog (by sensory signs such as sight, smell, taste, or onset of symptoms).

5.5. Confidence in authorities

Some participants questioned if their communities were visible to official agencies due to the lack of served information. Others questioned the breadth of understanding of community lifestyles and concerns by authorities, and the relevance of the provided advice. There was also concern about effective treatment and consistent advice regarding vog symptoms by medical doctors. The group in Ocean View expressed the importance of official recognition of the issues associated with vog to confirm the reality of their experience. The Ocean View group, in particular, felt like they were "hit really hard" by vog much of the time, and that it was a fundamental part of their lives that required official attention. As one person stated, in Ocean View "there is a price to living in paradise and we've chosen to pay it!" but, they said, that didn't mean that they didn't require help. It is acknowledged in the risk management literature that trust is easy to lose and hard to rebuild [62]; it is hoped that the work done following this study (Section 6) helped reassure communities that there is official validation of the challenges of living with vog.

A focus group contributor expressed concern about open discussions regarding vog. They questioned if minimising discussions of vog as a health problem was due to potential impact to real estate values, visitor numbers, and politics. The use of the word 'haze' instead of 'vog' on official National Weather Service forecasts was also perceived as a manifestation of this reluctance. Eiser et al. (2012) [7] explained that for trust to develop between communities and authorities people need to both perceive that the advice givers know what they are talking about and that they are acting for the safety and well-being of society and not for some ulterior motive. It is easy for conspiracy theories to develop, especially in the age of social media, if people perceive that agencies have been insufficiently communicative [63,64]. In this study, almost 60% of participants said that they had not received advice despite available web-based information. It was clear from the focus group discussions that some people purposefully chose not to have access to the internet, which would limit their access to self-serve information. This highlights the need to provide risk communication information via a variety of pathways to make it fully accessible [65].

Focus group contributors said they thought Civil Defense should be the primary advice-giving agency. Before the study was conducted, Civil Defense had little vog protection information on their website. It has been argued that effective risk messaging and uptake is possible if people trust a specific advice-giving authority [7]; however, it has also been argued that, in relation to complex hazards, people have to place their trust in the entire system of risk management, which depends on the collaboration among these different agents [66]. There is no doubt, however, that consistent messaging is required if there are multiple agents involved [9,67].

6. Study outcomes

6.1. Advice adaptation

Following analysis of data from this study, a report was distributed to the agencies who had participated in the focus group (see Section 3.2). Based on the study findings, discussions with agency representatives, and published best practices for public health messaging (e.g., Ref. [8]), we worked collaboratively with HDOH and additional agencies to produce new advice that was less generic and more relevant to the lifestyles and climates of Island of Hawai'i communities. Although 79% of questionnaire respondents who received agency advice thought it was helpful, and many participants took actions based on common sense rather than recommended advice, the revision of messaging was primarily in response to focus group feedback. Discussions had been clear that some generic wording was counter-productive and that consistent messaging from the multiple advice-giving agencies was also necessary for clarity. There was a need for the advice to be more socially relevant (or culturally appropriate) for the Island of Hawai'i communities [68]. The adapted advice acknowledged that some people may not be able to go indoors or close windows, that some houses may not be sealable, and that most people do not have an air conditioner or purifier. Words such as 'if possible' and 'if appropriate' were introduced to sentences, and alternative actions were given where recommended actions were not possible. An example of this is:

> New standardized advice: 'Stay indoors: When vog levels rise, go indoors and close all doors and windows to the outside and, if possible, seal obvious gaps under doors or around windows. Eliminate sources of indoor pollutants (i.e., smoking, candles/incense, and improperly vented fuel burning stoves) and beware of becoming overheated as a result of closing up your house. If your house is not well-sealed, it may still offer some protection. Alternatively, consider visiting indoor areas that are better-sealed and/or have air conditioning (e.g., commercial buildings or businesses).'[1]
>
> Old advice from HDOH: 'Stay indoors, and close the windows and doors tightly.'[2]

The self-developed interventions reported in the questionnaires and through the focus groups were also investigated and, where evidence was found (from the public health literature) of efficacy in related respiratory conditions (e.g., the use of nasal sprays for allergic rhinitis [69] and the use of hot drinks to loosen mucus [70]), such advice was incorporated into the new wording. Examples of new advice are:

> 'Manage congestion or irritation: over-the-counter nasal sprays or eye drops can help to reduce symptoms.'[1]
>
> 'Stay hydrated: Drink plenty of liquids to help loosen congestion. Warm or hot liquids in particular may help some people.'[1]

[1] HDOH FAQs at https://vog.ivhhn.org/FAQ.pdf.
[2] Original URL in Table 1 footnote.

6.2. Web-based and printable vog communication products

The adapted advice was packaged within three separate web-based and printable products, based on feedback from study participants on how they wanted to receive advice. The products provide different levels of advice tailored to different educational abilities, literacy levels [71], and learning styles to reach the widest audience possible. A simple poster was produced for placing on bulletin boards outside community centres and within schools. A double-sided rack brochure was produced for racks in health centres, libraries, and other public advisory spaces. A longer pamphlet/booklet, with much greater detail, was produced for agencies to distribute during crises or for people to pick up in community, education, and tourist centres.

Following development of the new advice, the agencies presented more cohesive web-based messaging to the public by linking to the new products from the agency websites or using the products' text on their webpages.

6.3. The Vog Dashboard

Since the study found that the participants were not aware of local websites hosting vog forecasts, monitoring data, and alerts, and there was confusion on the various sources of information, a dedicated portal of vog information for Hawaiʻi was created to provide a single location for accessing information about vog, its hazards, community protection, and forecasting/monitoring data. The authors created the International Volcanic Health Hazard Network (IVHHN[3])-hosted Hawaii Interagency Vog Information Dashboard[4] in 2016. The Dashboard represents a rare partnership between the IVHHN, HDOH, USGS, HCCD, NPS, CH, CSAV (Center for the Study of Active Volcanoes at the University of Hawaiʻi, Hilo), NOAA/NWS (National Oceanic and Atmospheric Administration/National Weather Service), and the U.S. Department of Agriculture Farm Service Agency. The printable products with vog protection and exposure reduction advice can be downloaded from the site, as well as comprehensive links to other vog fact sheets, eruption updates, vog forecasts, real-time and historical air quality data, as well as information on health and agricultural impacts, water catchment maintenance, and links to other data and scientific literature.

During the 2018 Lower East Rift Zone (LERZ) eruption crisis [19], the Dashboard was updated frequently with information on the eruption and advice for residents and visitors. It received up to 50,000 views per week and was recommended as a primary site for advice by various international media outlets (e.g., Ref. [72]).

In November 2022, Mauna Loa Volcano erupted for the first time since 1984. The Dashboard was again rapidly updated with a dedicated page on the eruption, including a set of frequently asked questions on air quality and health, and received around 46,000 views during the approximately 15-day eruption.

6.4. Social media presence

Survey results also identified the importance of social media for communicating vog information, so an additional study outcome was the creation of a social media ‘Vog Talk’ group. This group grew in popularity from its establishment and proved itself very useful during the 2018 LERZ crisis when it had almost 2000 followers and during the 2022 Mauna Loa crisis (1100 followers). In addition to pointing users to official agency advice, the group provided a conduit for experts to answer the community’s questions and concerns about vog and to dispel misinformation. In addition, it was clear that the community appreciated having a forum in which to share and discuss their experiences of living with vog.

6.5. Vog in weather forecasts

This study highlighted the need for transparent language when including vog in weather forecasts. NOAA/NWS policy constrains the language used in radio/television and other forecasts to official weather element terminology. The term ‘haze’ is listed as an official NWS weather element and has been used in place of the term ‘vog,’ which was not a nationally approved term. ‘Haze’ refers to a reduction of visibility and may be due to a number of causes which can be hard to differentiate. After many years of effort, NWS has recently approved the term ‘vog’ as a new official weather element so that it can be used in future weather forecasts (R. Bohlin, National Weather Service, Honolulu, personal communication, November 7, 2022).

6.6. Community involvement and advice uptake

It is well known that risk communication and uptake of advice is more effective, and trust in the advice-givers greater, if the beneficiaries are empowered by inclusion in the hazard management process [73]. This project focused on gathering community input and feedback and determining local social and environmental context through the social survey and focus group discussion process (as recommended by authors such as [8]). Feedback following the research process was achieved via community meetings in January and August 2016, and January 2017, where results of the study were presented, and input sought on the new informational products. Lessons learned in this study have contributed to an even more inclusive approach in developing subsequent IVHHN hazard communication products with community representatives directly involved in product development, including style and story board (in the case of videos).

A full evaluation of the response to the revised advice has not been undertaken, and, while time and distance from this project prevent a robust review, an effort to gather some feedback was made in 2018. An online survey (open responses) was advertised through the ‘Vog Talk’ social media group and by word of mouth but had a low response (n = 5). The questionnaire and results are presented

[3] IVHHN is an organization which provides information and advice for the public, scientists, emergency managers, and governments on the health hazards and impacts of volcanic eruptions, and community protection.

[4] https://vog.ivhhn.org/.

in the Supplementary Material (SM2). Respondents reported they had used the products and found them useful for general information, educating others, answering health related questions, and that the new wording on protective actions was relevant and helpful (n = 3). Respondents also reported that the products had enhanced their understanding of the health risks, how to protect themselves, and had changed behaviour based on the advice (n = 2). The Vog Dashboard was used and identified as a useful information resource (n = 4) and had led to behaviour changes due to improved access to information (n = 2). Respondents that reported on confidence in advice-giving agencies based on the newly available resources (n = 3), noted improved (n = 2), or unchanged confidence (n = 1). Incorporating an evaluation phase for future projects on hazard communications is an important lesson learned from this study.

7. Conclusions

Kīlauea's dynamic and frequent eruptive activity results in periods of poor air quality that exceed National Ambient Air Quality Standards on the Island of Hawai'i [32]. Following the 2018 eruption, Kīlauea entered its longest period of quiescence since 1983, with no activity until Halema'uma'u began erupting again in December 2020 [74]. Activity has waxed and waned, with a several months' pause in summer 2021, and a several-week pause in late 2022. Sulfur dioxide gas emissions during periods of quiescence are extremely low, and the island experiences vog-free conditions [28]. Emissions increased with the onset of the eruption in 2020, but magma effusion, gas emissions, and airborne gas and particle concentrations have been low to moderate [75]. There have been some impacts on downwind communities during trade wind conditions and on proximal communities during wind reversals; however, they are less than previous eras at Kīlauea [28].

Such times of lower-level or non-eruptive activity give us time to plan for future, larger eruptive episodes at Kīlauea and nearby Mauna Loa Volcano. Mauna Loa's 2022 eruption produced high gas fluxes, with SO_2 emissions of at least 250,000 tonnes/day [76]. These emissions rarely impacted populated areas as they were mostly dispersed at altitudes well above ground level [28,77]. Future eruptions of Mauna Loa with lower elevation vents may have a very different level of impact to populated areas [78,79].

While the sample size of the current study was small, and based on accessibility rather than random sampling, it gave us a snapshot of people's perceptions of vog impacts and official communication and mitigation efforts. The information and various products generated by this study allowed rapid response to the 2018 Kīlauea lower East Rift Zone and the 2022 Mauna Loa crises, with prompt deployment of information and knowledge via the Vog Dashboard. In response to the 2018 Kīlauea eruption, the U.S. Department of the Interior Strategic Science Group identified potential actions to mitigate consequences of vog in future eruptions. Many of these actions incorporated the findings and content of this study, e.g., develop regional vog push notifications, present consistent messaging, effectively communicate risk and provide education about health impacts of vog, include non-digital communication for warnings, and enhance vog modelling efforts. They even recommended creating an Island of Hawai'i vog officer to coordinate consistent communication across federal, state, and county agencies [80]. The USGS also noted in their Kīlauea 2018 eruption 'After Action Review' the relevance of creating a vog officer position to enhance consistent communication [81].

Results from this study also helped stimulate improved international products developed by the IVHHN. For example, the revised vog advice wording from this study was incorporated into new informational products on the hazards and health impacts of volcanic gases (currently available in English, French, Japanese, and Spanish[5]). It is hoped that the content of these products will be adapted by agencies around the world for use in their local communities. Also, the practice of producing printed media in various formats, and for audiences encompassing various educational levels, was used in new World Health Organization (WHO)-endorsed volcanic ash protection information products produced by IVHHN.[6]

Goals for future projects include involving local communities in the development of public advice and products. Co-design helps to ensure uptake of products and subsequent behaviour change, as communities feel included in the process [82,83]. Local communities are frequently best qualified to advise on social learning related to culturally relevant product design [84]. In addition, working to expand information accessibility across a variety of media beyond printable products and webpages will ensure that more sectors of the communities can access the advice. As communication technologies and populations evolve, repeating social studies of this type, on a larger scale, will help optimize risk communications, increase recognition of vog hazards, and encourage future epidemiological and clinical research. Incorporating an evaluation phase for future projects will help assess the uptake of new or revised information.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data availability

Data will be made available on request.

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[5] https://www.ivhhn.org/information/health-impacts-volcanic-gases.
[6] https://www.ivhhn.org/information/public-information-material.

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Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2023.103853.

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