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A Place-Based Teacher Engagement Program Using Low-Cost Air Quality and Weather Sensors in Hawai'i After the 2018 Kīlauea Eruption

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ABSTRACT: On the Island of Hawai'i, a low-cost sensor network that measures air quality (particulate matter and sulfur dioxide concentrations) and weather conditions was used for a two-year place-based engagement program with elementary and high school teachers and students (42 teachers, 553 students, grades 3-12). In this program, the sensors and their data were used to create new educational activities that meet U.S. Next Generation Science Standards. The program's first year, in the aftermath of the 2018 Kīlauea eruption, focused on atmospheric chemistry of volcanic smog ("vog"). With improved air quality after the eruption's end, the program shifted to emphasize weather and climate. To engage with local teachers and students, a unique combination of place-based approaches was developed: i) low-cost sensors hosted by schools to measure local conditions, ii) participation by local scientists and scientific institutions, and iii) inclusion of traditional Hawaiian environmental perspectives and observation techniques. Satisfaction survey feedback from teacher participants identified three main themes: i) teachers valued the sensor networks, though many needed additional technical support and training to integrate data and develop data-centered educational modules, ii) inclusion of cultural perspectives of vog and weather deepened appreciation and interest in local environmental phenomena, and iii) the program fostered valuable networks to connect participants with local educational resources and scientific institutions.

INTRODUCTION

Poor air quality impacts nearly the entire global population and is responsible for millions of deaths each year (WHO, 2022). In many locations, poor air quality is exacerbated by wildfire smoke and extreme heat driven by changing global climate (Jacob and Winner, 2009). To address these inter-connected and increasingly complex environmental challenges, STEM educators need new data-centered, place-based approaches and tools (Kennedy and Odell, 2014; Margot and Kettler, 2019). Despite the importance of earth and environmental science education, there are still limited learning modules and inquiry-driven activities that meet modern educational standards (e.g. US Next Generation Science Standards, NGSS) and integrate STEM concepts (e.g. data practices, use of models, computational thinking) across disciplines (Honey, et al. 2014; Takeuchi et al., 2020). A promising tool to address this is small, low-cost environmental sensors that collect quantitative data from their local surroundings. The sensors and their data are well-suited to develop data-driven education modules and to conceptually connect local measurements to global issues.

During the 2018 Kīlauea volcanic eruption on the Island of Hawai'i, the authors built a custom network of low-cost air quality and weather sensors (Crawford, et al., 2021, Figure 1) that was used to develop a prototype engagement program for local teachers. Overall, the primary goal of this program was to provide teachers and students with place-based tools (sensors and data) to develop classroom lessons and activities that target specific STEM practices (data analysis and interpretation, inquiry skills) for atmospheric chemistry and weather/climate. To effectively engage program par-

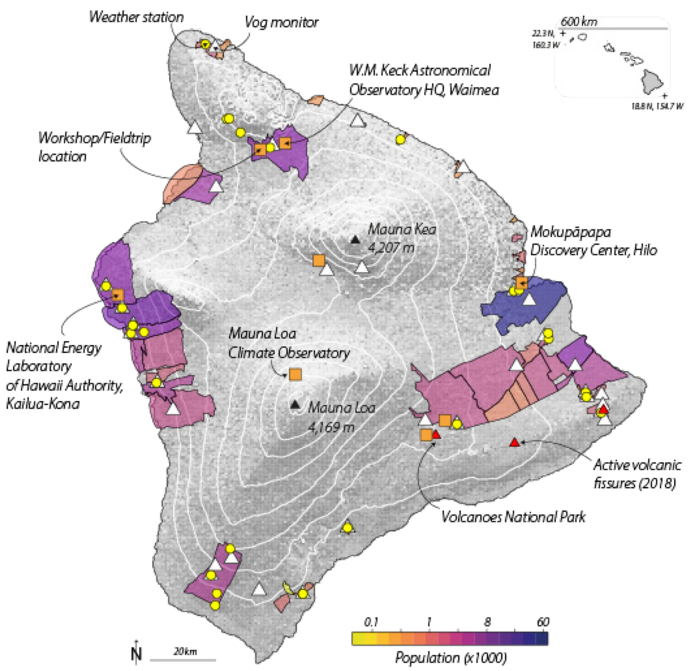

Figure 1. Hawai‘i Island with locations of vog monitors (white triangles), weather stations (yellow circles), and program workshop/fieldtrip locations (orange squares) during 2018-2020. Population is shown for census designated places (colored polygons). Total population is 200,629 people according to the 2020 census. Elevation is shown with 500 m contours (white lines).

Table 1. *Summary of place-based approaches used to design the education outreach program.*

Place-Based Component	Description	How This Was Actively Incorporated into the Program
Low-cost environmental sensor network	Vog and weather sensors located at K-12 schools around the Island provide local environmental data for classroom lessons.	• Teachers developed and shared lesson plans aligned with NGSS, based on sensor data. • Students used vog network data for original research projects • Classroom visits and activities were developed using low-cost PM sensors.
Local research institutions	Expert assessments, role models, and view of science work that is being done in the community.	• A range of local scientists participated in workshops as guest speakers. • Local research institutions hosted program workshops and field trips.
Traditional Hawaiian perspectives	Traditional cultural approaches to vog and *kilo* weather observations.	• Hawaiian cultural scholars participated in workshops as guest speakers and actively led participants in traditional chants and songs, focused on oral histories of volcanic eruptions and emissions. • Participants learned native Hawaiian names for environmental phenomena (types of clouds, precipitation, wind, and volcanic emissions) and actively participated in weather observations using traditional techniques.

ticipants, the research team designed the program around a unique combination of place-based learning approaches (Table 1, also see Section 2).

The program consisted of a series of workshops and classroom visits across two academic years (AY2018-2019, AY2019-2020, Figure 2, Table 2) to introduce teachers to the sensors and data and help incorporate them into classroom lesson plans. The first year's program (AY2018-2019) was focused on the chemistry of "vog" (volcanic smog, composed of fine particulate matter and sulfur dioxide gas) and air quality during the immediate aftermath of the 2018 Kīlauea volcanic eruption (May-August 2018). This portion of the program was approved as an accredited professional development (PD) course by the Hawaii Department of Education. The PD course was designed for three credit hours, with eight hours of contact time for each credit hour (please see the Appendix for full description of the PD program).

During the second year (AY2019-2020) the emphasis shifted to weather and climate due to the cessation of the eruption and resulting vog-free air. The intention is that this program could serve as a model for future community and educator place-based engagement programs to integrate sensors and data-based activities into classrooms, as well as merge complementary scientific and cultural environmental perspectives.

Place-Based Engagement. Place-based engagement programs can be a key mechanism for communities to connect and coordinate about important local environmental issues. In the United States (US), the Academic Competitiveness Council has listed informal education (including engagement and outreach programs) as one of three integral pieces of the US education system, alongside K-12 and tertiary education (NRC, 2009). These programs can provide freedom for educators and learners outside of normal curriculum

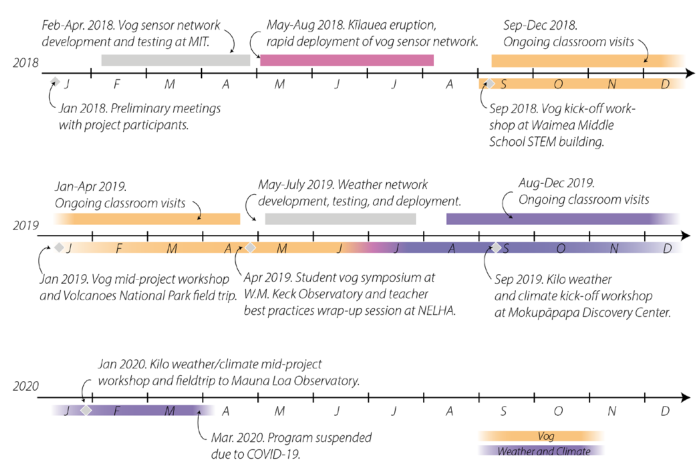

Figure 2. Timeline of the two-year education outreach program. The first year (AY 2018-19) was focused on vog chemistry and the second year (AY 2019-2020) transitioned to focus on weather and climate.

Table 2. *Summary of vog and kilo (weather & climate) workshops.*

Workshop Name	Date	Participating Teachers	Survey Responses
Vog Kick-off	Sep 2018	21	19
Vog Mid-Project	Jan 2019	20	14
Vog Wrap-up	May 2019	9	9
Kilo Kick-off	Oct 2019	18	14
Kilo Mid-Project	Jan 2020	19	19

standards and can create a fun and positive atmosphere for learning (Feldhausen, et al, 2018). Moreover, place-based learning approaches primarily use local environments and phenomena to engage communities, rather than knowledge developed about other places by people they will likely never meet. In this way, learning can be resituated within the context of local communities and bridge the gap between school classrooms and students' lived experiences (Smith, 2002). Furthermore, place-based learning can be a powerful tool for engaging learners from underrepresented groups (DeFelice, et al., 2014; Harris et al., 2021).

To engage participants and connect global concerns and concepts (e.g. air quality and atmospheric chemistry) with the local environment, a novel combination of place-based learning approaches was developed (Table 1): i) use of low-cost sensors hosted by schools to record local environmental conditions; ii) participation from local scientific institutions to provide expert guest speakers, informal mentors, and meeting venues; and iii) merging traditional Hawaiian cultural perspectives and knowledge about vog and weather with modern scientific practices.

The central place-based component of our program was the low-cost sensors to measure local air quality and weather conditions (Figure 3). Based on classroom experience and student evaluations, low-cost sensors are an engaging way to introduce modern scientific practices and expose students to authentic datasets and data science applications (Crawford et al., 2022). Additionally, hands-on experience with sensors introduces students to engineering design, construction of technological devices, computer programming, and tools to test scientific hypotheses (Hotaling, et al., 2012; Kelley and Grünbaum, 2018; Windleharth et al, 2022). By providing participatory experience with environmental sensors, data, and computing technology, students can directly observe their local environments.

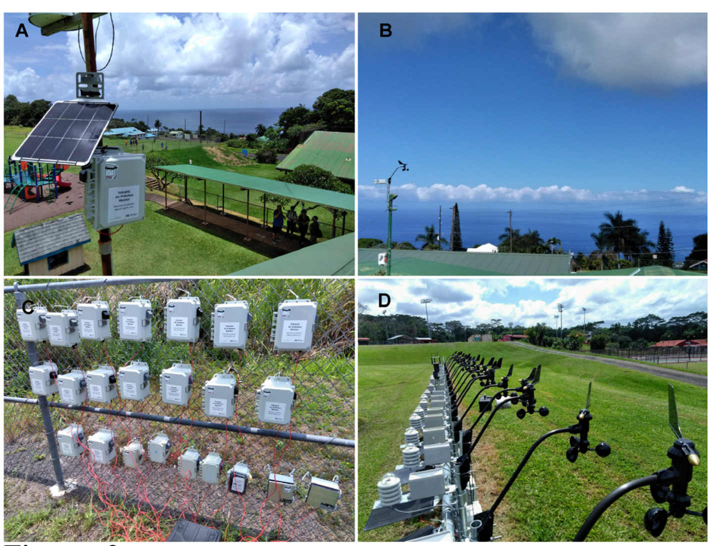

Figure 3. Example a) vog sensor and b) weather station installations on school rooftops. Testing and calibrating multiple c) vog sensors and d) weather stations with reference instruments before deployment at K-12 schools.

Additionally, through participation of local scientists and local scientific institutions, teachers and students were able to actively see scientists who live, work, and grew up in local communities. This type of exposure may encourage the perception of scientific careers as more realistic possibilities for students. Local scientific institutions may also elicit pride in local achievements and interest in local scientific and environmental issues. Importantly, this interaction also fosters local networks of educators and scientists to engage in future collaborations.

The third unique place-based aspect of this engagement program was the inclusion of Native Hawaiian perspectives on vog and weather observations. Approaching environmental phenomena through local socio-cultural viewpoints can have a positive effect on students' attitudes towards learning science (Jegede & Okebukola, 1991). This approach can reduce barriers to persistence in learning, as students from underrepresented groups often report they do not feel STEM is "for them" (Hinnant-Crawford, 2016). This is especially important given the diverse cultural makeup of Island of Hawaiʻi and the prominent intersections between Native Hawaiian bio-cultural heritage and local environmental concerns (Chapman, 2022).

Vog and the 2018 Kīlauea Eruption. On the Big Island of Hawaiʻi (USA), vog had been recognized as an air quality nuisance for the Island's nearly 200,000 residents for several decades prior to the 2018 eruption (e.g. Longo, et al., 2010). Kīlauea is one of the world's most active volcanoes and had been in a continuous, effusive eruptive phase from 1983-2018. During this time, sulfur dioxide (SO_2) gas was emitted continuously from volcanic vents. The volcanic plume was carried downwind to the southwest by nearly constant trade winds, and the SO_2 gas chemically transformed into fine particulate matter (PM). Epidemiological studies conducted in downwind communities found vog to be associated with a variety of adverse cardiorespiratory symptoms including increased risk of acute bronchitis in exposed children (Longo 2008). Heavy vog days were also associated with an increase in respiratory emergency medical visits (Michaud, et al., 2004), coughing (Tam, et al., 2016), and school absenteeism (Uchima, et al. 2018).

From May-August 2018, Kīlauea unexpectedly experienced its largest eruption in more than 200 years (Neal, et al., 2018). Near the eruption, environmental impacts were severe as hundreds of homes were destroyed and thousands of people were displaced by flowing lava. Additionally, elevated SO_2 emissions (>50,000 tons per day, Neal, et al., 2018) degraded air quality across the Island as the volcanic plume was carried downwind to populated areas.

To assist with community air quality monitoring during the eruption, the research team deployed a network of over 30 low-cost air quality sensors around the Island, primarily at K-12 schools, to measure SO_2 and PM concentrations (Crawford, et al., 2021). Low-cost sensors are defined by the EPA as less than $2,500 and these custom models cost approximately $1,000 each. The sensors were small standalone units with solar rechargeable batteries and cellular communications (see Crawford, et al., 2021 for full technical description, schematics, and calibration details). A primary motivation of this deployment was to make real-time air quality data publicly available at finer resolution than is provided by regulatory networks. In addition to providing scientific insights about vog chemistry, transport, and community exposure, interpreting the high-resolution data can help residents build awareness about air pollution sources, exposure pathways, and health outcomes (Clements, et al., 2017). After the eruption abruptly stopped in early August 2018 and skies were free of vog for the first time in decades, the public health imperative for the network subsided, and the network and data were used to engage local communities, particularly K-12 educators and students.

After the eruption stopped, the team built a separate network of 30 low-cost weather stations to complement the vog sensors. These stations measured seven weather variables: air temperature, relative humidity, atmospheric pressure, sunlight, precipitation, wind speed & direction (Figure 3). As with the vog sensors, each unit was powered by solar-charged batteries and transmitted data to an online database via cellular network. Weather station prototype units were constructed by an MIT class in January 2019 and the full network was built by a high school robotics club (Kealakehe High School) during a 2-day build session in July 2019. The majority of weather stations were co-located with vog sensors or in school gardens at K-12 schools (Figure 1).

PROGRAM DESCRIPTION

The educational engagement program occurred across two academic years (AY2018-2019, AY2019-2020, Figure 2, Table 2). Prior to the program's commencement, a series of meetings was held in January 2018 to meet with local educators and health professionals. The purpose of these meetings was to introduce the engagement program, establish working relationships, gauge interest in participation, and determine whether schools and health clinics would host sensors on their properties.

An introductory one-day kick-off workshop was held near the beginning of each school year to open the program and a second mid-project workshop and fieldtrip was held in January. Several local scientific research-based institutions were used as venues to host workshops and program fieldtrips and to provide participants with a behind-the-scenes view of science work happening in their communities (Figure 1). Both vog and weather/climate programs relied on diverse perspectives from working scientists and native Hawaiian cultural practitioners. The vog program culminated at the end of the 2018-19 school year with a student research symposium and teacher best practices wrap-up session. A planned symposium in April 2020 on weather/climate was cancelled due to the COVID-19 pandemic. Between workshops, a series of classroom visits using hands-on activities were conducted throughout each year (Figure 4). Overall satisfaction with the program and progress towards workshop goals were assessed with post-workshop surveys and a teacher best practices session.

The foundation of the project's successful partnerships was The Kohala Center (TKC). TKC is a community-based non-profit on the Island of Hawai‘i, focused on research, education, and *‘āina* stewardship for healthier ecosystems. Individuals from TKC and the university partner were previously acquainted through personal networks and collaborated to develop and secure funding for this project. As the local community partner, TKC connected individual teachers and schools to the vog program through relationships formed during prior environmental education programs and community connections. Once initial interest in the program had been established, individual teachers volunteered to host sensors and invited academic partners for classroom visits.

To ensure equitable collaboration, the University-TKC partnership relied on i) participation from both parties during all phases of the project, ii) a transparent and equitable funding structure where resources were distributed directly to each party for independent budgeting, and iii) responsive interpersonal relations that allowed open communication and flexible operations to meet project goals.

Year 1: Vog.

Teacher Professional Development Workshops. The year-long vog teacher training program was approved as an accredited Professional Development course by the Hawai'i Department of Education (please see Appendix for the PD description). The application was authored by Dr. Vandiver and included a leadership role for The Kohala Center personnel. To receive credit, teachers were required to participate in a series of workshops and develop a final Learning Portfolio including samples of student work, examples of sensor data used at grade level, and lesson plans aligned with Next

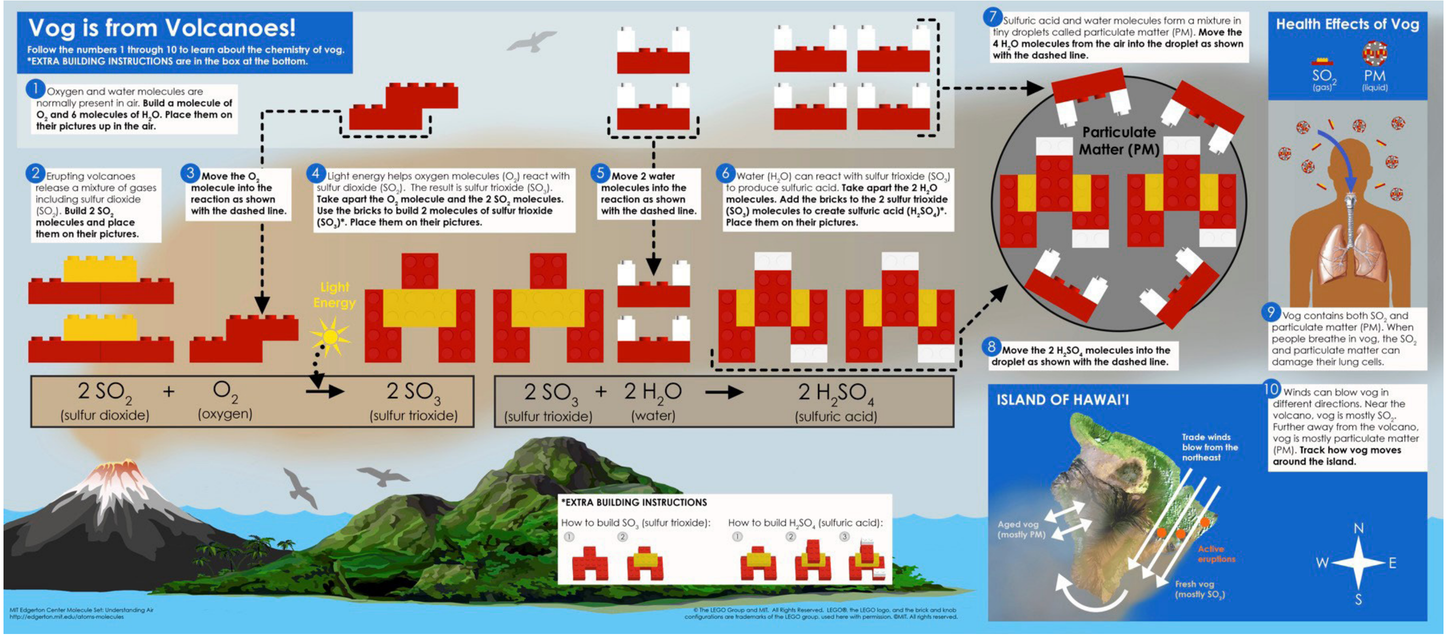

Figure 4. The MIT Edgerton Center "Vog is from Volcanoes" Mat models the formation of vog from sulfur dioxide; the health effects from breathing vog; and how weather patterns influence vog concentration over Hawai'i Island.

Generation Science Standards (NGSS) (see Appendix for example lesson plans). Teacher lesson plans were assessed in terms of alignment by whether specific listed standards and components were addressed with specific, age-appropriate activities.

The vog kick-off meeting was held at Waimea Middle School's STEM building in early September 2018, less than one month after the eruption had ended. The objectives of this day-long workshop were to introduce the year-long program, orient teachers on vog network data access, introduce additional instructional tools, and foster networking and communication amongst the program cohort. In total, 21 teachers attended, from a range of grades (5-12), school types (large public, small charter), and subjects (STEM & humanities).

During the workshop, teachers participated in several hands-on activities as examples of classroom lesson plans. Teachers were given a technical summary of the vog network sensors and instructions to access data online. Participants also constructed their own Arduino-based air quality sensor unit to demonstrate how unseen air pollution can still be counted and measured (MIT, 2022a and Appendix). Additionally, teachers were provided with access to custom LEGO™-based vog chemistry classroom Molecule Sets from the MIT Edgerton Center (MIT, 2022b and Supplemental Information). Each Molecule Set included a collection of LEGO™ bricks as model atoms and a set of building instruction to demonstrate what happens to atoms as SO2 gas is converted to sulfuric acid PM (Vandiver, 2019, Figure 4). These hands-on activities were designed to meet numerous NGSS goals including teaching cross-cutting concepts, such as the atomic nature of matter.

Participants also learned about Hawaiian perspectives on Kīlauea and vog from Native Hawaiian scholars. This involved identifying and discussing the role of the volcano and volcanic emissions in traditional Hawaiian chants and dance and cultural sensitivities around identifying this naturally occurring process as "pollution". Kīlauea is an important location in Hawaiian culture and is home to Pele, the animating essence of volcanism. Volcanoes are generally respected as a source of creative destruction and there are several Hawaiian language words for volcanic gases and emanations found in traditional chants and songs: "*uahi*" is a general term for smoke, "*ua'awa*" refers to acidic rain, and "*kūkae Pele*" describes the acrid sulfur smell associated with volcanic activity and landforms (i.e. sulfur banks). Several chants describe devastating historical eruptions, including firsthand descriptions of volcanic gas emissions. Most mentions of volcanic *uahi* are straightforward observations and do not include fear or other negative expressions. When *uahi* appears and inundates the environment, it is taken as a reminder that Hawai'i Island is actively creating new land. From this contextual analysis, it appears that vog was accepted as a part of daily life and a constant indication that humans are only temporarily occupying the *'āina*, or land, and that Pele will remain long after humans are gone.

In January 2019, a follow-up one-day mid-project workshop was held with 45 participants, including teachers, students, and a panel of five expert speakers. These speakers presented diverse perspectives on geochemical, meteorological, health, ecological, and Hawaiian cultural aspects of vog. During this workshop, the group also participated in a guided tour of volcanic features at Hawaii Volcanoes National Park. The workshop was held in Volcano Village, just outside of the National Park, to be inclusive of teachers on the southern and eastern sides of the Island.

The vog workshop series culminated at the end of the academic year at a Student Research Symposium, held at the W.M. Keck Observatory astronomy headquarters (Waimea, Big Island, HI). At this event, student groups (grades 5-12; 14 total students) presented their vog-related projects to peers, teachers, parents, and other community members. The symposium also included student research from a separate environmental education project about marine ecology. Student projects took a wide range of forms: several focused on statistical analysis of vog data from during the eruption and identified spatial and temporal extreme events and averages from across the network. Another project used vog data in conjunction with a podcast where local residents shared stories and reflections about the eruption. This event also included a keynote speaker from the USGS Hawaii Volcano Observatory who shared perspectives about the 2018 eruption and the speaker's personal path to becoming an environmental scientist. After the student symposium, a best-practices wrap-up session for teachers was held at the NELHA facility (Natural Energy Laboratory of Hawaii Authority, Kailua-Kona) as an opportunity for teachers to share lessons, submit feedback, and formally conclude the first year of the program.

In-Class Visits. Throughout the school year, the research team developed an age-adaptable presentation and sensor-based activity focused on vog chemistry and air quality. During a series of ten school visits (grades 3-12; 553 total students; Table 3), the eruption was found to be to be a strong shared "anchoring" event (Theobald, 2015; Thompson, 2018), or shared experience, that provided an effective pathway to introduce concepts about air quality, atmospheric chemistry, and meteorology. Anecdotally, this was evident through informal class discussions where students and instructors shared stories about their experiences during the eruption and their impressions of vog and its health effects. This seemed to help form tangible links between recent real-world events and more abstract scientific concepts.

The sensor-based activity was a hands-on exercise using several low-cost particulate matter (PM) sensor units (Figure 5). Each sensor was equipped with a digital display to show one second readings of $PM_{2.5}$ (PM with a diameter less than 2.5 micrometers, measured in units of micrograms per cubic meter). Student groups (2-4 students) were given one sensor each and instructed to make measurements of PM concentrations from a range of provided sources (e.g. matches and candles; chalk dust; paper, which releases PM when ripped; dirt and soil; exhaust from contrasting vehicle types). Students recorded baseline PM values and were encouraged to experiment with each PM source and compare and contrast measurements. Presentations and activities were tailored for specific grades and when appropriate, students were instructed to venture outside the classroom and find additional PM sources on their own. With these activities, students developed hypotheses about the magnitude of different air pollution sources and were able to directly test these using measurements from the low-cost sensors.

Table 3. *Summary of in-person classroom visits during the vog program AY2018-19. Multiple classrooms were visited during trips to elementary schools.*

Grade	Classrooms Visited	Students	Contact Hours
Elementary (grades 3-5)	15	278	15
Middle (6-8)	3	117	3
High (9-12)	4	158	4
Totals	***22***	***553***	***22***

Figure 5. Photos of a) presentation during the weather/climate teacher workshop at Mokupāpapa Discover Center, Hilo in September 2019, b,c,f) students actively measuring and recording PM readings with low-cost sensors during classroom visits, d) an example low-cost air PM sensor built by teachers during the vog workshop program opening, e) program participants learning outdoors about *kilo* personal sensory-based weather observations near the Maua Loa Climate Observatory in January 2020.

Year 2: Weather Sensors. During Year 2 of the program (AY2019-2020), the eruption had stopped and the focus of the program pivoted to weather. Teacher workshops were held following the format of Year 1 and at the kick-off workshop (September 2019 at NOAA's Mokupāpapa Discovery

Center in Hilo), 18 teachers were introduced to the weather sensor network and provided with sample classroom datasets and activity guides. Teachers also learned about atmospheric science and teaching resources from professional meteorologists (National Weather Service), climatologists (Mauna Loa Observatory), and actively participated in Hawaiian weather observation practices ("*kilo*").

"*Kilo*" is a fundamental skill of environmental observation, engagement, and problem-solving based on personal sensory awareness of one's local surroundings. Traditional *kilo* is based on the Hawaiian lunar calendar ("*Kaulana Mahina*") and was employed by navigators to observe environmental conditions and weather patterns during long ocean voyages. The concept of *kilo* can be applied broadly to many types of environmental activities and domains (e.g., agriculture, wildlife, astronomy), including meteorology. During this educational program, teachers and students learned to use *Kaulana Mahina* as a tool to organize daily weather observations (e.g., wind direction and cloud types) and analyze seasonal weather changes and trends. Students were taught how to make observations, how to record and organize the information, and how to identify trends and specific natural environmental indicators. For example, students learned that a specific cloud type ("*ao pua'a*", a form of *cumulus humilis*) can indicate fair weather with no impending storms, while different cloud formations ("*ho'oweliweli*", or threatening *cumulonimbus*) indicate approaching severe weather. The collected observations helped students describe seasonal meteorological patterns and the *kilo* concept gave personal sensory-based observations context as a continuation of effective historical practices. This approach aligns with fundamental skills of scientific inquiry and complements technological sensor-based measurements with personal sensory-based observations.

At the mid-project workshop (January 2020), 19 participants toured Mauna Loa Observatory, a NOAA climate monitoring facility at 3,394 m (11,135 feet) elevation, best known for measurements of global background CO_2 concentrations dating back to 1958 (Keeling, 1976). During the two-day workshop, the teachers also shared and participated in breakout sessions devoted to network weather data practices and activities; climate and weather teaching resources and strategies; and *kilo* observations. Following this workshop, as teachers and students were preparing research projects for a planned symposium in April, in-person classes across Hawai'i were cancelled due to the COVID-19 pandemic. After consultation with participating teachers, the planned April 2020 symposium was also cancelled.

RESULTS

Program Evaluation and Assessment. Surveys were administered to all program participants to assess perceived benefits of and overall satisfaction with the program. Surveys were designed by the authors and administered after each workshop. The surveys contained questions to assess specific program components, as well as levels of interest in, confidence with, and intention to integrate project-related content and information into their teaching curricula. The surveys also contained open-ended questions to identify lessons learned and solicit opportunities for improvement. This section integrates survey results from both years of the program. Three themes were identified:

1. **Teachers were interested in the sensor data and recognized its value but needed additional support to use and integrate data in their lessons.**

Overall, teachers evaluated the vog sensor network and data components of the program positively. On a five-point ordinal scale from (1) "not very" to (5) "very", teachers (n=9) reported: i) high levels of satisfaction regarding the quality of the vog network (mean=4.2, 78% of respondents reported being satisfied or very satisfied); ii) the potential usefulness of the network (mean=4.2, 89% satisfied or very satisfied); and iii) the accessibility of the network data (mean=4.3, 100% satisfied or very satisfied).

Although teachers reported overall satisfaction with the network, there was some uncertainty about how to integrate this into their teaching curriculum. In the same survey, even though teachers reported great interest in integrating the vog information (mean=4.4, 56% very interested) and that their "*awareness and understanding of air quality significantly increased*" (mean=4.3, 56% completely agree), they were less confident in their ability to integrate the material (mean=3.2, 44% were confident) and thought they were less likely to do so in the future (mean=3.7, 67% thought they were likely to do so). Despite this uncertainty, teachers did report classroom activities that used the vog network, including data analysis, graphing, and as a "*springboard for further development of sensor-based data collection and experimentation.*"

Based on responses to the open-ended survey questions, this disconnect likely resulted from several factors. One element is that the volcano stopped erupting and there was no longer vog, so interest in this environmental issue waned. Another important factor was teachers' comfort and facility working with large environmental datasets and teaching scientific data practices. Teachers commented that "*more assistance with network data analysis, interpretation, etc.*"and "*more lesson planning around data analysis*" would have been helpful.

This indicated a further need to build capacity and additional training for teachers in statistics and data analysis. To address these concerns, the research team took several measures. First, smaller sample datasets to be more accessible for students and teachers (Appendix) were created. These datasets consisted of averaged data (hourly and daily averages, instead of high-frequency samples) from a limited number of stations (5-7), for a short period of time (1 week – 1 month). The research team then held technical data-analysis sessions where teachers could practice using widely available spreadsheet programs (Excel, Google Sheets) to create graphs and statistical descriptions of the pared-down dataset.

2. **Teachers valued and enjoyed learning about cultural perspectives of vog and *kilo* and how this complements quantitative sensor network data.**

Responses to open-ended survey questions indicated program participants valued the inclusion of cultural perspectives and integration with scientific knowledge. One way the program attempted to bring cultural and scientific perspectives together was via a broad range of guest speakers at the teacher workshops. After the January 2019 mid-project vog workshop, participants responded that "*the diversity of speakers really gave a full picture of the impact of vog*" and "*the variety helped me think of different ways to incorporate this training into my classroom*."

Teachers reported they "*loved the cultural parts*" and enjoyed learning both about "*the science and the connection to the cultural knowledge of the land*" and "*seeing how a concept could be approached from different ways: cultural, mathematic, scientific, and historic.*" For weather, teachers saw how *kilo* observations and quantitative data were complementary: a weather station measurement "*backs up the claims of kilo with numbers/data.*" For vog, teachers saw how scientists' relatively "*'new' understanding is reflected in the oral histories of Hawai'i.*" Teachers reported high satisfaction (mean=4.7 out of 5, 100% reported satisfied or very satisfied, n=19) in terms of relevance to student learning in survey responses after the January 2020 mid-project *Kilo* and Weather workshop. Overwhelmingly, teachers also reported a desire to incorporate Hawaiian perspectives on vog and *kilo* into their regular teaching practice. Representative comments include "*I want to bring this context to my students before getting into the Vog science*" and "*I will be incorporating more kilo into my lessons.*"

3. **The program created a network of educators and connected participants to local resources, new contacts, and field-trip opportunities.**

Another theme from open-ended questions was the importance of the social and community-building aspects of the program. The workshops gave teachers an opportunity to network, exchange ideas, and learn from each other. Teachers stated "*I enjoyed getting to build my community connections*" and valued opportunities for lesson sharing. Also, "*There is a collective of educators with passion, aloha, and dedication to their students learning. Harnessing and providing resources and opportunities to connect and share resources and experiences helps to support all.*" A suggested point of improvement from the participants is to build in even more time for teachers from similar grade cohorts to collaborate.

The opportunity to engage with expert speakers also introduced teachers to new resources, contacts, ideas, and field-trip opportunities. Teachers thought a major benefit to students was "[having students see] *real science happening in our community.*" Teachers also were exposed to local research activities and facilities: speaking of the visit to the Mauna Loa Observatory, one teacher remarked: "*I didn't even know this existed, what an awesome resource.*"

DISCUSSION AND CONCLUSIONS

In the aftermath of the 2018 Kīlauea eruption, low-cost air quality and weather sensors, combined with native Hawaiian perspectives and concepts, were used for a two-year environmental engagement program. The primary goal of the program was to provide teachers with tools (sensors and data) to develop classroom lessons and activities for atmospheric chemistry and weather and climate that addressed specific STEM concepts. Though the lessons that were developed are tailored for the specific context and location of this program, there is potential to adapt them to other environments using open-source data from burgeoning commercial low-cost sensor networks, without the need for a custom sensor network. For example, there are several platforms where air quality data, including from low-cost sensors, are freely available to download (e.g. OpenAQ, 2022). Weather data are also freely available from many sources, including public archives (e.g. NOAA National Centers for Environmental Information, 2022). Data from these platforms can be downloaded and explored by students using a variety of open-source data analysis tools (e.g. spreadsheet applications, R, Python etc.). These open-source data and tools could potentially form the basis for future engagement efforts so that communities can lead independent monitoring efforts and interpret results.

Additionally, the research team learned several lessons during the program that may be useful for future environmental community engagements that use sensors and data. Overall, the low-cost environmental sensors and their data were an effective means to engage and educate K-12 teachers and students. In particular, the low-cost sensors are amenable to hands-on classroom activities in which students can develop and directly test hypotheses. However, in terms of working with sensors' data, challenges remain to provide support for teachers to i) develop statistical analysis and data visualization skills needed to teach students and ii) further incorporate environmental datasets into lesson plans that meet NGSS standards. This was a limitation of our program and future workshops could benefit from additional training activities (e.g. targeted teacher visits, webinars, online learning and resource lists) directed at teachers to build capacity for data-based lessons and instruction.

In addition to the low-cost sensor network, this program was able to successfully incorporate other aspects of place-based education. One feature of the program was that local scientists and experts from the community, including native Hawaiian cultural scholars, participated to act as informal mentors and to provide specialist perspectives. Based on survey responses, the inclusion of local, traditional perspectives on environmental phenomena was a strength of the program that deepened interest in vog and weather and increased appreciation for different forms of knowledge production. Additionally, workshops and program field trips were held at local scientific facilities and by leveraging local scientific resources in this way, students were able to witness science-based work happening in their own communities, gain perspectives on what a STEM career could look like and develop local networks. Future programs in other environments could benefit from reaching out to local research communities and cultural practitioners.

While the partnership achieved success and fulfilled the project's objectives, there remain challenges with securing sustainable funding streams, ensuring personnel consistency, and upholding project connections across distances. Notably, maintaining operational relationships and the functionality of the sensor network presents difficulties due to time zone disparities and the absence of face-to-face interactions, given the physical separation of project partners between the mainland and Hawaii. One approach to address these challenges was the recruitment and instruction of local university students to oversee the technical aspects of the sensor network and to act as liaisons for participating educators. This strategy not only addresses technical needs but also imparts valuable training and guidance to the students involved.

After a two-year pause, Kīlauea began a new eruptive phase in December 2020. As of this article's publication, Kīlauea is still erupting, the vog measurement program continues to run, and sensors are still hosted at schools across the Big Island collecting data. Though the formal teacher outreach program has concluded, there is still communication between academic and community partners and individual teachers remain interested in vog data for classroom use and to support environmental safety and school closure decisions. This interest and wide-spread community demand for operational air quality data was also evident during December 2022 when Mauna Loa volcano, also on the Big Island, erupted for the first time since 1984. Though fortunately there were no severe air quality impacts on the Island from this eruption, there was a surge in interest for high-quality, hyper-local air quality data. As the frequency of extreme air pollution episodes continue to increase from events such as wildfires, there is a growing role for academic-community partnerships to facilitate community-led monitoring efforts and data interpretation.

ASSOCIATED CONTENT

Supplemental material mentioned in this manuscript can be found uploaded to the same webpage as this manuscript.

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ABBREVIATIONS

NELHA: Natural Energy Laboratory of Hawaii Authority; NGSS: Next Generation Science Standards; PD: Professional Development; PM: Particulate Matter; SO2: Sulfur Dioxide; TKC: The Kohala Center; US: United States

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