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Global Ozone (GO3) Project and AQTreks: Use of evolving technologies by students and citizen scientists to monitor air pollutants

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ABSTRACT

Over the past decade, new and emerging technologies in air pollution instrumentation have made it possible to involve students and citizen scientists in air pollution monitoring. Similarly, advances in data communication and transmission have made it increasingly easy to share and graphically display data. Two educational programs, the Global Ozone (GO3) Project and AQTreks, have used these advances to get air pollution monitors into the hands of thousands of students around the world and to automate data sharing. The pilot project for AQTreks, GO3 Treks, is also discussed. These educational projects began in 2009 with the GO3 Project, a stationary ground-level ozone monitoring project. In the GO3 Project, students and teachers at more than 100 schools from around the world installed ozone and weather monitoring stations at their schools with automatic uploading of their data every 15 min, resulting in more than 12 million ozone measurements along with associated weather data. Over the years, new technologies became available for students to expand their measurements from stationary to mobile platforms. Since 2016, the AQTreks educational program has been developed concurrently with the Personal Air Monitor (PAM), a mobile sensor suite paired with a smartphone app. Complementing the technology are online curricula and other resources for students and citizens to learn about air pollution and climate change. In these projects, a focus on data quality and the careful selection of monitoring technologies have resulted in scientific use of the student-collected data, including their incorporation in several research campaigns that have furthered understanding of ground-level ozone formation. This approach has demonstrated the utility of these types of educational programs both in terms of furthering scientific research and educating the next generation about air quality issues.

1. Introduction

For centuries communities around the world have been making observations about our Earth. People want to understand their environment, and making measurements gives them the ability to advance their personal knowledge, as well as our collective knowledge, of our planet. The invention of the internet and new monitoring technologies have made data collection and sharing exciting and accessible to all. Data sharing across the world breaks down geographical and cultural boundaries and reminds us that we all share one atmosphere. Educating children on our atmosphere and environment has been the primary focus of several programs. These programs give Kindergarten through 12th grade (K-12) students the tools to participate in scientific inquiry, thereby learning about environmental issues. For example, the U.S. government announced the Global Learning and Observations to Benefit the Environment (GLOBE) Program in 1994 as a multi-agency effort for students and citizens from around the world to collect data on our Earth system and global environment (www.globe.gov). In the GLOBE program, students and citizens collect data about the environment under the direction of a series of well-defined protocols and manually upload the data online.

One of the most critical issues facing us today is air pollution, and globally air pollution data are relatively sparse. For air pollution observations, one GLOBE protocol focuses on the collection of ground level

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ozone concentration data using colorimetric test strips and an "Ozone Test Strip Scanner" that reads the color-change of the strip more accurately than the human eye. This method of collecting ozone data helps K-12 students learn about tropospheric ozone and provides data where there currently are none (Creilson et al., 2008). For ozone specifically, this strip measurement was at the time one of the only affordable ways for K-12 students to easily measure ozone internationally. Traditional ozone instrumentation is expensive, heavy, and requires extensive training to operate. However, recent developments in ozone monitoring technology have made it possible to include instrumentation and continuous data collection in community- and school-based education programs. For example, the U.S. Environmental Protection Agency's (EPA) Village Green Project focuses on the continuous, long-term measurement of outdoor air pollution, including ozone measured with the 2B Technologies Model 106-L Ozone Monitor (Jiao et al., 2015). The data collected are streamed online and updated by the minute, or can be displayed on a smartphone when at a Village Green station. The project seeks to provide real-time data to communities previously not available and to engage communities in air pollution awareness. Additionally, the St. Louis Ozone Garden uses an innovative approach to air pollution education centered on ozone's effect on plants and crops. The program uses ozone-sensitive plants in conjunction with ozone measurements (from a similar ozone monitor as the one used in the Village Green Project) for visitors to relate ozone concentrations to visible plant damage (Fishman et al., 2014).

The convergence of the public's increasing concern about air quality with the new technologies available for air pollution monitoring has created the opportunity for wide-scale participation in educational and community monitoring programs. Similarly, advances in data communication and the wide availability of the internet have made automated data collection and sharing possible. Here we discuss our educational air monitoring programs (GO3 Project, GO3 Treks, and AQTreks) centered on giving students access to sophisticated instrumentation that allows them to collect meaningful data in real-time and share data online. The projects focus on four main objectives: 1) education and awareness, 2) ease of data transmission and sharing, 3) data quality, and 4) scientific value. Our approach allows students to collect high-quality data and make valuable contributions to the science of air pollution. In addition to designing their own studies and learning about the science of air pollution, collecting high-quality data can lead to a sense of empowerment for students and citizens, as their data can be viewed as accurate and in some cases actionable. Since 2009, our educational programs have evolved through student and teacher feedback, lessons learned, and the incorporation of new air monitoring and data communication technologies. We discuss highlights of the programs and the ways in which our focus on data quality, instrumentation, and a rental model for sensors have shaped the usefulness and scientific value of the data collected by students and the public.

2. Materials and methods

This paper discusses our three educational initiatives as summarized in Table 1 and describes each program in more detail below.

2.1. Measurement equipment, installation, and data uploading

2.1.1. GO3 Project: stationary ozone monitoring

The GO3 Project (www.go3project.com) is a stationary ozone monitoring program for schools around the world, in which students and teachers install an ozone monitor and weather station at their schools and acquire data over a long period that enables them to study daily and seasonal ozone variations. Each school in the GO3 Project is provided with a GO3 Project Package (shown in Fig. 1), which consists of an ozone monitor, weather station, laptop computer, Teflon lined Tygon tubing for sampling outdoor air, and various accessories, including an external ozone zeroing cartridge for checking the instrument's zero monthly. The GO3 Project is made possible by the development of a portable, light weight, low power ozone monitor that has high precision and accuracy. The ozone monitor used is a 2B Technologies Model 106-L Ozone Monitor (2B Technologies, Boulder, CO, USA) and is based on ozone's absorbance of UV light at 254 nm. A few schools made use of 2B Technologies Model 202 and Model 205 Ozone Monitors, which are based on the same measurement principle. All three models of ozone monitors are employed in the U.S. by state and local agencies in monitoring for compliance with the Clean Air Act and are designated by the EPA as Federal Equivalent Methods (FEMs). The Model 106-L Ozone Monitor has a precision and accuracy of the higher of ± 2 ppb or 2% of the reading for 10-s measurements. Averaging for 15 min improves precision by nearly an order of magnitude to $\sim$0.2 ppb at typical ambient levels. The solar-powered Davis Vantage Vue Model 6250 (Davis Instruments, Hayward, CA, USA) weather station used measures temperature, pressure, relative humidity, wind speed, wind direction, and precipitation. Weather data are transmitted wirelessly from the outdoor station to the indoor console. With the weather station console and

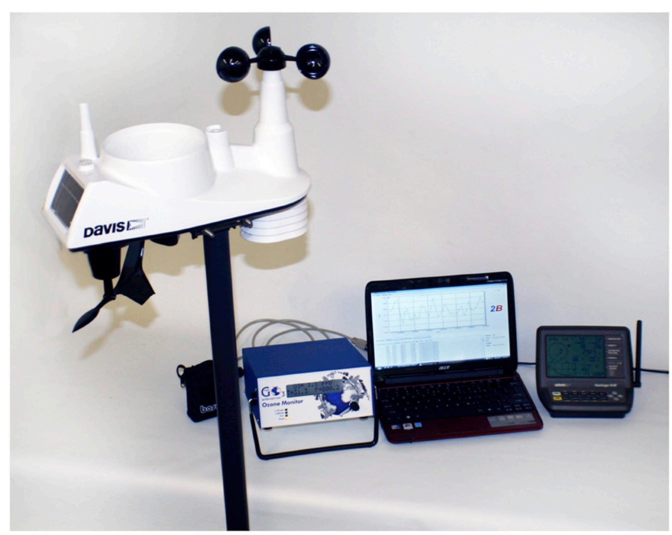

Fig. 1. The GO3 Project Package with Davis Vantage Vue weather station, 2B Technologies Model 106-L ozone monitor, and laptop computer.

Table 1
Summary of the educational air pollution monitoring programs.

Program	Type of program	Measurement type	Parameters measured	Time frame	Number of schools/ students
GO3 Project	stationary	instrument-based	ozone, temperature, pressure, relative humidity, wind speed and direction, precipitation	2009-present	112 ($\sim$11,200)
GO3 Treks	mobile pilot project	instrument-based	ozone, black carbon	2015–2016	63 ($\sim$3500)
AQTreks	mobile	sensor-based	PM_1, $PM_{2.5}$, PM_{10}, CO, CO_2 [a]	2016-present	95 ($\sim$4500)

[a] Particulate Matter (PM) as PM_1, $PM_{2.5}$ and PM_{10} (particles having diameters less than or equal to 1, 2.5 and 10 μm, respectively), carbon monoxide (CO), carbon dioxide (CO_2).

ozone monitor connected to a laptop computer running Microsoft Windows, the data are combined and automatically uploaded to a MySQL database by the pre-installed GO3 Software.

The GO3 Package is sent to schools along with an instructional video and written manuals describing the installation procedure. Additionally, GO3 staff are available for assistance, as well as an online discussion forum for students and teachers. The installation process requires that the weather station be set up and secured, typically on the roof of a building. The ozone monitor set-up requires access to outdoor air via up to 25 feet (7.6 m) of PTFE-lined Tygon® inlet tubing. Once the ozone monitor and weather station are set up and connected to the internet-connected computer, GO3 staff ensure that data are being uploaded successfully, after which the ozone monitor is set to 15-min averaging timeframe, automatically uploading a data point every 15 min. Data are immediately available for online display on a Google Earth map, time series graphing, and download of a CSV or Microsoft Excel file.

In most cases, the weather station is placed on the roof attached to a metal stand with sand bags securing the stand. Schools are able to install the weather station with relative ease with the involvement of facility maintenance personnel. The ozone monitor requires that the inlet tubing run to outdoor air, with one end of the inlet tube connected to the ozone monitor and the other end placed outdoors with an inverted funnel and mounting bracket to prevent precipitation from being drawn into the sample line. One of the most challenging aspects of the ozone monitor installation is running the tubing to outside air. Schools often have to wait long periods of time for the approval to gain this access, which in some cases requires drilling a hole through a window frame or even the building's wall. In other cases, the tubing is run through ducts to a vent on the roof of the building.

Once installation is complete, the computer uploads data every 15 min (5 min for some setups that use the 2B Technologies Model 202 or 205 Ozone Monitors). This requires constant internet access, which often presents problems during both installation and throughout monitoring. Gaining access to a school's network often proves difficult, and some networks experience many outages. A few networks in foreign countries operate only during school hours. During these outages data are saved locally but are not uploaded, and the uploading has to be manually restarted once internet service is restored.

2.1.2. AQTreks and its pilot program, GO3 Treks: mobile monitoring

From 2015 to 2016 we created and executed a pilot program to test the concept of mobile monitoring of air pollutants in and around schools, called GO3 Treks. The project used miniaturized traditional air monitors to measure ozone and black carbon: the 2B Technologies Personal Ozone Monitor (POM; 2B Technologies, Boulder, CO, USA) (Andersen et al., 2010) and AethLabs microAeth (AethLabs, San Francisco, CA, USA), shown in Fig. 2. In GO3 Treks, students took the monitors on mobile explorations, testing their own hypotheses of where air pollutant concentrations might be high or low. After their data collection was complete they connected the monitors to a computer to upload the data. The data were displayed on an interactive Google Earth overlay embedded in a blog where the students described their data collection process and discussed their results with other students. As shown in examples given in Fig. 3, the Google Earth plugin provided for attractive mapping of the data, with the ability to zoom in and out and change perspective. The choice of both a secondary pollutant (ozone) and a primary pollutant (black carbon) allowed students to observe the contrasting behaviors of these two types of pollutants. Ozone remained nearly constant along Treks, while black carbon would show large spikes when diesel trucks passed by, for example. Students at 63 schools participated in GO3 Treks and uploaded nearly 500 Treks. Survey results found that short-term mobile monitoring in which students could go outside and explore the air in their own neighborhoods was far more interesting overall to students and teachers than fixed-base monitoring.

Since the POM and microAeth are relatively expensive instruments (~$6000 USD each), they are not well suited to widespread distribution

Fig. 2. The 2B Technologies Personal Ozone Monitor (top) and AethLabs microAeth personal black carbon monitor (bottom) used in the GO3 Treks pilot project.

for educational programs where funds tend to be extremely limited. Our GO3 Treks program evolved to become AQTreks at a time when there was rapidly rising interest in the use of low-cost air quality sensors for citizen monitoring. In AQTreks we evaluated the possibility of creating a sensor suite that would be more affordable for educational applications. During the development of a custom-built, sensor-based Personal Air Monitor (PAM) for AQTreks, we took into consideration factors of sensor accuracy, portability, ease of use, and data communication. Due to the project's focus on data accuracy and quality, the measurement principles and the available sensor reviews and testing literature were evaluated to determine which sensors would meet the project's standards (AQ-SPEC, 2019; EPA, 2019). We decided to limit the measurements to those species that are most accurately and reliably measured using currently available sensors. We further decided to limit the number of air pollutants measured to three primary pollutants that are indicative of combustion sources: carbon monoxide (CO), carbon dioxide (CO_2) and particulate matter (PM) as PM_1, $PM_{2.5}$ and PM_{10} (particles having diameters less than or equal to 1, 2.5 and 10 μm, respectively). Of these, CO and PM (specifically $PM_{2.5}$ and PM_{10}) are two of the six EPA Criteria Pollutants, and CO_2 is the most important greenhouse gas responsible for climate change. The CO sensor (Model CO-A4; Alphasense, Essex, UK) is a four-electrode amperometric sensor. Of the currently available electrochemical sensors, the CO sensor is by far the most reliable and accurate – most likely due to the fact that it is based on the oxidation of a reduced species rather than the reduction of an oxidized species (e.g., ozone, nitrogen dioxide, sulfur dioxide) for which selectivity in the atmosphere is difficult to achieve. A number of carbon dioxide sensors, which are based on non dispersive infrared (NDIR) absorbance, are available due to their widespread use in heating, ventilation, and air conditioning systems. We chose the Telaire NDIR sensor, Model T6713 (Amphenol Advanced Sensors, St. Mary's, PA, USA) for measurements of CO_2. The Plantower PMS5003 (Plantower, Beijing, China) was chosen for measuring particulate matter as this sensor has been shown to give excellent results relative to conventional regulatory instrumentation in

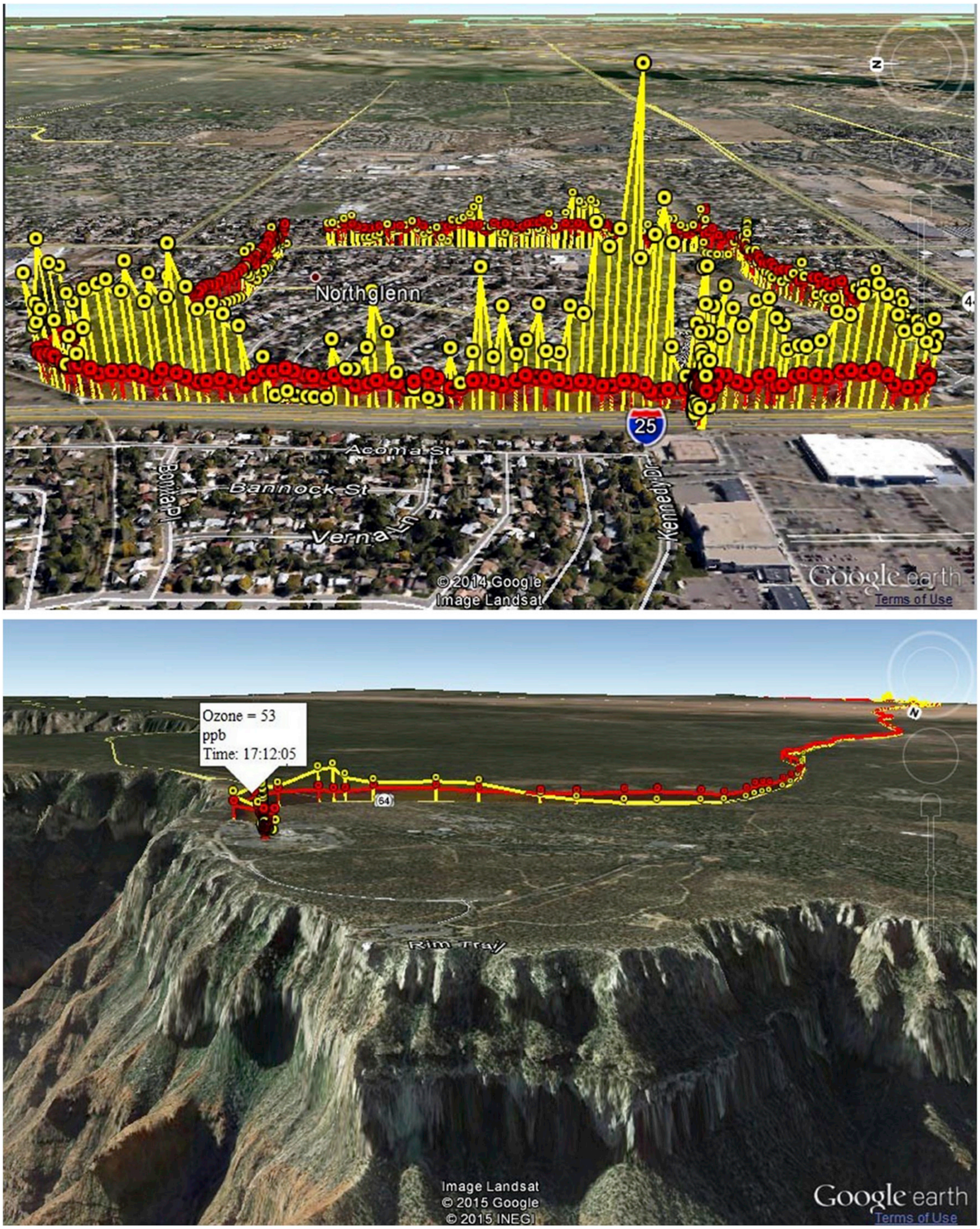

Fig. 3. Examples of GO3 Treks data, as displayed inside a blog on the GO3 Social Network. Ozone is shown in red and black carbon is shown in yellow. Upper panel: Trek around Northglenn High School (Northglenn, Colorado). The secondary pollutant ozone remains relatively constant, while black carbon shows large spikes along the portion of the Trek adjacent to Interstate Highway 25. Lower Panel: A Trek to the rim of the Grand Canyon obtained from an automobile. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

recent field tests (see http://www.aqmd.gov/aq-spec/home). The PAM shown in Fig. 4 also contains temperature, pressure and humidity sensors.

The PAM is extremely easy and intuitive to use, requiring virtually no set-up. Each school or community group participating in the AQTreks program receives the monitoring equipment as a rental, typically for three weeks. A quick-start manual is provided, along with an online curriculum and Trek-planning resources. The PAM, battery charger, and a pre-paid return label are shipped to the user in a small Pelican™ case. The PAM is tested and calibrated before each rental to ensure that AQTreks participants collect and share meaningful, accurate measurements. The motivation behind the rental model for sensors and the PAM is discussed in more detail in Section 2.3.2.

The difficulty of using school networks and internet in the GO3 Project was addressed with the development of the PAM by the use of a smartphone app for data collection and transmission over a cellular connection. This development circumvents the need to use the school's internet resources, which proved to be a large obstacle in consistent data

Fig. 4. The Personal Air Monitor (PAM) used in AQTreks.

uploading and sharing in the GO3 Project. The PAM uses Bluetooth technology to broadcast its measurements every 8 s using one-way communication. The use of one-way communication does not require that the smartphone pair to the PAM. Therefore, any smartphone within Bluetooth range can view the data from the PAM within the AQTreks smartphone app. This feature makes the project more inclusive, as an entire class of 30 students can see real-time data collection happening with only one PAM per class. Location services are provided by the individual smartphones, obviating the need to include GPS in the PAM, thereby reducing cost and increasing the reliability of mapping of the data.

The AQTreks app automatically displays the data from any PAM in Bluetooth range. The incoming data are displayed in real time as numerical values on a dashboard, in time-series graphs, and on a map. The user has the ability to insert a comment or picture on a selected data point, allowing them to annotate their data with information on what was happening during data collection. The PAM tracks GPS location using the phone's GPS data and assembles the incoming data into individual Treks. After the user completes their Trek, the app saves the data, which is then stored locally on the phone. The user has the option to upload the data to the CommunityAQ website (www.CommunityAQ.com) to be made publicly available. If the user selects this option, the data are uploaded over cell service if available or via WiFi if cell service is unavailable.

2.2. Data storage, display, and communication

2.2.1. GO3 Project

The GO3 Project uses computer-installed software developed to upload ozone and weather data to a MySQL database hosted on a LAMP (Linux-Apache-MySQL-PHP) server. The data are all publicly available without a login. In addition to CSV file and Microsoft Excel downloads, the data are also made available for visualization in two ways: on a Google Earth overlay and as time series graphs. When viewing data on Google Earth, the user selects a specific date and chooses either current, maximum, minimum, average or maximum 8-h average ozone values. The ozone levels are shown as 3D, color-coded bars centered on the monitoring location with their height and color indicating the ozone level at that location, as shown in Fig. 5. The color scale, provided on the graph, corresponds to the standard Air Quality Index (AQI) color scheme (but with gradations) adopted by the EPA. This display method provides a highly visual representation of the data for students and citizens. If a graph of ozone values is desired, the user is able to customize a database query and see data displayed as a time series for any location and any date range. The ozone data can also be overlaid with meteorological data to evaluate trends. Additionally, from 2010 to 2013 GO3 staff provided a monthly summary on the GO3 website containing graphs of ozone values at all the participating GO3 sites around the world, so that participants could easily compare ozone measurements at their schools with those of other schools, both nearby and far away. The graphs included comments on trends, maxima and minima, as well as any monitor issues such as a zero offset or excessive noise. These monthly summaries became the "digest" of the project and were utilized by students to compare data and draw conclusions about their own data.

The GO3 Project was imagined as a global program with many international participants. This was important considering that ozone and its precursors can be transported thousands of miles and thus ground-level ozone is a truly global issue. For this reason, the GO3 Project's goal was for each school in the U.S. that was provided with free instrumentation, an international sister school would also be funded. GO3 staff made connections to International Schools by attending the Global Issues Network (GIN) conference in Bangkok, Thailand in 2010. Generally, International Schools follow a national or international curriculum different from that of their host country. Additionally, an emphasis is placed on global citizenship, with such programs as the International Baccalaureate Diploma Program. International Schools are usually taught in English and thus served as the perfect candidates for the international expansion of the GO3 Project. Through the connections made at the GIN conference, the GO3 Project reached out to the leaders of International Schools around the world. The schools were surveyed to determine whether they would be interested in participating in the project if funding could be secured for their instrumentation. Fifty-three International Schools signed up to participate, a list from which U.S. schools could select a "sister school" for collaboration. The GO3 Foundation, a 501(c)(3) nonprofit organization, was able to secure funding for 35 U.S. and 35 international sister schools.

Due to the widespread, international nature of the project, it was important to establish both easy online access to the data and a means of communication for the participants. Therefore, to foster international communication and collaborative data analysis, the GO3 Social Network was established. The GO3 Social Network has a structure and functionality similar to Facebook and is run as a dedicated social network for the GO3 Project and discussion of environmental issues worldwide. Students from international sister schools are encouraged to communicate with each other and discuss their data, as well as local environmental problems. Various other means were established to encourage participation in the GO3 Social Network, including the "Ask a Scientist" forum, student blogs, and most importantly contests run by the GO3 Project. The contests consisted of many categories and associated prizes. For example, the GO3 Social Network held contests for the school with the most consistent data uploading. Additionally, environmental contests were run each year with categories that included best environmental blog, artwork, video, and photo.

2.2.2. GO3 Project data and the AirNow program

Because the GO3 Project stations make use of an accurate FEM ozone monitor, staff from Sonoma Technologies, Inc., which supports the AirNow program, became interested in evaluating the usefulness of including GO3 data in their air quality maps and forecasts. Therefore, GO3 and AirNow staff worked together to create a protocol for

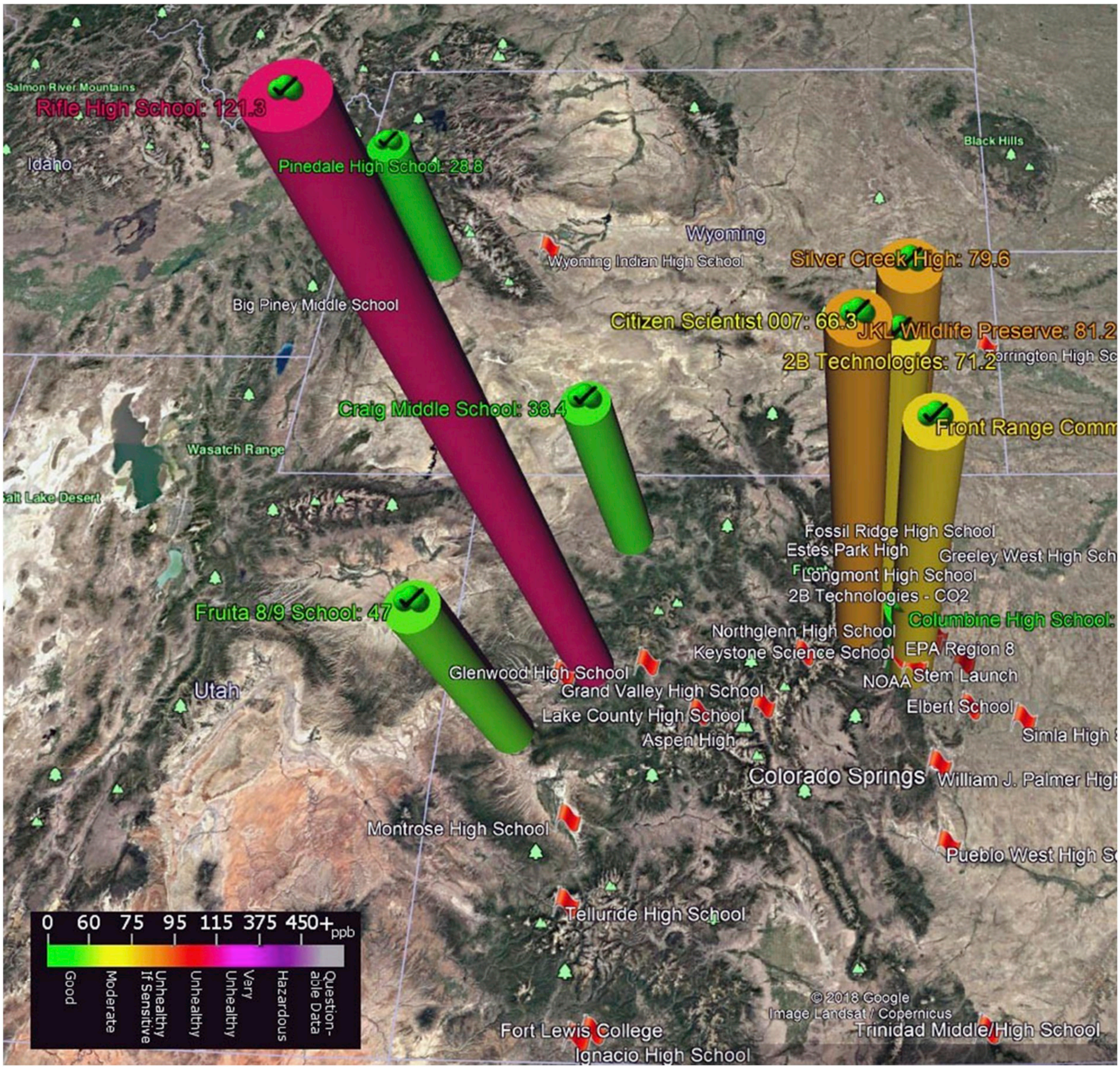

Fig. 5. GO3 ozone data on a Google Earth overlay centered on Denver, Colorado on July 4, 2014.

transmitting all of the GO3 data to AirNow. The GO3 data were made available in an area of AirNow Tech (www.airnowtech.org, an online data repository for air agencies across the U.S.) designed for experimental and community data. AirNow data also were queried and copied daily to the GO3 database, so that GO3 data could be displayed on Google Earth alongside data from those of state and local air monitoring stations.

2.2.3. *AQTreks*

To enhance the flexibility and capacity of data storage, AQTreks uses a PostgreSQL database that supports JSON (JavaScript Object Notation) data. When the PAM is used in AQTreks as a mobile device in conjunction with the AQTreks app, the mobile app receives data from a PAM via Bluetooth broadcast (one-way communication from PAM to app). The app interprets the raw data from the PAM and performs analysis and visualization of the incoming data. Once a Trek is completed, if the user chooses to upload the data from within the app, the app makes a connection to the server and uploads the data. The server receives the data from the app, reformats it, and writes the data to the database. The data from the app is assembled into a distinct Trek and is assigned a Trek ID number. The Trek ID is communicated back to the app and is displayed in the Saved Treks page of the app.

All uploaded data are publicly available on the CommunityAQ website and selectable from a map, as shown in Fig. 6. The user can go to the website and find their Trek on the map where all uploaded Treks are displayed or search their Trek by ID number. The user can also search by device number and date range to see all of the Treks uploaded by a particular device during a specified period of time. All data from any uploaded Trek can be downloaded by the user as a CSV file.

2.3. *Quality assurance*

2.3.1. *GO3 Project*

GO3 Project quality assurance focuses on two main factors: instrumentation and data quality. Ozone monitors are calibrated against a NIST-traceable ozone standard prior to shipping to schools. Schools are encouraged to zero their instruments with a provided external ozone scrubber at least once monthly and adjust the zero if an offset is found. A video demonstrating this procedure is provided to the schools and is available online. All ozone monitor diagnostic data (cell temperature, pressure, flow rate and photodiode voltage) are uploaded along with the ozone measurements, and automatic emails are triggered to GO3 staff if

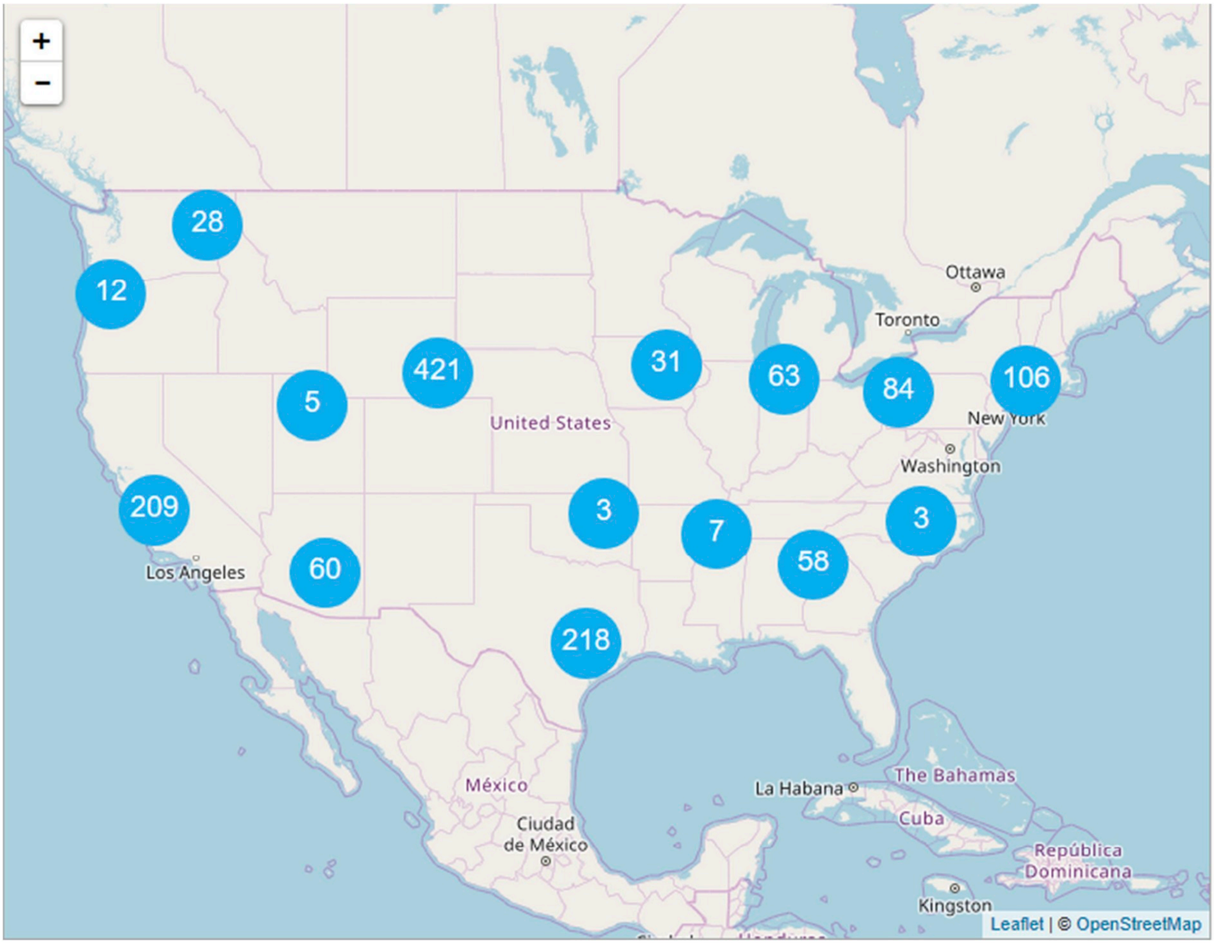

Fig. 6. Website display of AQTreks locations indicating the number of Treks uploaded from each region.

an ozone monitor is reporting diagnostic data outside set parameters. The ozone monitors are scheduled for recalibration and cleaning yearly and are called in for repair if an issue is identified.

In addition to the ozone monitor calibration and maintenance procedures, a number of measures were put into place to encourage the consistent uploading of data and to control the quality of data that were uploaded. Due to many factors at the school level, data uploading was interrupted frequently and needed to be restarted manually. This led GO3 staff to establish automatically generated emails to GO3 staff, teachers, and students if a station stopped reporting data. These emails were critically important when students and teachers were absent from the school building for extended periods of time for summer break and holidays. Summer break also typically coincided with the peak ozone season for many locations, adding to the importance of keeping monitors running over the summer.

Quality control of the data begins with ozone measurements coming into the database out of range (<-10, >200 ppb) being flagged in the database as possibly invalid. The ozone data are graphed and critiqued by GO3 staff for each station on a monthly basis and then combined into a single downloadable pdf document for that month. At that time, instruments producing noisy or spurious data, or data with large nighttime offsets (when ozone levels often go to zero), are identified. GO3 staff then work with the schools to correct the problem, which is often a dirty sample inlet filter. If the school cannot solve the issue with the monitor, it is returned for service and recalibration. The quantity and quality of data are assessed and posted online in a manner similar to what AirNow does for data continuously reported by government monitoring agencies. Where possible, data are compared with nearby stations for assessment of span accuracy. It was found that instruments retain their span accuracy to better than 5% over a period of at least two years.

2.3.2. *AQTreks*

An important aspect of data quality is its scientific value. Since the GO3 Project was established in 2009, we have received guidance and feedback from the EPA, the Colorado Department of Public Health and Environment (CDPHE), and other air monitoring agencies across the U. S. One concern with sensors has been the inevitable flood of inaccurate data from citizens who purchase sensors that do not produce accurate results. Additionally, citizens often do not understand how the sensors need to be maintained and replaced. The team felt that it was our responsibility as the creators of the PAM to ensure that citizens make accurate measurements. Furthermore, the scientific value of the ozone measurements produced with the GO3 Project (which used a well-established instrumental technique) was significant and is discussed further in sections 3.1.2, 3.1.3, and 3.1.4 below. Our experience with the GO3 Project drove our commitment to creating community science projects that produce valuable data.

The shift in AQTreks to using a personal monitor meant that users would be measuring their personal exposure to air pollutants, making measurement accuracy especially important. As the extensive testing of sensors shows, they need frequent maintenance and calibration (Jiao et al., 2016; Feinberg et al., 2018). Sensors drift over time, have short lifetimes, and electrochemical sensors require complete replacement after a given time period (typically one year of operation). In the GO3 Project, where robust instrumentation was used instead of sensors, the ozone monitors often maintained their calibration to within a few ppb for more than two years. Teachers have extreme demands on their time, and even though service was seldom required with the instrumentation used in the GO3 Project, it often took months to get an ozone monitor sent back to us. Alternatively, the PAM sensors require much more frequent calibration (at least quarterly) than the instrumentation used in the GO3 Project (yearly for the ozone monitor). Due to the frequency of required calibration, we were aware of the near impossibility of the proper maintenance of the sensors at schools. Therefore, a key aspect of the AQTreks program is the application of a rental model, in which the PAM is returned every three weeks between rentals for maintenance and recalibration. This provides a significant check on the accuracy of the citizen-contributed data as well as traceability of the specific sensor packages. For longer-term rentals, the user is required to send the PAM back to us quarterly for recalibration.

Sensors are calibrated by placing the entire PAM unit within a PVC chamber and flushing the chamber with calibration standards containing known amounts of either CO or CO_2. Humidity within the chamber is varied by combining two flows of zero grade air (US Welding) via calibrated mass flow controllers (0–10 sLpm). The first flow is added without alteration and constituted dry (RH < 1%) air. The second flow is passed through 4 strands of Nafion® tubing plumbed in parallel that are submerged in a water bath. This serves to humidify the second airflow, and variation of these two flows yield different humidities inside the PVC chamber. Humidity in the chamber is measured via a calibrated RH/T sensor (Omega, HH311) placed at the exit of the chamber.

Known CO (0–15 ppm) and CO_2 (300–1500 ppm) concentrations are added either by directly flushing the chamber with undiluted standards (15 ppm CO/air and 579 ppm CO_2/air, both from Matheson) or by addition of small calibrated flows (MKS 1179A, 0–100 sccm) from higher concentration standard mixtures (151 ppm CO/air, Airgas, and 5% CO_2/air, Scott Specialty Gas) and subsequent dilution by the dry and humid flows described above (total flow ~ 2 sLpm). The dilution method allows for concurrent variations in humidity to assess humidity dependencies of the CO and CO_2 sensors.

Basic response of the Plantower PMS5003 sensor to aerosols is tested in the calibration chamber by addition of ammonium sulfate particles produced by nebulizing aqueous $(NH_3)_2SO_4$ solutions (~0.5 g/L). However, particulate mass densities from the Plantower PMS5003 were not calibrated since a lab-generated aerosol standard that successfully mimics atmospheric aerosol distributions does not exist. The varying ranges in composition, size distribution, and optical properties of ambient aerosols are nearly impossible to reproduce in the laboratory. Therefore, field calibrations based on side-by-side comparisons with existing well-established methods are necessary for calibration of particulate mass sensors (for example, see Zheng et al., 2018). Additionally, over the course of the project it became clear that humidity corrections were needed (Zheng et al., 2018) and we began incorporating those corrections into the PAM firmware. In the described procedures we validated that the sensors operated uniformly and as expected in the lab. For educational use, the field PM calibrations were not logistically possible with the PAM being used in hundreds of locations across the U. S.

In addition to the laboratory calibration procedures, the user can also be involved with the quality control of their sensors. The AQTreks app displays all available data from the nearest regulatory monitoring stations (drawn from the AirNow database). The app displays all available parameters, their last hourly averages, and a map pinpointing the station's location. If the station is located nearby, the user can walk or drive by the station to get a general sense of how well their PAM measurements agree with nearby regulatory measurements.

2.4. Curriculum

2.4.1. GO3 Project

The GO3 Project curriculum was created to support teacher and student learning and to train teachers on the science of ozone. The curriculum consists of 13 lessons with 239 slides available as commented PowerPoint presentations and self-paced online Moodle courses. A summary of the GO3 Project curriculum and the available lessons are listed in Table 2. Moodle was chosen as the online platform since it is free and well-known to teachers. Moodle is an open-source personalized learning environment, with more than 153 million registered users. Three supplemental activities are also available for the teachers to complete with their students. All the materials are publicly available as downloads from the GO3 Project website, and the Moodle course is available at no cost with a free Moodle login.

2.4.2. AQTreks

The AQTreks curriculum, also summarized in Table 2, incorporated feedback from students and teachers on the GO3 Curriculum. The teachers found the GO3 Curriculum very informative and in-depth, but suggested short, online lessons for the AQTreks curriculum to be more easily utilized by students. Teachers preferred the self-paced format of online lessons and suggested that PowerPoint presentations are becoming an antiquated learning format. Moodle was again chosen as the online platform for the AQTreks lessons. The online lesson units contain multi-media images and videos intended to engage learners with various interests and learning styles. The units contain an average of eight slides (ranging from 5 to 12) and take approximately 20–30 min each to complete. Four units cover the basics of air pollution and the three primary pollutants measured by the PAM (particulate matter, CO, and CO_2). Lesson plans, worksheets and instructional resources are also available for teachers. The lesson plans and worksheets are downloadable Microsoft Word and pdf documents detailing how to plan and execute a Trek.

3. Results

3.1. Key results of the GO3 Project

3.1.1. Participation in the GO3 Project – educational benefits

From initiation in 2009 to present, students and teachers at 112 schools, including 72 U.S. schools and 40 international schools, have participated in the GO3 Project as shown in Fig. 7. Each school's monitoring duration varied, but was a minimum of a year, with many

Table 2
Curricula in the GO3 Project and AQTreks.

	GO3 Project	AQTreks
Format(s)	• PowerPoint Presentation or self-paced online Moodle lessons • 13 topics, 239 total slides, ~20 slides/lesson • Free access from GO3 Project website or Moodle online learning platform	• Self-paced online Moodle lessons • 4 topics, shorter lessons, ~8 slides/lesson • Free access from Moodle online learning platform
Supplemental materials	3 supplemental activities	Lesson plans and worksheets Instructional resources
Topics covered	Air Pollution Basics Ozone Formation in the Troposphere Carbon Sources (CO) Methane Volatile Organic Compounds Oxides of Nitrogen Sunlight and Weather Harmful Effects of Ground Level Ozone Stratospheric Ozone and the Ozone Hole How an Ozone Monitor Works Data Collection and Integration Sustainable Technologies and Renewable Energies What Can You Do?	The Basics of Air Pollution Particulate Matter Carbon Dioxide Carbon Monoxide

locations monitoring for multiple years. Some locations continue to monitor nine years into the project. During the varying monitoring durations, an estimated 100 students per school were involved in the project, for a total participation of more than 11,200 students. More than twelve million ozone measurements and a comparable number of each weather parameter have been uploaded to the GO3 database.

A large number of GO3 students participated frequently in the GO3 Social Network, which currently has 4622 members, 32,500 posts, 6680 comments on posts, and 1074 blogs. In 2011, the Colorado and Wyoming students came together in Denver on May 2, 2011 for an Ozone Summit, during which they networked with other students, ozone monitoring professionals, and air quality scientists. The students Skyped with their international sister schools, learned about ozone monitor maintenance, and attended sessions and workshops on ozone monitoring, health effects of ozone, and careers in atmospheric science. The Ozone Summit was attended by 107 students and 31 teachers from 25 schools.

We did not require that the teachers use the project and curricula in any prescribed way. The teachers were allowed to incorporate the project in their classes as they desired. This proved very important, as teachers are more willing to take on extra projects if they have control over how they are executed in the classroom. From 2012 to 2018 we tracked downloads of the PowerPoint curriculum, during which time there were 443 downloads. A pdf version of the ozone curriculum is also available on ResearchGate where additional downloads occurred. The online Moodle curriculum was utilized by 378 users.

Teachers were given online surveys investigating their use of the project in their schools and the students' interest in the project, for which we received 40 responses. Teachers reported using the GO3 Project both in class and outside of class in grades 7–12, and in one community college and one university. In class, the teachers used the project in a wide variety of classes, including: Biology, General Science, Chemistry, Environmental Science, Advanced Placement (AP) Environmental Science, Earth Science, Gifted and Talented, Environmental Research Methods, AP Statistics, Environmental Systems and Societies, Agriculture, Physical Science, and Physics. Outside of formal classes, teachers used the project in after school clubs, such as green clubs or environmental clubs. Several schools established GO3 Clubs dedicated to the GO3 Project. The aspects of the project teachers reported using most were: 1) data collection and uploading, 2) the PowerPoint curriculum, 3) online data graphing, and 4) the GO3 Social Network. Eighty-one percent of teachers said their students found the GO3 Project interesting.

Students participating in the GO3 Project were encouraged to take online pre- and post-project assessments on their knowledge of ground level ozone. We received 1429 student responses to the assessments. The surveys showed that an average of 43% of middle and high school students had never heard of ground level ozone before the project began, and after completing the project 98% of students reported familiarity with ground level ozone. The surveys also contained more in-depth questions about the formation of ground level ozone and its effects on humans and the environment. The same questions were given pre- and post-project. When presented a list and asked to identify the ingredients of ground level ozone, the students' post-project scores increased significantly. The percentages of students that identified the ingredients correctly pre- and post-project are presented in Table 3.

Table 3
Student knowledge of ingredients of ground-level ozone pre- and post-participation in the GO3 Project.

	2011 pre-project	2011 post-project	2012 pre-project	2012 post-project
Oxides of Nitrogen	45%	75%	56%	65%
Carbon Source (like CO or VOCs)[b]	43%	87%	52%	82%
Sunlight	46%	81%	50%	71%

[b] Carbon monoxide (CO) or volatile organic compounds (VOCs).

3.1.2. Student observation of data and ozone phenomena – scientific contributions

3.1.2.1. Ground level ozone formation and diurnal variation of ozone. In the GO3 Project, students learn about the photochemical creation of ground level ozone and are able to observe its creation and destruction through the measurements they make. We consistently received feedback that this link to real data collection and observation of learned

Fig. 7. Map of GO3 Schools worldwide.

phenomena is often missing in K-12 schools, primarily due to a lack of funding for instrumentation. The GO3 Curriculum provided the instructional foundation for ground-level ozone formation, transport and destruction, and the students' analysis of the diurnal variation of ozone reinforced these concepts. Furthermore, the students were able to evaluate not only their own data, but data from schools around the world collected in the same manner with the same instrumentation. The online graphing program allowed students to plot a time series of any two variables. This allowed students to analyze the correlations between their measured ozone values and various meteorological parameters, including temperature, pressure, relative humidity, wind speed, wind direction and rainfall. As a secondary pollutant produced by photochemical reactions during the daytime and destroyed by reaction with nitric oxide and surface deposition at night, ozone is particularly interesting when measured at fixed-base stations. (For mobile monitoring experiments, ozone is much less interesting because its spatial distribution is fairly uniform due to being produced everywhere at the same time.) In highly polluted cities, students observed very strong diurnal variations, with ozone levels often reaching near zero values every night due to reaction with nitric oxide (NO), which continues to be emitted by traffic into the shallow nocturnal boundary layer. Ozone rises rapidly the next day as the convective boundary layer is established which mixes ozone down from higher altitudes and is then followed by photochemical production of ozone. Examples of observations with strong ozone diurnal variations are shown in Fig. 8 for the cities Jakarta, Indonesia and Lima, Peru.

3.1.2.2. Wyoming wintertime ozone

It has long been observed that ground-level ozone concentrations peak during summer months when solar intensities and air temperatures are favorable for ozone formation from NO_x and hydrocarbon precursors. For this reason, ozone is often not monitored during winter months. Thus, it was a huge surprise to air quality scientists when in 2005 the Air Quality Division of the Wyoming Department of Environmental Quality recorded highly elevated ozone levels in the Upper Green River Basin during winter months (Wyoming Department of Environmental Quality, 2019; Schnell et al., 2005; Schnell et al., 2009). Several field campaigns were mounted by the National Oceanic and Atmospheric Administration (NOAA) and others to elucidate this winter ozone phenomenon. It was discovered that the production of high ozone levels at temperatures down to −17 °C occurs under a very specific set of meteorological conditions in which a stagnant, high-pressure system promotes cold temperatures, low wind speeds and limited cloudiness. Under these conditions, a shallow temperature inversion develops in the lower 100 m of the atmosphere that traps VOCs and NO_x emissions from the highly productive Jonah–Pinedale Anticline (JPA) natural gas field. The VOCs are from natural gas leakage, and the NO_x is produced by the very large number of diesel engine compressors. During daytime, photolytic ozone production leads to the observed high ozone concentrations. The actinic flux is increased by nearly a factor of two if snow is present. Under these special conditions, ozone levels were found to rise from 10 to 30 ppb at night to more than 140 ppb shortly after solar noon (Schnell et al., 2009).

Pinedale High School in Pinedale, Wyoming joined the GO3 Project and began making ozone measurements as of January 19, 2011. Pinedale is located at the northern end of the JPA natural gas field. Although the largest ozone events had been previously reported to the south of Pinedale, students were anxious to determine whether there were ozone events in their neighborhood. As seen in Fig. 9, students had to wait less than six weeks before observing several winter ozone events with ozone peaking at 100 ppb and above. In 2012, Pinedale High School teacher Deborah Noble and four students, Morgan Buckendorf, Caitlin Tan, Dulce Perez and Perla Perez, presented a poster summarizing their collected data at the EPA's National Air Quality Conference/Ambient Air Monitoring Conference in Denver, Colorado (Buckendorf et al., 2012). The GO3 Project gave them the tools and resources to make a meaningful contribution to the conference, and they were able to discuss their observations with monitoring professionals from around the U.S.

3.1.2.3. Ozone variation with elevation

During the summer of 2011, a few months into their monitoring, Hinkley High School students of Aurora, Colorado (Denver metro area) began to notice that a mountain school 65 miles to the northwest, Estes Park High School, often reported higher maximum ozone values than their site. This was shocking to the students, who considered Estes Park to be a place of refuge from the high levels of big city air pollution. Further investigation of ozone measurements being made by other schools in the Colorado mountains, such as in Aspen, Lyons, Black Hawk and Telluride, consistently showed higher ozone levels than schools to both the west (e.g., Glenwood Springs, Fruita, Montrose, Craig and Rifle) and east (e.g., Boulder, Denver, Aurora, Northglenn, Longmont and Fort Collins) of the Rocky Mountains. One distinguishing factor observed was a much smaller diurnal variation at mountain sites. This is likely due to a combination of greatly reduced NO_x emissions in the mountains coupled with continual subsidence of ozone-enriched air from higher altitudes in the atmosphere. Then, nocturnal mountain drainage flows subsequently transport this air to lower elevations while slowly losing ozone via deposition at the same time. Monthly averages of ozone along the urban Front Range in Boulder, Colorado (elevation 1589 m) and at a mountain site near Black Hawk, Colorado (elevation 2875 m) are shown in Fig. 10 for the four years 2013–2016. Monthly ozone averages are higher at the mountain site during every month of the four years. Annual ozone averages at 14 sites provide a trend of 1.3 ppb per 100 feet of elevation ($R^2 = 0.61$). A similar trend of 1.5 ppb per 100 m along the Colorado Front Range was observed by Brodin et al. (2010). The increase in ozone levels with elevation was interpreted to be caused by the confounding effects of the high elevation of these sites (e.g., higher UV intensity), increased ozone in long-range transported air, and anthropogenic ozone production in air transported from nearby urban and suburban areas east of the Colorado Front Range Mountains.

3.1.3. GO3 data and the AirNow program

The additional coverage in ozone data that GO3 ozone monitors provided was significant, especially in Colorado where at one point there were 31 GO3 stations and 20 CDPHE stations reporting data, as seen in Fig. 11. Sonoma Technology, Inc. began a series of studies to determine the accuracy of the GO3 data, as well as their potential to improve AirNow's ozone mapping and forecasts. Sonoma Technology's studies showed very good agreement between GO3 station data and data from a regulatory monitor within 0.8 km in Rifle, Colorado ($R^2 = 0.90$ for ozone measurements made during February through August 2010). Furthermore, they found that the GO3 data reduced uncertainty in the AirNow maps and increased the population served by their forecasts by as many as 207,380 people during one moderate to high ozone day (Dye et al., 2011).

3.1.4. GO3 data used in large scientific study of ozone in Colorado

As word circulated about the availability of additional ozone data across Colorado, local researchers became interested in the data. Owen Cooper (National Oceanic and Atmospheric Administration/Cooperative Institute for Research in Environmental Sciences) and Rainer Volkamer (University of Colorado, Boulder) began to evaluate the value of GO3 data for inclusion in a 2014 study of ozone in Colorado. They determined the data could "be applied to their model simulations of ozone production and transport across Colorado's Front Range, providing valuable information in areas typically devoid of routine observations" (Cooper et al., 2015). As a result, Dr. Volkamer's group sponsored the calibration of 11 GO3 ozone monitors prior to NASA's 2014 study DISCOVER-AQ (Deriving Information on Surface Conditions from COlumn and VERtically Resolved Observations Relevant to Air

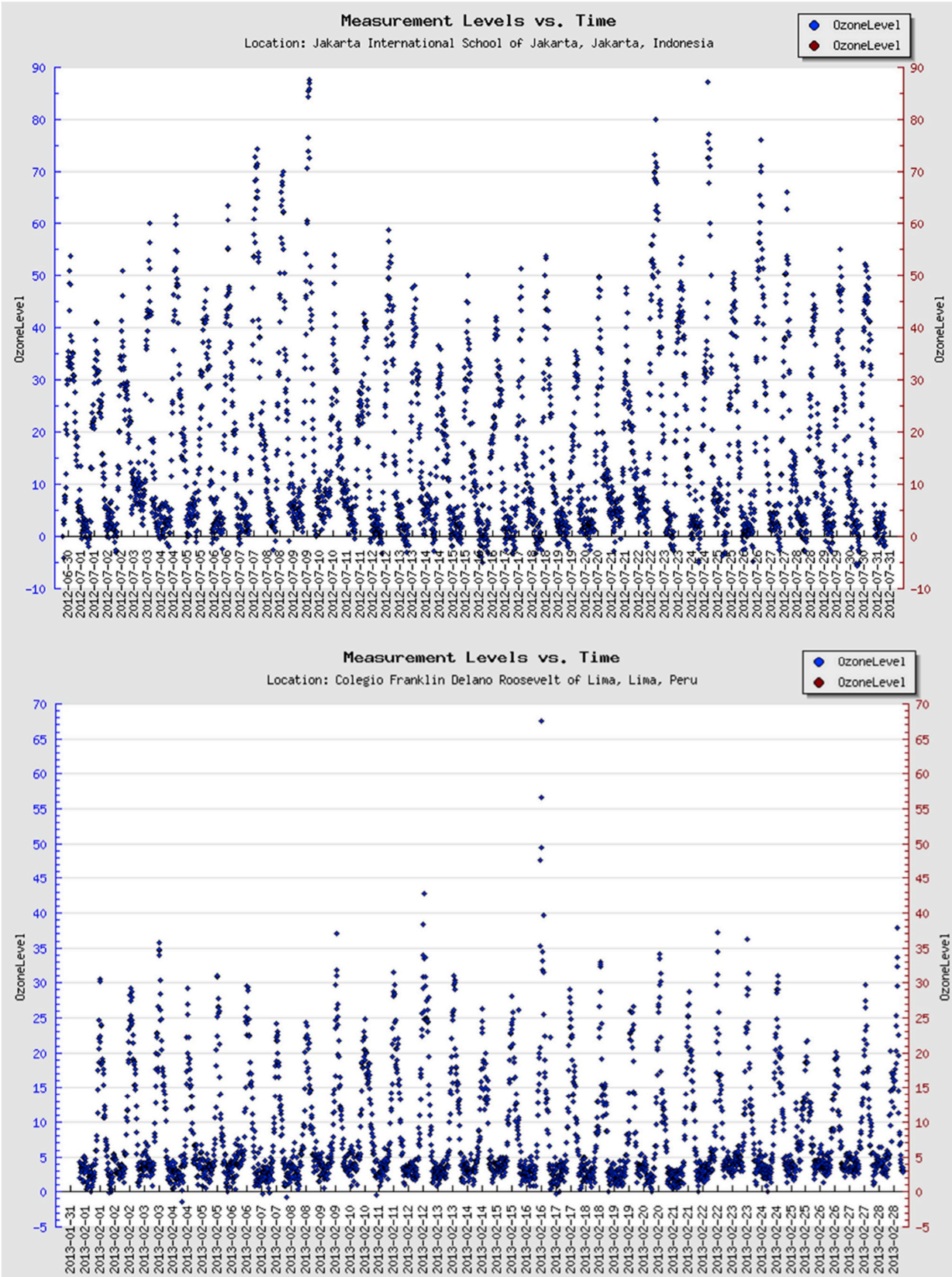

Fig. 8. Ozone measurements during July 2012 at the Jakarta International School, Jakarta, Indonesia (above) and during February 2013 at the Colegio Franklin D. Roosevelt of Lima, Peru (below). Note the large diurnal variations, with ozone reaching near zero values during the night.

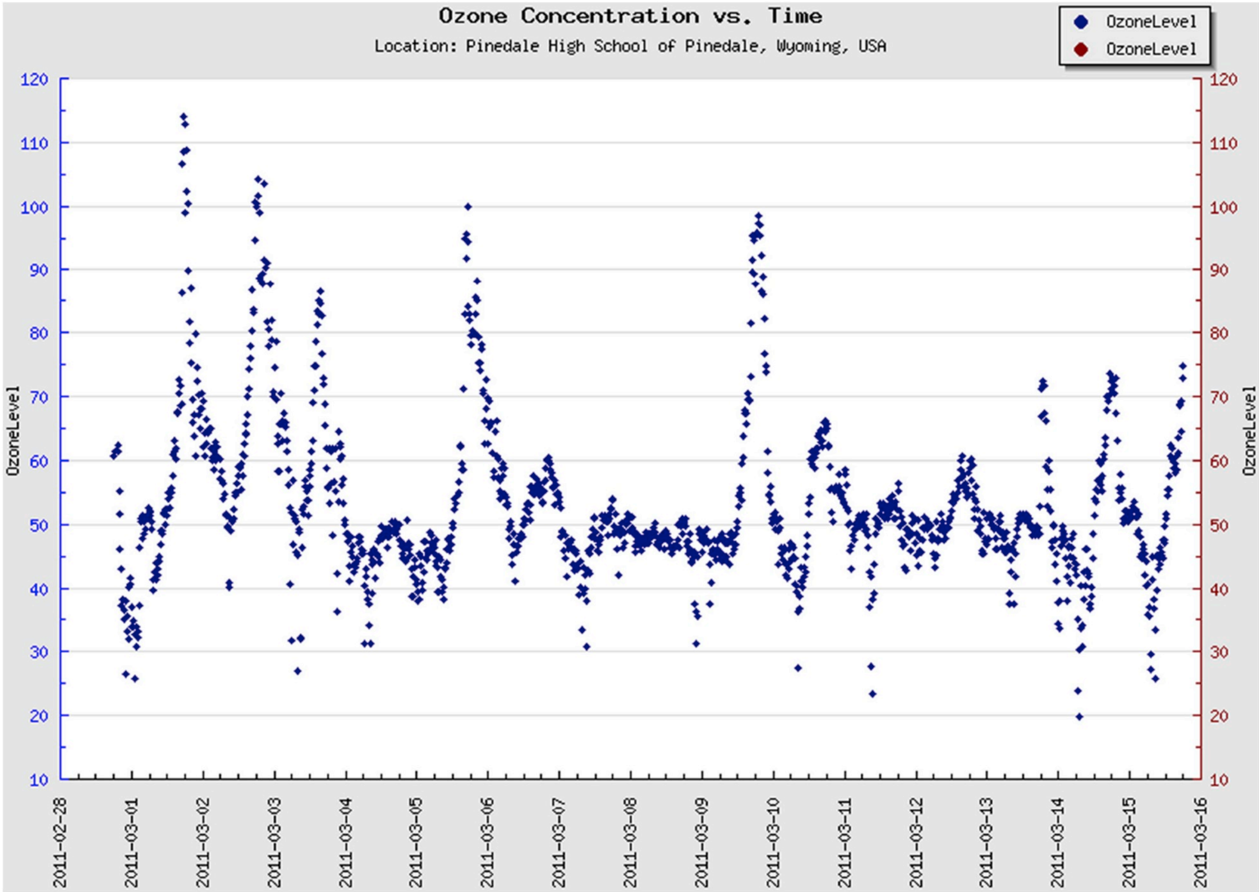

Fig. 9. Ozone measurements made by Pinedale High School in Pinedale, Wyoming during the period 2 Feb to 16 Mar 2011.

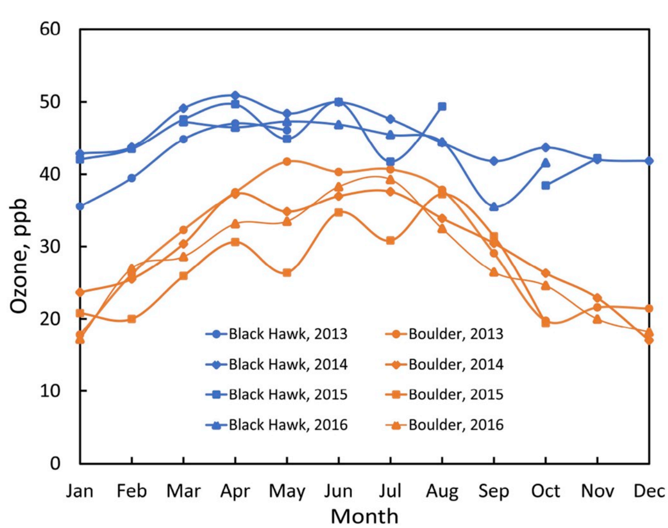

Fig. 10. Average monthly ozone measurements made in Boulder, Colorado and Black Hawk, Colorado during the years 2013–2016.

Quality). Data from four of the GO3 monitoring sites were complete enough over the summer of 2014 to be included in the data archive for DISCOVER-AQ.

3.2. Key results of AQTreks

3.2.1. Participation in AQTreks – educational benefits

GO3 Treks was the pilot project for our exploration into mobile monitoring. With GO3 Treks we tested the concept of mobile air pollution monitoring in middle and high schools. From 2015 to 2016 approximately 3500 students at 63 schools across the U.S. participated in GO3 Treks. The schools had the instruments for two weeks each and uploaded a total of 449 Treks to the GO3 Social Network. The GO3 Treks students were provided three online surveys, and we received 5863 responses. The surveys indicated that sixty-four percent of students had never heard of ground level ozone before the project began. After two weeks with the project, high school students' scores on surveys testing knowledge of ozone and black carbon increased an average of 14% from pre-to post-project (from 50% to 66%). Middle school students' scores increased an average of 16% (from 55% to 69%). Surveys showed that 68% of the students wanted to participate in GO3 Treks again and 48% of students were inspired by the project to increase environmental awareness at their school.

Teachers were also surveyed, and 100% of teachers said that their students enjoyed GO3 Treks. Eighty-six percent of the teachers in GO3 Treks used the curriculum, versus 51% of teachers in the GO3 Project. We concluded that a shorter time period with the instrumentation motivated the teachers to more fully utilize the resources, as their time with the project was limited. However, 62% of the teachers thought that two weeks with the instruments was not enough time; therefore, in AQTreks we increased their time with the instrumentation to three weeks.

After the GO3 Treks pilot project ended, AQTreks was launched in 2016. To date approximately 4500 students and citizens at 95 schools and other organizations across the U.S. have participated in AQTreks and have uploaded 1308 Treks. The new bite-sized, online Moodle curriculum has been utilized by 178 users.

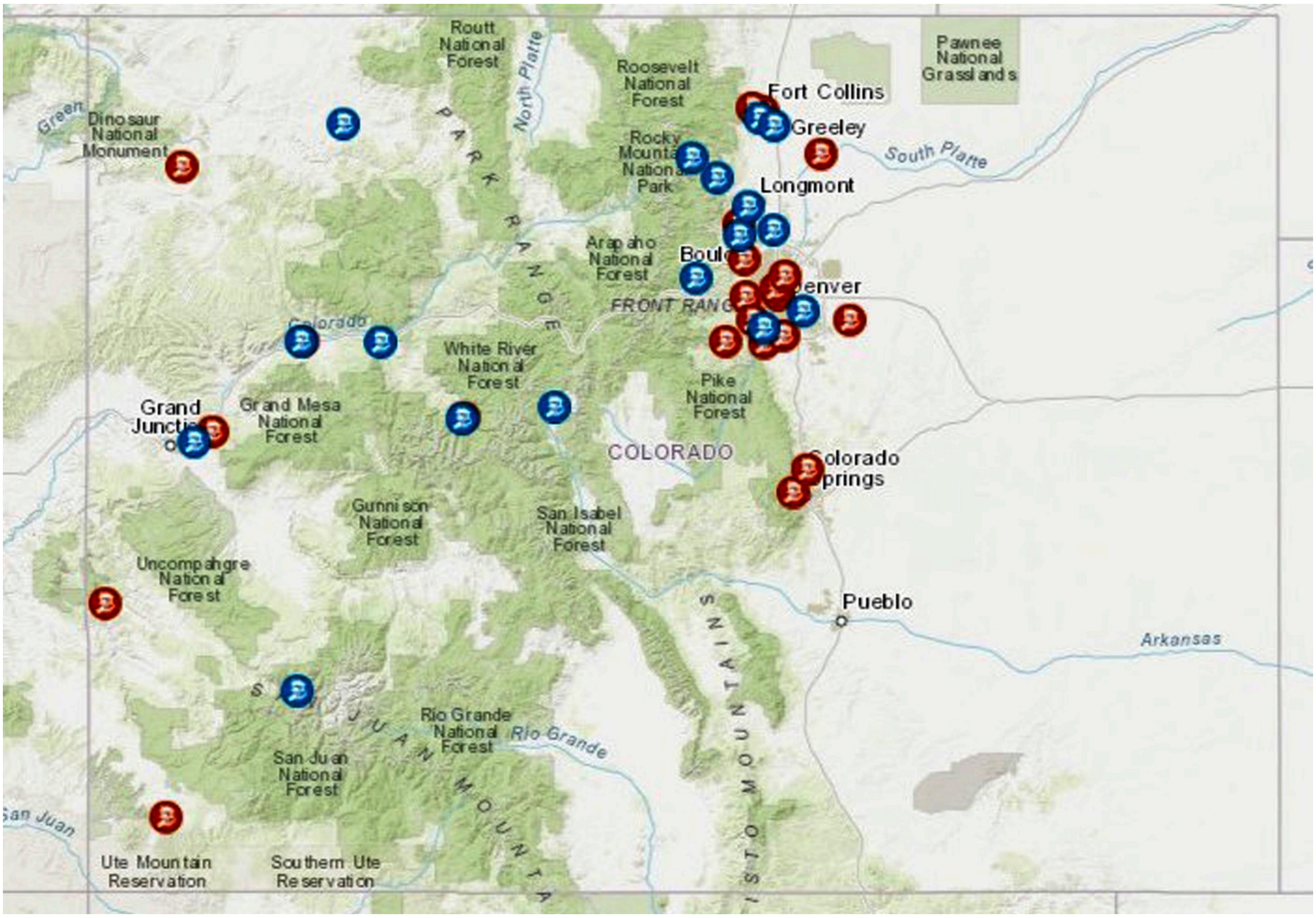

Fig. 11. GO3 sites are shown in blue and CDPHE sites are shown in red. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.2.2. Example uses of AQTreks

AQTreks and the PAM have been used by a wide variety of schools and organizations across the U.S. for both indoor and outdoor air monitoring. CO and PM are both important indoors, and recent studies suggest that levels of indoor CO_2 above 1000 ppm are cause for concern and can affect building occupants' cognitive abilities (Allen et al., 2016). Schools have used the PAM indoors for the evaluation of classroom air. A high school in Medford, Massachusetts used the PAM and AQTreks throughout their school building and found high levels of CO_2 (2344 ppm) in their classrooms. The students also discovered elevated levels of PM_{10} (131 μg/m^3), $PM_{2.5}$ (168 μg/m^3), PM_1 (183 μg/m^3) and CO (7.35 ppm) in their auto laboratory where they learn to repair cars. Other organizations and schools have focused on outdoor air health. For example, one organization in Texas used AQTreks and the PAM in an effort to reduce student exposure to vehicle exhaust, with the ultimate goal of passing a city-wide anti-idling ordinance. Government agencies, community groups, and researchers are using the PAM during wildfire and prescribed burning events, including personal exposure monitoring for firefighters. Fig. 12 shows the use of the PAM during a wildfire smoke event in Golden, Colorado and the resulting data displayed for public viewing online. These examples represent only a few of the ways schools and other organizations have made use of the PAM and AQTreks.

4. Discussion

The most overwhelming conclusion from our ten years of experience getting students and communities involved in air pollution monitoring is that students, teachers, and citizens are extremely eager to participate and make measurements of their own. When we began the GO3 Project in 2009 we started a sign-up list for schools that wanted to participate in the project but lacked funding for the instrumentation. We eventually had to suspend additions to the list when it reached nearly 400 U.S. schools and 53 international schools. The GO3 Project was created primarily as a K-12 program, however with the addition of AQTreks, interest in the program has expanded greatly and we have been contacted by many community groups and government agencies with various monitoring applications. The primary reason these groups have been widely unable to participate in air monitoring is lack of funding for instrumentation.

In terms of using stationary versus mobile educational monitoring projects, our experience shows they each have their respective benefits. Mobile monitoring with low-cost sensors allows large-scale participation for short monitoring increments of a few weeks. Because of its hands-on nature, mobile monitoring is very interesting and exciting for students and provides an engaging platform for air pollution education. It allows students to see the spatial variability of pollution and to explore any location they are curious about. Mobile monitoring also stimulates more of a social data-gathering mission than does fixed-base monitoring, as only 33% of GO3 Project teachers (stationary monitoring) reported using the GO3 Social Network, while 70% of GO3 Treks teachers (mobile monitoring) used the social network. GO3 Treks students and teachers reported enjoying the social network feature of mobile monitoring, since the blog format made their data "come alive" with a story. This data commentary feature will soon be added to the AQTreks website for students to discuss and analyze their Trek data collaboratively.

Stationary monitoring, on the other hand, is more likely to be

Fig. 12. AQTreks data shown on the CommunityAQ website (top) during a wildfire smoke event in Golden, Colorado (bottom) on September 4, 2017.

scientifically useful. There are primarily three reasons for this. First, stationary monitoring is not subject to as much variability as mobile monitoring, such as moving point sources, and the monitors can be installed to avoid measuring point source emissions. Second, stationary monitoring makes it possible to use somewhat larger, more expensive instruments with higher accuracy. Third, stationary monitors are easier to calibrate since they stay in one place and are controlled by one organization for long periods of time. From a student learning standpoint, stationary monitoring gives students a deeper understanding of the pollutants they are measuring and allows them to see diurnal trends, seasonal variability and long-term trends in the pollutant concentrations.

When building programs for community monitoring, it is critically important to provide teachers and citizens with monitors that make

Fig. 13. The Community Air Monitor (CAM).

accurate measurements. Teachers have extremely limited time for extra projects. We have found that they are unable to maintain monitoring equipment without significant assistance, including financial assistance for calibration and maintenance, detailed instructions, and frequent reminders. This becomes an even more significant issue when sensors are introduced into educational and community settings. The rental model for AQTreks is a responsible way to distribute sensors in the community, where students/citizens have pre-calibrated PAMs for three weeks and are required to send their PAMs back for calibration if they have them for longer than three weeks.

5. Conclusions and future directions

As sensors become ubiquitous, stationary air monitors will begin to play an important role in "on-the-fly" mobile sensor calibrations. We envision smaller, low-cost traditional monitoring stations being distributed around a city, where citizens can take their sensors for a walk-by or drive-by calibration. The sensor calibration parameters can be adjusted in the cloud when it is recognized that a sensor is near a calibration station. This will become more important as sensors are made publicly available, such as in libraries for check-out. Cities can provide their citizens with the sensors as well as the ability to calibrate them on their own. Data from sensors that have not been co-located with a calibration station for a certain period of time can be flagged and suspended until a calibration is performed.

Due to the importance of a blended stationary and mobile approach to air monitoring, and our positive experiences with both the GO3 Project and AQTreks, we recently introduced the stationary Community Air Monitor (CAM), as shown in Fig. 13. The CAM combines the PAM and a 106-L ozone monitor in a weatherproof enclosure for continuous, stationary monitoring of CO, CO_2, PM_1, $PM_{2.5}$, PM_{10}, and ozone. Data communication is done over 4G cellular service with a direct upload to the server. Community members can see the real-time data from CAM stations on their mobile devices, either on the web or in the app. Since the station can be used as a calibration station for mobile monitors, the ozone monitor inside the CAM is calibrated yearly, and the PAM is changed out quarterly with a calibrated PAM.

From 2009 to 2019 we were able to provide a total of approximately 20,000 students with air quality education and tools. We have found that schools and the general public are extremely eager to get involved in air monitoring. Schools are searching for real-world data collection experiences for students and the opportunity for students to analyze data they were responsible for collecting. Additionally, air pollution monitoring fits student interest and teacher requirements for authentic data collection. The scientific community has likewise recognized the value of data gathered in education-based projects when the data are gathered with sound protocols and an emphasis on calibration of the monitoring instruments. Since the introduction of AQTreks, interest in these projects has expanded from schools to communities and air monitoring agencies, due to the ease of data collection and our focus on data quality. We recognize that it is the responsibility of air pollution educators to provide accurate monitors to schools and communities, as well as easily executable plans for calibration and maintenance.

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.

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