Final Report

to the Transportation Planning Organization
of Hillsborough County

on Research Agreement

Low-cost monitoring to reduce traffic-related air pollution exposure and inequality, a pilot study

Project Period: September 2021–August 2022

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Executive Summary

Many marginalized communities in the US, including in Hillsborough County, are disproportionately exposed to traffic-related air pollution (TRAP) and experience disparities in air-pollution-related health impacts. Novel low-cost air pollution monitors are emerging as an approach to assess neighborhood air quality and improve urban and transportation planning. There is substantial interest by community organizations, non-profit organizations, local government agencies, and individual residents in the potential of these new technologies to inform decision making. Due to the emerging nature of these devices, there is a need to understand the quality of data they produce, to educate device and data users, and to develop context-appropriate approaches for their implementation, calibration, and use, so that these new technologies can be applied most effectively in a large-scale monitoring network for the county.

To address these needs, a collaborative university-government-community partnership was formed to begin work toward the establishment of a community air monitoring network using novel lower-cost monitors in Hillsborough County. Collaborative partners included the Transportation Planning Organization (TPO), the Environmental Protection Commission, the University of South Florida (USF), and several community organizations, civic organizations, and public schools. The cooperation of the City of Tampa and Hillsborough County was also instrumental to successful siting of monitors. As a component of this partnership, a research agreement was established between the TPO and the University of South Florida (USF) providing funding to USF for our activities on the project from September 2021 through August 2022. This document serves as the final report on these activities. We note that all activities were performed in collaboration with the larger collaborative partnership. The process of working together through the project activities proved successful for achieving the project goals with each partner contributing their expertise where needed. Three types of project activities were performed: monitor selection and performance testing, community site selection and pilot monitor installation, and community education and outreach.

To select potentially appropriate monitors for community sites, we developed a list of criteria, performed an extensive literature review, identified seven low-cost monitors to test, and conducted useability and performance testing of six of those monitors in field settings. In parallel, potential community field sites were identified through the development of site selection criteria, mapping analyses, community-involved site-selection activities, and field visits for site scoping. Following the field visits, six monitors were installed at four community field sites during the project period (September 2021–August 2022). Finally, we developed community education and outreach materials and presented at multiple activities to engage the community.

Results of monitor selection activities suggest that reasonable data quality, low price, small size, simple use and maintenance, longevity, and facile data collection with public sharing are important criteria for a successful community monitoring device. Results of field performance testing results show that the Clarity Node-S device provided good data quality for $PM_{2.5}$. Calibrated values were strongly linearly correlated (R^2 = 0.80) with data from a co-located reference monitor throughout the testing period. The Clarity device was also found to

be the easiest fixed-site monitor to use and most flexible for use under variable site conditions. However, data quality for NO_2 from the Clarity device is weaker than for $PM_{2.5}$, even after calibration; measured values may only be useful for comparative analysis. Further, manufacturer-required NO_2 calibration procedures are time consuming and cumbersome; they may not be routinely achievable in a community-run network. The PurpleAir II particle monitor also showed promise for fixed-site $PM_{2.5}$ monitoring for some community sites, but its data quality performance was found to change over time. A linear regression of 24-hr average concentrations measured by the PurpleAir II compared with a reference monitor resulted in an R^2 of 0.82 during the first two months of operation, but decreased to 0.36 by months seven and eight of the testing period. Hence, device maintenance, replacement, and/or routine recalibration accounting for varying seasonal meteorology are likely needed. The PurpleAir is also best suited for sites that have access to plug-in power and continuous high-quality Wi-Fi; this proved to be limiting for the community organization sites and public building sites piloted here. Finally, the Atmotube Pro was found to be a wearable monitor with reasonable data quality performance for $PM_{2.5}$ measurement (R^2 = 0.41); it may be useful for supplemental personal mobile monitoring by community members and public engagement. Additionally, its data quality could potentially be improved through calibration.

USF also contributed to several educational outreach activities that were used to engage community members. These included an interactive on-line meeting where community participants provided graphical, textual, and verbal input on the community site selection process, two activities with K-12 students to discuss project content and facilitate student interaction with the air pollution monitors, poster installations at community monitoring sites to inform and engage the general public, and presentations on project progress and data.

Overall, the outcomes of this work indicate that community-engaged monitoring of neighborhood air quality in Hillsborough County, using a network of low-cost monitors, has substantial potential for supplementing regulatory air quality monitoring and informing decision making by local government agencies, civic organizations, and individuals. Further work is needed to develop context-specific methods and protocols for implementation and sustainability of the network, to improve and communicate data quality from these monitors, and to educate government stakeholders and community members on the appropriate interpretation and use of the data as a supplement to that from the regulatory network. Nonetheless, we anticipate this work will help build trust by marginalized communities in local urban decision-making processes, empower community members to contribute to those decisions, and ultimately lead to better decisions, better air quality, and improved equity.

1 Introduction

Air pollution is one of the greatest environmental risks to health, leading to respiratory and cardiovascular diseases, premature death, additional health costs, and loss of work productivity (Brunekreef & Holgate, 2002; Cohen et al., 2017; Lee et al., 2014). Traffic-related air pollution (TRAP) is a particular concern in urban areas (Abdull et al., 2020; Künzli et al., 2000; Xia et al., 2015), with previous studies finding that people living near major roadways are exposed to more TRAP and experience higher health risks from air pollution (Wang et al., 2011; Zhang & Batterman, 2013). For Hillsborough County, both modeling and measurement studies have shown that African Americans and households living in poverty are disproportionately exposed to TRAP (Gurram et al., 2019; Stuart & Zeager, 2011; Yu & Stuart, 2013). The 2021 State of the System Report of the Hillsborough County Transportation Planning Organization (TPO) found that more than one-quarter of Hillsborough County's total population lives within 300 meters of a high-volume road. This figure increased by nearly 7% from 2018 to 2021, while the percentage of the vulnerable population living within 300 m increased by 14%. A further complication is that marginalized populations generally feel disempowered to participate in government decision making processes that can affect their air pollution exposures and health (Brickle & Evans-Agnew, 2017). Hence, there is a need to characterize air quality in neighborhoods near roadways in the county, particularly in vulnerable communities. There is also a need to engage the population of these communities in transportation decision-making processes.

Community-based air quality monitoring may provide a means to fill these needs. Although the current network of regulatory air quality monitoring sites provides high-quality ambient pollution data, the cost and logistical requirements of regulatory monitoring sites has led to a network that is too sparse to characterize[1] individual and neighborhood air quality. Due to their lower-cost and small size, newly emerging monitoring technologies are promising tools for affordable collection of real-time air quality data at a network of community sites. However, due to novelty of these technologies, there remain many questions about their potential use. Aspects that need resolution include characterization of monitor performance and longevity, best methods for using and integrating monitor data appropriately across community sites and regulatory sites and in the context of data uncertainties, and best methods for engaging individuals and community organizations in network implementation and maintenance to ensure sustainability of the network. Finally, approaches that engage and empower vulnerable populations in decision-making processes while building trust between communities and government agencies are needed.

The goal of this project was to address these questions. Specific objectives were 1) to inform methods for the integration of low-cost monitoring data, including its uncertainties, into community and TPO decision-making processes, 2) to determine ambient levels of traffic-related air pollution in a historically-disadvantaged neighborhood near the I-275 and I-4 highways, and 3) to inform best practices for building government-university-community partnerships for sharing air quality monitoring data and expertise.

[1] 'to characterize' means to describe the features in detail.

In this report, we describe the progress and outcomes of Year 1 of this project. This includes discussion of the government-university-community partnership that formed for the project (Section 2), the identification and testing of potential monitors (Section 3), the establishment of community sites for pilot assessment of air quality in near-road communities (Section 4), and community education and engagement activities (Section 5). Finally, we summarize the findings and next steps needed toward the overarching goals (Section 6).

2 Establishment of a government-university-community partnership

One of the overarching goals of this work is to build trust and engage vulnerable populations in TPO decision making. Hence, it was important to pursue this project as a partnership among multiple stakeholders with a range of interests and expertise (Kaufman et al., 2017; Symanski et al., 2020). The collaborative team formed for the project includes staff members of the Transportation Planning Organization, members of the air monitoring and sustainability teams of the Hillsborough County Environmental Protection Commission (EPC), researchers in the Stuart research group in the College of Public Health and Department of Civil & Environmental Engineering at the University of South Florida (USF), as well as numerous individuals affiliated with community monitoring pilot sites. Within this group, the TPO has played a facilitator role, including coordinating regular meetings among the TPO, USF, and EPC, planning and facilitating meetings and events for community collaboration and engagement, developing engagement materials and the project webpage, overseeing the analysis and selection of community pilot sites, coordinating with community sites, and compiling and submitting proposals for supplemental external funding. The USF team has been responsible for low-cost monitor identification and evaluation, providing expertise and analyses for community pilot site selection, leading the field work for selection and installations at community sites, analysis and interpretation of monitor data, and development and presentation of materials for community education and engagement. The EPC has contributed air monitoring expertise and guidance, assisted with site selection and logistics, enabled regular access to the regulatory monitoring site, provided expertise and assistance with installation and maintenance of the novel monitors at that site, provided ongoing internet access for data collection, and provided reference data for evaluation analyses. Community site hosts, the City of Tampa, and Hillsborough County also provided substantial assistance with the selection of installation locations and with installation logistics. Finally, numerous community members have contributed their ideas and time to enable selection of community monitoring sites, site installation logistics, and engagement events and opportunities.

3 Selection of low-cost monitors for community use

3.1 Identification of candidate monitors

The first step of the process to select appropriate monitors for community use was an extensive review of the available literature on existing monitors. We were interested in investigating three topic areas—air pollution, community, and low-cost sensor/monitor —around which our search terms were built. To identify relevant articles, we searched the scholarly literature using the Web of Science Core collection. The Web of Science Core collection includes approximately 22,000 journals plus books and conference proceedings (clarivate.libguides.com/librarian resources/coverage). The following search terms were used, where TS is a topic search. TS=("air pollution" OR "particulate matter" OR "air pollutants" OR smog OR visibility OR combustion OR atmosphere OR meteorology OR concentrations OR "exhaust gas" OR emissions) AND TS=(community OR poverty OR "low income" OR vulnerability OR inequity OR disparity OR "economic disadvantage" OR "health care disparity" OR "environmental risk" OR "sensitivity group") AND TS=("low cost sensor" OR "chemical sensor" OR "gas detectors" OR "portable sensor" OR "wireless sensor" OR "sensor network" OR "mobile sensor"). Using these search terms, we identified 121 results to explore. Several additional articles were also identified based on the research group's previous work. Subsequently, we reviewed all titles and abstracts of all articles. This process helped to build familiarity with each topic area, while selecting relevant articles that combined two or more of these topic areas together. Selected articles were read in detail, with additional relevant papers identified for review iteratively from the references of the reviewed articles. Overall, approximately 46 articles were reviewed in detail.

In addition to searching the academic literature, we also explored relevant government and professional reports, manufacturer materials and community organization documents, primarily through web searches and references of the scholarly articles. It is notable that the USEPA has been conducting research into low-cost air pollution monitors for several years with the objectives of advancing sensing technologies and facilitating their use for applications that supplement regulatory monitoring (www.epa.gov/air-sensor-toolbox/epa-air-sensor-research-overview). Importantly, the USEPA has a website clearinghouse for low-cost monitor information, the "Air Sensor Toolbox" (www.epa.gov/air-sensor-toolbox). Within this site, we particularly focused on the pages for "Sensor Performance, Evaluation and Use", "Understanding Your Sensor Data Readings", and "Research Projects". We explored these websites and the relevant articles cited therein to study the sensor evaluation results, operating procedures, collocation methods, sensor data quality and interpretation, as well as community projects. In addition, the South Coast Air Quality Management District (AQMD), which is responsible for managing air quality in southern California, has a program called the "Air Quality Sensor Performance Evaluation Center (AQ-SPEC)" (www.aqmd.gov/aq-spec/home). The AQ-SPEC performs evaluation of many low-cost monitors and disseminates performance data through its website. The information provided through AQ-SPEC was also instrumental to our identification of potential community monitors for this project.

3.2 Criteria for appropriate monitoring devices

Based on the above literature review, we identified several criteria that are important to the success of a monitoring device as a community air quality monitor. A summary of the set of criteria is shown in Table 1 and include air pollutants measured, measurement quality, cost, size, useability, and mechanisms of data collection and sharing.

The most important criterion was that the monitor reliably measures pollution of interest to the project. Here, we are focused on traffic-related air pollution (TRAP), which is a mixture of pollutants including particles, nitrogen oxides, carbon monoxide, and volatile hydrocarbons, that tend to be elevated within about 300 to 500 m of a roadway (HEI, 2010). Some pollutants that are of particular focus in the TRAP literature are fine particles, especially ultrafines, black carbon, benzene, 1,3-butadiene, formaldehyde, and acetaldehyde. The latter four are called mobile-source air toxics. Based on the other criteria discussed below, we ultimately focused on monitors that measure fine particles, called $PM_{2.5}$, nitrogen dioxide (NO_2), and volatile organic carbon (VOC). $PM_{2.5}$ and NO_2 are both US criteria air pollutants; these are common pollutants that have known health effects and have established levels in air that should not be exceeded, called National Ambient Air Quality Standards (NAAQS) (U.S. Environmental Protection Agency). $PM_{2.5}$ is fine inhalable particulate matter, with nominal particle size less than 2.5 μm in diameter. It can reach deep into the lungs and enter the bloodstream to cause harmful effects, resulting in respiratory and cardiovascular diseases and symptoms, reduced lung function, increased risk of cancer, and premature death (Pope et al., 2002; Richards, 2008). Roadways provide an important source of $PM_{2.5}$; it is emitted with engine combustion effluent from vehicle tailpipes, from brake and tire wear, as resuspended road dust, and from construction and road maintenance activities. $PM_{2.5}$ is also formed in the air from gaseous vehicle emissions. The established NAAQS levels for $PM_{2.5}$ concentration are 35 $\mu g/m^3$ on a 24-hr average basis and 12 $\mu g/m^3$ on an annual average basis; above these levels sensitive populations may experience detrimental effects. NO_2 is a gas formed during burning of fuel and in the exhaust fumes from vehicles. Short-term NO_2 exposure can irritate airways and aggravate respiratory diseases, while long-term exposure may lead to the development of asthma and respiratory infections (Weinmayr et al., 2010). NO_2 has both an hourly and annual NAAQS standard level of 100 ppbv and 53 ppbv, respectively. Finally, we also identified monitors that measure VOCs. The pollutant category of VOCs includes a wide variety of compounds that are emitted from many sources including car exhaust, gasoline dispensing stations, paints, and industrial coating operations. It is not an ideal pollutant to study here because, as a category, VOC levels are not particularly associated with traffic, and because compounds within the category have a wide variety of health impacts ranging from no detrimental effect to severe. Currently, VOCs are studied and measured as a category primarily due to their contribution to the formation of photochemical smog. Nonetheless, several important TRAP pollutants are VOCs, and it is the only pollutant category measured by novel monitors that includes traffic-related hydrocarbons and air toxics. Hence this pollutant category was a secondary focus here for identification of monitors.

Table 1. Criteria for Selection of Low-Cost Monitors for Community Network Use

Pollutant	Quality	Price	Size	Useability	Data Collection / Sharing
TRAP ($PM_{2.5}$, NO_2, VOCs)	Moderate (1-hr) R^2 vs EPA FRM/FEM	Lowest, <$2000	Small or wearable	Easy, few ancillaries, low maintenance, longevity	Easy transfer, public sharing website

TRAP signifies traffic-related air pollution. FRM and FEM are used to signify federal reference method and federal equivalent method for air quality monitoring, respectively.

Regarding measurement reliability, we sought to identify monitors that could measure TRAP pollutants with reasonable data quality. Although we looked at multiple metrics of measurement quality in our overall selection of community monitors, for the purposes of identifying monitors to field test, we focused on the coefficient of determination (R^2). This measure was most readily available in previous literature, allowing comparison across studies and monitors. Specially, we looked for at least moderate R^2 for a linear model comparing 1-hr average values from the novel monitor against paired reference data that was measured to meet the specifications of a Federal Reference Method (FRM) or Federal Equivalent Method (FEM) of the US Environmental Protection Agency (EPA) (40 CFR Part 53).

Our second set of criteria for an appropriate community monitor was that the device be inexpensive and small. These criteria are important because they allow for affordable monitoring at many disparate locations within the community and by individuals. They also distinguish this monitoring initiative from routine regulatory monitoring. Regulatory monitoring of air pollutant levels is routinely performed by government state, local, and tribal agencies under the guidance of the US EPA to meet the requirements of the US Clean Air Act, as codified in the US Code of Federal Regulations (and in state and local codes). To meet these extensive regulatory requirements, monitoring sites are expensive and have a large footprint (see Figure 0), limiting the potential network granularity and the ability to capture neighborhood air quality. Novel monitoring devices for some traffic-related air pollutants are available as both fixed and portable devices at the size of approximately a large key fob to a clock radio (see Table 2), with prices as low as approximately $150.

Figure 0. Example regulatory air monitoring site images, including the Hillsborough County near road site (left).

Third, we are interested in devices that are easy to use and maintain and collect and provide their data in a manner that facilitates direct public data sharing and interpretation. These conditions are particularly important to enabling community monitoring engagement. However, they are also difficult to attain, as most regulatory air pollution monitoring devices require complicated installation with substantial ancillary equipment, along with regular human interaction for maintenance, data collection, analysis, and quality assurance. Although most novel devices also do not meet these criteria easily, some have been designed toward these goals. In particular, some do provide a public website for sharing and crowdsourcing data.

A final set of criteria were that the device could be easily purchased by the TPO or USF and did not use contract language that limited sharing of device data analyses. Although these criteria were not initially on our list, they emerged as we negotiated with potential vendors. Ultimately these criteria limited the selection of devices primarily to those manufactured in the US or that have a 3rd party seller in the US.

3.3 Candidate low-cost monitors

Based on the criteria in Table 1, several candidate monitoring devices were identified. Table 2 provides a list of those devices that we identified as most promising for field testing. For ease of discussion, the devices are categorized into those that only measure particulate matter, those that only measure NO_2, and those that measure levels of multiple pollutants simultaneously. Here, we summarize the characteristics of these categories of devices as well as those of individual candidate monitors.

The stand-alone PM monitors include the PurpleAir II (www2.purpleair.com/) and AirBeam 2 (www.habitatmap.org/airbeam). These devices measure multiple size ranges of particles simultaneously; this includes PM_1, $PM_{2.5}$, and PM_{10} (where the subscript indicates the nominal particle size in μm). The monitors are approximately the size of a large fist or hand and can be purchased for a one-time price that is less than $250. Moderate to strong correlation has been found for these PM monitors in comparison with regulatory monitors, according to the field tests of the Air Quality Sensor Performance Evaluation Center (AQ-SPEC) established by the South Coast Air Quality Management District in California (www.aqmd.gov/aq-spec). The PurpleAir II is designed for fixed installations and requires continuous plug-in power supply. It generally also requires continuous access to a Wi-Fi for data collection and transmittal; however, an optional SD card can be used to collect a limited amount of data during off-line use. The AirBeam 2 is designed for both fixed and portable operation. It requires daily charging or plug-in power, a data logger with Wi-Fi or cellular access, or a co-located Android cell phone with Bluetooth. Both device manufacturers maintain a website that can be used to upload (automatically or manually), visualize, map, and share data with the public.

Table 2. Candidate Low-Cost Monitors

Monitor	Image	Pollutants[a]	Price	Data Quality[b]	Useability	Data Collection / Sharing
PurpleAir II		$PM_{1,2.5,10}$ (T, RH, P)	$249	$PM_{2.5}$: $R^2 > 0.86$	Fixed use. Requires a plug-in power connection. Continuous Wi-Fi is preferred, but a SD card is optional for data storage.	Data can be set for automatic upload to a public website that includes data download, mapping, and trend plots.
AirBeam 2		$PM_{1,2.5,10}$ (T, RH)	$249	$PM_{2.5}$: $0.68 < R^2 < 0.79$	Fixed or portable use. Requires daily charging or plug-in power, data logger with Wi-Fi, cellular or a co-located Android cell phone.	Manual or automatic data upload to a public website, includes download, map, trends
Liveable Cities NO_2		NO_2	$569 + $309/yr	$0.47 < R^2 < 0.59$	Fixed use. Connects to a street-lamp for power, includes cellular.	Private data management and visualization software
Cairsens NO_2		NO_2	$1,300	$R^2 < 0.13$	Fixed or portable use. Standard version requires continuous power.	Cable connection to computer with app for data collection and visualization
Clarity (Node-S)		$PM_{1,2.5,10}$ NO_2, (T, RH)	$1,200 /yr	$PM_{2.5}$: $R^2 > 0.73$ NO_2: $R^2 > 0.7$ (Manufacturer)	Includes solar panel and cellular; manufacturer provides active support and calibration	Automatic data upload to public website available, includes map and trends
Flow2		$PM_{1,2.5,10}$ NO_2, VOCs	$149	$PM_{2.5}$: $0.02 < R^2 < 0.22$ NO_2: $0.06 < R^2 < 0.21$	Requires co-located cell phone and daily charging	Data visualization and download via cellphone app
Atmotube		$PM_{1,2.5,10}$ VOCs (T, RH, P)	$179	$PM_{2.5}$: $R^2 > 0.79$	Requires co-located cell phone and weekly charging	Data visualization and download via cellphone app

[a]Pollutants and other entities measured. $PM_{1,2.5,10}$ indicates that the monitor measures three separate types of particulate matter, specifically PM with nominal diameter less than 1µm, 2.5µm, and 10µm, respectively. T indicates temperature, RH indicates relative humidity, and P indicates pressure.
[b]R^2 here indicates the coefficient of determination from a regression of the novel monitor's 1-hr average measured values against those from a co-located Federal Reference or Equivalent Method monitor. Values listed are based on AQ-SPEC monitor testing, unless otherwise noted.

The single-pollutant NO_2 monitors identified include the Cairsens NO_2 (www.envea.global/s/ambient/micro-sensors/cairsens-no2/) and Liveable Cities NO_2 monitors (www.liveablecities.com/for-air). The cost of these devices is higher than the PM monitors; with total annual costs during the first year from about $900-$1300. Despite the increased cost, data quality is poorer than for the PM monitors, with weak to moderate correlation found previously with a co-located reference monitor. We note that NO_2 is more difficult to measure than PM, leading to higher monitor cost and poorer data quality. NO_2 is a reactive pollutant, with known interferences that can affect sensors response, including changes in temperature, relative humidity, and levels of other pollutants, such as ozone (Duvall et al, 2021b; Miech et al., 2021; Miskell et al., 2018). The Cairsens NO_2 monitor is the only standalone NO_2 monitor that we have field tested to this point. It can be used as both a fixed and portable monitor. The standard version (without internal battery and cellular) is appropriate for stationary long-term monitoring and requires continuous plug-in power-supply. Internal data storage enables the monitor to collect data every minute for up to 3 weeks, but data transfer and visualization require a wired connection to a computer with manufacturer-specific software. The Liveable Cities NO_2 monitor is designed to be integrated onto a streetlamp, drawing its power from the lamp power infrastructure. It samples concentrations every minute, with integrated cellular enabling the automatic transfer of data to the manufacturer's data management platform. Although the Liveable Cities NO_2 monitor may have potential as a community monitor, it only emerged in 2021. Although it has been tested by the AQ-SPEC, when we reached out to the manufacturer, they indicated that they are still in the process of adjusting the device. Therefore, we have not yet been able to purchase a monitor for testing.

Finally, the multi-pollutant monitors comprise two types of devices, those designed for fixed-site operation, and those designed to be worn by individuals for personal monitoring. The Clarity monitor (Node S) (www.clarity.io/products/clarity-node-s) is an example of the former type. It simultaneously measures three particle size cuts and NO_2, as well as the ambient temperature and relative humidity, in a device the size of a large clock radio. Using a subscription service fee approach, it costs approximately $1200 annually. It has an integrated solar panel and cellular connection for power and data transfer, respectively, making it the most versatile fixed-site monitor we have tested. The Clarity team also provides consultation and analysis services that can simplify the calibration process. Clarity data for $PM_{2.5}$ can be shared and visualized via a public website. Manufacturer reported data quality in comparison with reference devices is strong. AQ-SPEC testing also showed good performance for $PM_{2.5}$, but no testing data are available for NO_2. Atmotube (www.atmotube.com/atmotube-pro) and Flow2 (www.plumelabs.com/en/flow/) monitors fall in the second type of multipollutant monitor. At a fixed cost of approximately $150, both measure particles and VOCs, while the Flow2 also measures NO_2. Each must be paired with a cell phone for data collection; integrated batteries must be regularly charged. Based on AQ-SPEC testing, the $PM_{2.5}$ measurement quality is strong for the Atmotube and weak for both $PM_{2.5}$ and NO_2 measurement by the Flow2. No information was found on the data quality for VOC measurement.

3.4 Field testing

3.4.1 Methods

Although several of these monitors were previously tested by the USEPA AQ-SPEC (www.aqmd.gov/aq-spec/sensors), local testing is an important aspect of this project. This local testing allowed us to understand issues in installation, operation, and data collection and interpretation that could impact the device's use for monitoring in community settings. Field performance testing under local conditions was also needed because meteorology can affect performance (Wallace et al., 2021). Here we describe the testing performed for this project.

To determine the local performance of each monitor, we performed several different testing procedures to understand the logistics of installation and use and to characterize the quality (accuracy and precision) of each monitor's measurement data for each focus pollutant. Our performance testing procedures and metrics were based largely on the base testing outlined for $PM_{2.5}$ in the USEPA performance testing guidance document (Duvall et al., 2021a), hereafter referred to as the 'USEPA Testing Guidance'.

Testing campaigns. To determine monitor accuracy, each monitor tested was co-located with (i.e., installed next to) a reference monitor over a period of time. Accuracy concerns how correct or true the data are, i.e., how closely the measured values match the true concentration levels in air. To evaluate accuracy, the novel monitors were installed at the Hillsborough County Munro EPC regulatory air monitoring site; the Munro site measures both $PM_{2.5}$ and NO_2 using FRM/FEM, hence these pollutants have been evaluated to date. For the $PM_{2.5}$ regulatory monitor, the instrument used at Munro is a Teledyne T640, while the instrument used for measuring the NO_2 is Teledyne-API Model 200EUP or T200UP. Both instruments are FEM monitors. Two PurpleAir II monitors were installed on the roof of the regulatory monitoring trailer at the Munro site on 11/30/2021. One of each of the remaining monitors listed in Table 2 (except the Liveable Cities monitor) was installed at the Munro site on 04/08/2022 (along with an additional PurpleAir II). Figure 1 provides images of these co-location installations.

PurpleAir II Clarity Node-S Other monitors

Figure 1. Images of co-location installations of the candidate low-cost monitors. The additional monitors shown in the rightmost image are the Atmotube Pro, AirBeam 2, Flow2, and Cairsens (from left to right).

Determining measurement precision for each monitor requires the co-location of replicate devices over time. Precision concerns how consistent the measurements are, i.e., how closely repeated measurements match each other. The USEPA recommends co-location of 3 replicate monitors over at least a two-month period (Duvall et al., 2021a). This latter standard was not achievable for most of the candidate monitors during this reporting period due to limitations in funds and time. Some monitors were too expensive to buy replicates despite being less expensive than regulatory monitors. Also, due to community input, the TPO needed to expand monitoring coverage beyond that originally envisioned in the pilot phase. This resulted in several PurpleAirs successfully deployed at community sites but limited the time available for precision testing. Hence, only the PurpleAir II and AirBeam 2 underwent precision testing during this reporting period. Specifically, 3 PurpleAir II monitors were co-located at the Munro EPC site since 04/08/2022, allowing analysis of precision. Additionally, a fixed-term precision testing campaign, in which three AirBeam 2 monitors were co-located at an alternative private field site, was conducted from 3/21/2022 to 5/6/2022.

Data acquisition and preparation. We obtained the pollutant level measurements from each device either through a wired connection to the device, from the data logger (or cell phone) or by downloading the data from the device's website. Native data from each of the monitors are reported in sub-hour frequencies (see Table 3) and contain some missing and invalid data. To prepare ('clean') the $PM_{2.5}$ data from all the novel monitors except the Clarity, negative values and those equal to zero were first removed from the data set. Zero values for fine particles have previously been shown to be unmeaningful (Wallace, 2022), as the number of particles in the smallest size category (0.3 – 0.5 µm) never falls to zero in the ambient environment. For the Clarity monitor, the manufacturer's service team performs data cleaning and data calibration; both the (cleaned) raw data and calibrated data can be downloaded from the device website. For the NO_2 data from the Cairsens and Flow2 monitors, no cleaning was performed.

Table 3. Frequency of native data acquisition of each monitor

Monitor	**Sampling frequency**
PurpleAir II	Every 2 minutes
Clarity Node-S	Every 15 minutes
AirBeam2, Cairsens, Atmotube, Flow2	Every 1 minute

We obtained reference pollutant levels for the Munro site reference instruments directly from the EPC staff. Both minute frequency and 1-hour average concentrations were provided, with flags included for invalid minutes and hours. Invalid data were removed prior to longer-term averaging for comparison to the novel measurements.

Calibration. Due to changing field and instrument conditions, the response of all monitoring devices (including regulatory instruments) typically requires calibration to improve the accuracy of reported values. Many factors specific to each measurement technology and pollutant being measured can affect instrument response and lead to the need for calibration. Some factors that commonly affect response include environmental temperature, relatively humidity, and the presence of other pollutants. In particular, the need to calibrate data from novel air pollution monitors prior to interpreting the data is well established in the literature (Malings et al., 2019). Hence, for the novel monitors installed at the community field sites (the

PurpleAir and Clarity devices), we evaluated performance using data values both before and after calibration. Here, we describe the calibration methods used. Although several different calibration methods have been applied to correct data from low-cost monitors (e.g., Williams, 2019), we focused during this reporting period on methods that directly rely on environmental conditions surrounding the monitor.

For the PurpleAir data, we calculated the calibrated values using a model equation recommended by the USEPA for situations where relatively humidity data are available (Barkjohn et al., 2021). Relative humidity has a substantial impact on measurements from optical devices, such as from the PurpleAir, because it affects the particle size distribution. This, in turn, affects the assumptions necessary to convert the particle counts measured by the instrument to the reported mass concentration. The calibration equation we used is the following:

$$\mathrm{PM}_{2.5(\mathrm{Calibrated})} = 0.52 \times \mathrm{PM}_{2.5(\mathrm{Raw})} - 0.085 \times \mathrm{RH} + 5.71,$$

where, $\mathrm{PM}_{2.5(\mathrm{Calibrated})}$ and $\mathrm{PM}_{2.5(\mathrm{Raw})}$ are the calibrated and the directly-measured 24-hr mean $PM_{2.5}$ concentrations ($\mu g/m^3$), respectively. RH is the relative humidity (%), as measured by the PurpleAir device.

For the Clarity data, model development and calibration were performed by the manufacture's service team. The following models were ultimately chosen for calibration of $PM_{2.5}$ and NO_2 data, respectively:

$$\begin{aligned}\mathrm{PM}_{2.5(\mathrm{calibrated})} &= 2.55 - 0.94\,\mathrm{PM}_{1.0(\mathrm{raw\_mass})} + 0.89\,\mathrm{PM}_{10(\mathrm{raw\_mass})} + 9.22\,\mathrm{PM}_{1.0(\mathrm{raw\_num})} \\ &\quad - 8.69\,\mathrm{PM}_{10(\mathrm{raw\_num})} + 0.06\,\mathrm{T} - 0.03\,\mathrm{RH}\end{aligned}$$

where $\mathrm{PM}_{2.5(\mathrm{calibrated})}$ is the calibrated 1-hr average mass concentration ($\mu g/m^3$) of $PM_{2.5}$, $\mathrm{PM}_{1.0(\mathrm{raw\_mass})}$ and $\mathrm{PM}_{10(\mathrm{raw\_mass})}$ are the raw mass concentration of PM_1 and PM_{10} ($\mu g/m^3$), respectively, and $\mathrm{PM}_{1.0(\mathrm{raw\_num})}$ and $\mathrm{PM}_{10(\mathrm{raw\_num})}$ are the raw number concentrations of PM_1 and PM_{10} (particles/cm^3), respectively. T is temperature (°C) and RH is the relative humidity (%).

$$\begin{aligned}\mathrm{NO}_{2(\mathrm{calibrated})} = {} & \mathrm{c}_1\mathrm{NO}_{2(\mathrm{raw})} + \mathrm{c}_2\mathrm{Baseline}_{\mathrm{Temperature}} + \mathrm{c}_3\mathrm{Baseline}_{\mathrm{RH}_\mathrm{n}} + \mathrm{c}_4\mathrm{T}_{\mathrm{Internal}} \\ & + \mathrm{c}_5\mathrm{RH}_{\mathrm{Internal}} + \mathrm{c}_6\end{aligned}$$

Where $\mathrm{NO}_{2(\mathrm{calibrated})}$ and $\mathrm{NO}_{2(\mathrm{raw})}$ are the calibrated and uncalibrated NO_2 approximately 15-minute measurement, respectively, $\mathrm{Baseline}_{\mathrm{Temperature}}$ is a baseline correction for temperature, $\mathrm{Baseline}_{\mathrm{RH}_\mathrm{n}}$ is a baseline correction for relative humidity (which is specific to each measurement n), and $\mathrm{T}_{\mathrm{Internal}}$ and $\mathrm{RH}_{\mathrm{Internal}}$ are the temperature and relative humidity measured inside the device. The model coefficient values (c_1–c_6), baseline corrections, and internal temperature and relatively humidity values used in the calibration are kept confidential by the manufacturer.

Data analysis. To enable comparison of data between monitors, the cleaned data from each monitor was first summarized into average values for distinct averaging times. For the $PM_{2.5}$ performance evaluation, we calculated and compared 24-hr averaged concentrations, as indicated in the USEPA Testing Guidance (Duvall et al., 2021a). This averaging time also corresponds to the short-term averaging time used for the $PM_{2.5}$ NAAQS. For NO_2, no performance guidance is currently available. Hence, we calculated and compared 1-hr average values because this averaging time corresponds to the short-term NAAQS for NO_2. Since no VOC data is available at the Munro site, no evaluation of VOC measurements has yet been performed. For each distinct averaging time, averages were only calculated (and included in subsequent analyses) for those periods with valid values for at least 75% of the time.

For accuracy evaluation, concentrations measured simultaneously by the novel monitor and reference monitor were compared using both graphical and statistical methods. In addition to graphically comparing concentrations using paired-value scatter plots and trend plots, we calculated a few statistics of accuracy consistent with the USEPA Testing Guidance (Duvall et al., 2021a). Specifically, we used the linear regression slope and intercept from the paired data to measure bias, the coefficient of determination (R^2) to measure linearity, and the root mean squared error (RMSE) and normalized RMSE (NMSE) to measure overall error. For $PM_{2.5}$, statistical metrics of performance were compared to USEPA Testing Guidance target value benchmarks.

As with accuracy, precision was evaluated both graphically and statistically using paired scatter plots, side-by-side replicate trend plots, and two statistical measures of precision: the standard deviation (SD) and coefficient of variation (CV) of replicate values (Duvall et al., 2021a).

3.4.2 Useability of each monitor

For monitors to be appropriate for use in a network that is overseen and sustained by community members and organizations, ease of use it important. Hence, during our testing with each monitor, one of our goals was to identify and record usability aspects of each monitor. This includes what type of ancillary equipment and resources are required to set up and install the monitor, how easily the monitor connects with those resources and is configured, data transfer connectivity, and the resilience or frailty of the monitoring instrument itself, for example. Here we detail our experiences with each monitor that contribute to assessment of the monitors useability for community monitoring.

PurpleAir II. The PurpleAir monitor is a small device, approximately the size of a cantaloupe (90 × 90 × 127 mm). It is designed for fixed outdoor operation and requires continuous plug-in power to operate. A version of the device that includes an SD card allows for manual collection of data. However, automated data collection and transfer requires continuous upload access to a Wi-Fi network. We found the power cord connection to the monitor to be somewhat flimsy; it is also unprotected from tampering or accidental disconnection. However, we have not experienced any instances of such disconnection during site operation. The device includes an integrated shelter cap made of a thick sturdy plastic, so that the pollutant sensors have some protection from the weather, however the power adapter is external from this shelter.

Common locations for installation are on the side of a building or on a standing pole. The PurpleAir manufacturer indicates that appropriate installation locations should be relatively shady, preferably north facing, in a protected spot (such as under a roof edge), and away from hyper-local sources of pollution (such as AC unit vents, grills, or car idling) (www.aqmd.gov/aq-spec/special-projects/star-grant). An elevated location at about three meters above ground, with no obstructions within at least three meters on all sides (or at least three sides) is optimal; this ensures unobstructed airflow to the monitor, capture of concentrations relatively representative of the human breathing zone. For better community involvement with the network, we also included a criterion that the installation site be visible to community members from a well-used area of the facility (park, playground, etc.), accessible enough for maintenance by the site host and project team, but not so accessible as to invite tampering. We found identifying appropriate installation locations at community building and park sites to be challenging. Meeting all the location criteria was often not possible. Access to power and strong Wi-Fi were particularly problematic, as described below.

Access to power from appropriate installation locations was limiting for most community locations. Specifically, many older community buildings did not have many power outlets outside. Newer infrastructure (buildings, park lamp poles) often had outlets, but many were locked, presumably to ensure that community members do not draw power. Furthermore, most available outlets were not found to be located close to an appropriate monitor installation location. Hence, installation of a new power receptacle would have been needed for many promising installation locations. This would have substantially increased the cost and logistical coordination requirements of installation. To date, we have limited PurpleAir installations to sites close enough to an available power outlet that an extension cord could be used.

Access to an appropriate Wi-Fi network was also limiting for some community locations. This was particularly true for public parks, for which there was often no Wi-Fi available except in very limited locations, such as near buildings. However, even in locations near to community buildings (community center, library, church, police building), access to Wi-Fi was problematic. Some issues we encountered included networks without enough areal coverage to reach promising installation sites, networks with bandwidth limitations, and networks limiting continuous connection or upload privileges. The SD card version of the PurpleAir device is recommended to ensure the data are backed up in the case of intermittent Wi-Fi failure. The use of a Wi-Fi hotspot using a cellular node was considered and tested, but would increase the ongoing costs of a community monitoring site substantially due to the cellular subscription fee. Additionally, the cellular node also requires power and shelter from the weather in an appropriate protected location near to the installation location.

Ancillary equipment necessary for installation of the PurpleAir monitors typically included an extension cord, mounting hardware and supplies, a tall ladder, standard tools (including an appropriate drill, drill bits, screw drivers, scissors, a tape measure, and a pencil), and a portable computer (for configuration). For installations on brick or masonry buildings, a small wooden board attached to the building with masonry screws (using a masonry drill) was used for mounting the monitor and power adapter; this was done to limit damage to infrastructure from any needed replacement or maintenance. For installations on poles, either plastic zip ties, metal duct/hose clamps, or direct installation with screws can be used for mounting. Finally, it is important that the power cord does not become submerged in water, provide a conduit for water to the outlet, or provide a physical hazard. Hence, plastic cord ties were used to secure the cord to the building, with slopes and circular sections placed in the cord to ensure that any water does not collect or flow to the outlet.

As long as appropriate Wi-Fi was available at the installation site, we found data collection, transfer, download, and public sharing to be easily accomplished via the PurpleAir website. Further, no missing data was found in the recorded data for the testing periods analyzed (see Tables 4 and 6), but Wi-Fi connectivity issues early in some of the community site installations did lead to loss of some initial loss of measurement data.

Overall, enabling access to both power and existing Wi-Fi for continuous use by a monitor often required coordination of multiple civic entities, slowing or limiting the placement of PurpleAirs for many public sites. Hence, we found the PurpleAir monitors likely to be most appropriate for privately-owned facilities, such as homes near a park or community feature (e.g., a trail), or on community buildings that are overseen by a single private organization (e.g., a church).

Clarity Node-S. The Clarity Node-S monitor is slightly larger than the PurpleAir II, at approximately the size of a large shoe box (the dimensions without the antenna, shield, or solar panel are 188 × 128 × 98 mm). It is designed for fixed site outdoor operation and includes a weather-protective housing around the sensors, an integrated cellular node, and a solar panel. The monitor's construction materials appear to be relatively sturdy, but the device (especially the solar panel) must be handled with care to prevent damage prior to installation. Some preassembly of the monitoring device is required to connect the solar panel (using hardware provided); we found this process to be somewhat confusing for novices, requiring practice to achieve the correct orientation of the parts. Hence installation could be frustrating for potential community site hosts unless they are provided with adequate training or support.

Because the Clarity device includes an integrated solar panel for power and a cellular connection for data transfer, it is much more versatile than the PurpleAir monitor. Access to power and Wi-Fi do not limit potential installation locations, though it must be charged for 24 hours prior to first use. Appropriate installation locations are south-facing places (for good solar capture) and are elevated above ground and away from obstructions and hyper-local sources of pollution (as detailed for the PurpleAir II). Installation of the monitor is relatively simple; it can be mounted to a solid surface using screws or to a pole (or similar) using metal duct clamps. Needed ancillary installation equipment included a tall ladder or bucket truck, mounting clamps (and/or screws), standard tools, and a portable computer.

We found configuration of the Clarity device to be relatively straightforward but requires some information on the latitude and longitude of the device, its installation elevation above ground, and the distance to the nearest road. Once the device was configured, collection and transfer of the measurement data to the Clarity website for visualization and data download was automatic. We found no missing data in the record for all periods of testing and operation (see the completeness statistics in Tables 4 and 7). Public access to the $PM_{2.5}$ data via the website can also easily be enabled, although the manufacturer doesn't currently support public access to the NO_2 data.

Notably the Clarity Node-S operates on an annual subscription model. Hence, initial costs are higher, but several useful services are included for the annual fee. Specifically, the Clarity service team provides active support and expertise, including monitor replacement (or maintenance) if needed. They also perform calibration of the device's monitoring data, including development of a calibration model and ongoing provision of calibrated values on the device website. This substantially facilitates community use of the monitor for $PM_{2.5}$ monitoring. For calibration of $PM_{2.5}$ data, local network facilitators must co-locate one Clarity Node-S monitor at a reference monitoring site. After development of the calibration model from this co-located data, the Clarity service team applies this model to the data from all monitors in the local network, allowing facile calibration of all network $PM_{2.5}$ data. However, calibration of the NO_2 data is substantially more cumbersome for the user. To calibrate the NO_2 data, the manufacturer recommends that each monitor be co-located with a local reference monitor for a period of two months. This requirement is difficult to achieve, due both to the limited space available at reference co-location sites, and the time of air quality monitoring staff (such as EPC staff) dedicated to enabling this co-location. Further, co-location for two months of an annual subscription period limits the period that the monitor is collecting community site data, particularly if the monitor must be replaced or recalibrated regularly.

AirBeam 2. The AirBeam 2 device is approximately the size of an outstretched hand (100 × 28 × 130 mm). It is designed for both mobile and fixed-site monitoring and can be powered for short-term mobile operation using its integrated battery and daily charging, or for fixed-site operation by plugging in to an electricity receptacle. We found the AirBeam 2 to be substantially more difficult to use and less reliable than the other monitors tested here. Specifically, set up requires a wired or wireless connection to a data logging device that has access to cellular or Wi-Fi for data transfer. For collection of data at the Munro site field installation, we used a Bluetooth connection to a continuously co-located Android cell phone (a TCL-A3 model) that had the AirCasting app installed. Using this approach, data are collected by the Android cell phone, but transfer of the data to the AirBeam website required routine user intervention every few weeks. Additionally, data collection and transfer routinely failed; although we were not able to fully diagnose the reason for failure, it appears to occur during the ending of the data collection session and synchronization of data with the cellphone. Hence, co-location at the Munro site did not produce enough data for accuracy performance evaluation. For precision evaluation, we used an alternative approach for collecting data. In this case, we used a wired connection of the AirBeam 2 to a Raspberry Pi computer that functioned as a data logger. Although some helpful instructions for this configuration are available (www.habitatmap.org/blog/raspberry-pi-airbeam-data-logger), set up was difficult for the graduate students involved. Additionally, the datalogger sometimes stopped collecting data for extended periods for unknown reasons. During the precision testing, many periods of missing data were found, with only 62 to 74% 1-h averaged data completeness for the three monitors tested (see Table 6). Hence, we are concerned with the long-term stability of this data collection methods. Overall, we the process of set up and use of the AirBeam may be too complicated and unstable for use by many community site hosts.

Cairsens NO_2. The Cairsens NO_2 monitor is a small device that is about the size and shape of a roll of quarters (length: 62 mm, diameter: 32 mm). Although the optional integrated battery and cellular can enable mobile operation, the standard version (which we purchased) is most appropriate for fixed-location operation, as it requires continuous plug-in power and a wired connection for data transfer. Configuration of the device after plugging it into power is automatic. The device’s internal storage can collect and store minute frequency data for about 3 weeks before overwriting the data. To off-load the data from the device for analysis, regular intervention by the user is required using a wired connection to a computer that has the manufacturer's software installed. Using the software, the measurement data can be easily saved to the computer or transmitted elsewhere. No manufacture website is provided for data sharing or visualization. Data loss during the testing period was substantial, with only 52% completeness for the 1-h averaged values (Table 7). The lifetime of the device filter is one year before replacement is needed.

Atmotube Pro. This is a small device, with dimensions of 50 × 22 × 86 mm, that attaches to a backpack (or similar) for mobile monitoring of individual air quality. With limited internal storage, it is designed to be paired via Bluetooth with a co-located cell phone that has the manufacture's app installed for data storage, transfer, and limited visualization. An integrated battery provides power during mobile operation. Approximately weekly charging, using a USB Type-C cable is required. Full charging takes approximately two hours and must be performed prior to first use. Both the Atmotube Pro device and its cell phone app are easy to use. The app provides some visualization of the collected data for interpretation. Data can also be manually downloaded by the user for further analysis. Based on our testing, intermittent connectivity can lead to loss of data. Twice during the Munro field testing period, a problem with the cellphone requiring factory reset led to loss of all stored data. Hence, only 35% of the 24-h averaged $PM_{2.5}$ data was collected during the co-location testing period, suggesting limited reliability of data collection from the standard set up of this monitor.

Flow2. The Flow2 is very similar to the Atmotube Pro (with dimensions of 40 × 35 × 125 mm). It is designed for similar operation, including Bluetooth pairing with a co-located cell phone for data collection, transfer, and visualization via a manufacturer app. Some differences include that the Flow2 requires daily charging using a provided dock (or USB cable), the app shows spatial traces of pollutant levels based on the cell phone's location data, and data are manually exported using the app via a link sent to the user's email address. One issue with this transfer process is that no selection for export time period is available. Hence, each time an export is requested, the entire history of data collected since first use is sent. Additionally, the link expires after 24 hours, so the data should be quickly downloaded via the link. Only 35% of the 24-h averaged $PM_{2.5}$ data and 28% of the 1-h averaged NO_2 data were collected during the field-testing period (Tables 4 and 7), likely due to similar reasons as discussed for the Atmotube Pro monitor.

In conclusion, the Clarity Node-S is the easiest monitor to use for fixed-site community operation of those we tested thus far. This is largely due to its integrated Wi-Fi and solar panel, as well as the services provided as part of the subscription purchasing plan. Additionally, the processes of installation and configuration are quite straight forward. The PurpleAir II is also quite easy to configure and use, but installation can be more time-consuming. Operation also requires access to power and Wi-Fi, which limits possible installation locations. Hence, the PurpleAir II may be more suitable for fixed-site monitoring by private households rather than at public sites. The AirBeam had the most complicated set up process of the monitors tested here that have public data sharing websites. Additionally, data collection failed during our accuracy field testing (using a cell phone with Bluetooth set up). However, it may be worth trying other connection methods in future testing. The standard version of Cairsens NO_2 monitor is easy to set up and reliable, but data collection is somewhat cumbersome and there is no public sharing website. For the personal monitors, the process of set up and data collection is simple.

Manufacturer apps on paired cell phones also enable facile visualizations of the data and information relevant for interpretation by the user. However, completeness of the data record collected indicated limited reliability. Nonetheless, they are very usable monitors that may provide some data for individuals to supplement fixed community site monitoring.

3.4.3 Performance of novel monitors for $PM_{2.5}$ measurement

Five of the monitors tested here can measure ambient particulate matter, including the PurpleAir, AirBeam, Clarity, Atmotube, and Flow2. However, due to data transfer connection issues for the AirBeam, discussed above, performance could only be evaluated for the remaining four monitors. Here, the performance of these monitors for accuracy, accuracy changes over time, and precision are presented and discussed.

Accuracy. Figure 2 presents the trends in time of the 24-hr mean $PM_{2.5}$ concentration measured by each monitor for approximately a 4-month co-location period (4/9/2022 – 7/31/2022) at the Munro EPC site. Values from the reference EPC monitor are shown in black. Figure 3 provides paired scatter plots of each evaluated monitor's values against the regulatory monitor's values for the same period of time. Table 4 provides the statistical metrics of accuracy for each monitor in comparison the USEPA Testing Guidance target values. The PurpleAir data shown in all results is the average of the values measured by sensors A and B from the monitor installed on the same date as the other monitors (PurpleAir 3).

It is evident from Figure 2 that data from most of the novel monitors showed similar trends in time and variation as the reference monitor during the testing period. However, Figures 2 and 3 also indicate that most monitors tended to overpredict the measured highs and underpredict the measured lows. All monitors measured data that has an apparent linear correlation with the reference monitor values (Figure 3), except the Flow2 monitor, for which no relationship is evident in the figure.

The statistical results in Table 4 corroborate the findings from the figures. The calibrated Clarity data had the highest accuracy in comparison with the reference data; it has the lowest RMSE (0.84 $\mu g/m^3$) and highest linearity (R^2 = 0.8). However, calibrated Clarity values are slightly biased low overall, with a linear regression slope (0.63) that does not meet the performance target. Nonetheless, calibration substantially improved the linearity and error for the Clarity data but overcorrected the original slight positive bias in the raw data. Hence, we suggest that the $PM_{2.5}$ data from the Clarity should be calibrated prior to use for interpretation of air quality.

Conversely, calibration of the PurpleAir data did not substantially improve performance. Although the error decreased somewhat, linearity improved negligibly, and bias performance degraded so that the slope was no longer attaining the target value. Overall, the PurpleAir's performance was not strong, with R^2 of 0.39, which is substantially less than that found during AQ-SPEC testing, for which the $PM_{2.5}$ data correlated with the corresponding FEM GRIMM and FEM BAM values with $R^2 > 0.93$ and $R^2 > 0.86$, respectively (www.aqmd.gov/docs/default-source/aq-spec/field-evaluations/purple-air-pa-ii---field-evaluation.pdf?sfvrsn=11). This suggests that a different calibration approach may be needed for the PurpleAir in the local setting.

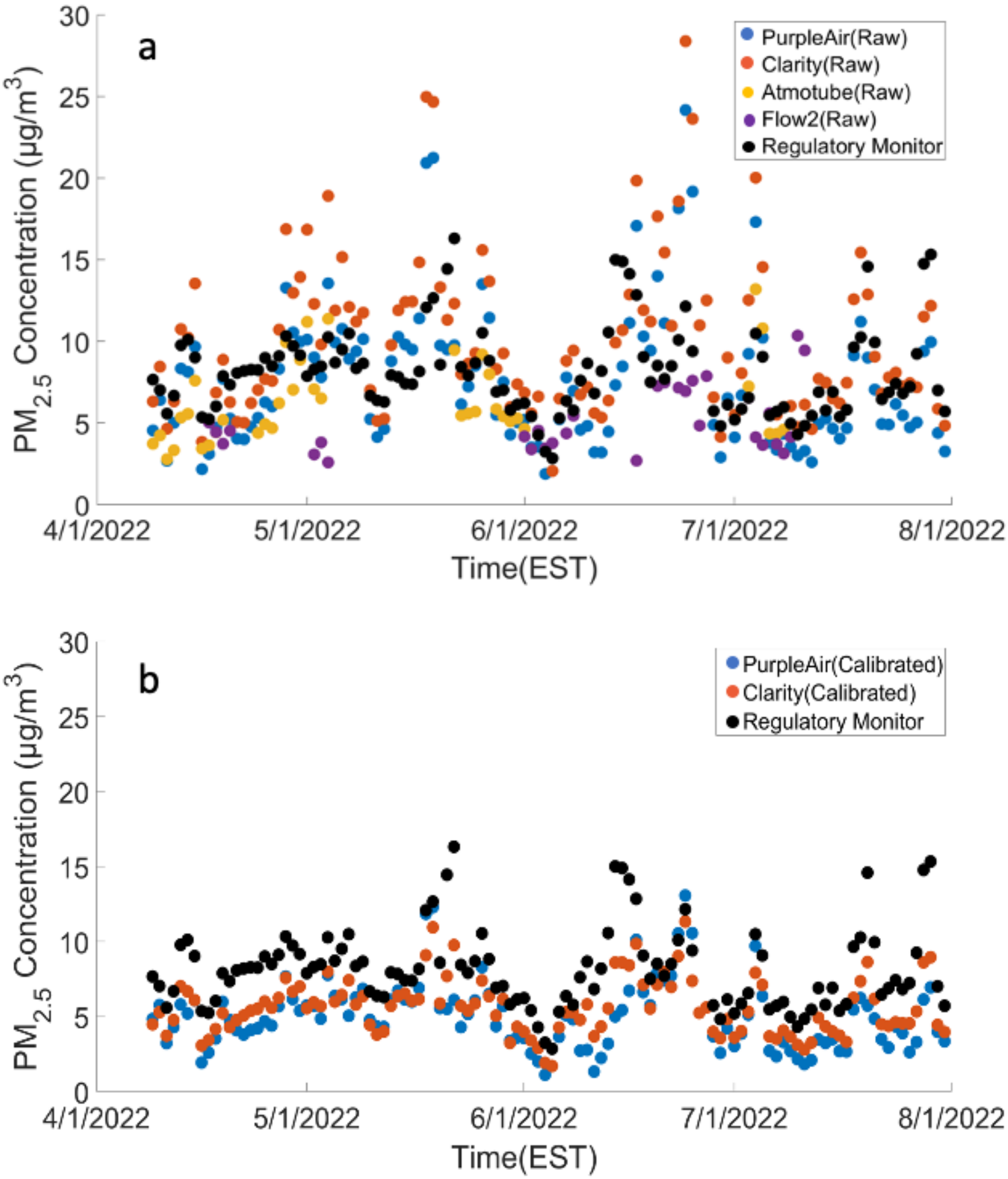


Figure 2. Trends in 24-hr mean $PM_{2.5}$ concentration during co-location of multiple monitors. (a) provides raw data values, while (b) provides calibrated values compared with the reference monitor.

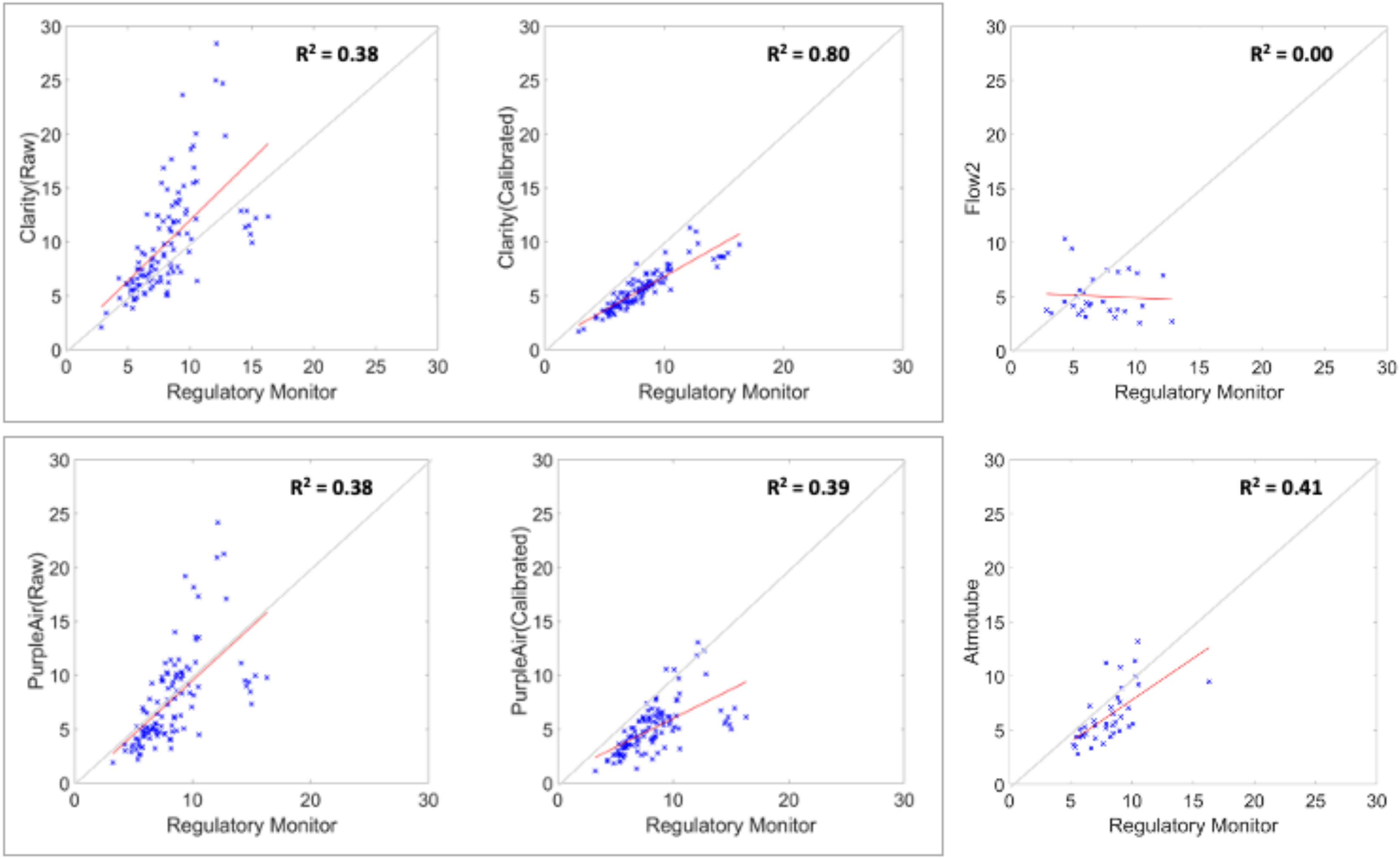


Figure 3. Bivariate scatter plots of co-located 24-hr average $PM_{2.5}$ concentrations ($\mu g/m^3$) measured by each novel monitor compared with the reference monitor data for the period 4/9/2022 –7/31/2022. The red lines provide the regression lines, while the grey diagonal lines provide the 1:1 benchmark.

Table 4. Accuracy performance statistics for 24-hr average $PM_{2.5}$ measurement by novel monitors.

Quantity	Completeness[b] (%)	Linearity	Bias		Error	
		R^2	Intercept ($\mu g/m^3$)	Slope	RMSE ($\mu g/m^3$)	NMSE (%)
Target Value[a]	≥ 75	≥ 0.70	$-5 \leq b \leq 5$	1.0 ± 0.35	≤ 7	≤ 30
Clarity (Raw)	100	0.38	0.75	1.12	3.88	47.6
Clarity (Calibrated)	100	0.80	0.49	0.63	0.84	10.4
PurpleAir (Raw)	100	0.38	-0.54	1.00	3.38	41.5
PurpleAir (Calibrated)	100	0.39	0.63	0.53	1.78	21.8
Atmotube	35	0.41	0.08	0.77	1.96	24.2
Flow2	28	0.00	5.41	-0.05	2.04	28.7

[a]Target values for all but completeness are based on the USEPA Testing Guidance (Duvall et al., 2021a). Values in grey do not meet the target.
[b]Refers to the percent of days during the testing period that have enough valid data to calculate a 24-hr average.

Raw data from the Atmotube Pro shows some promise for interpretability, meeting the USEPA target values for bias and error, but the linearity (and correlation) is somewhat low (R^2 = 0.41) and lower than that found during AQ-SPEC testing. Only the error statistics (RMSE and NMSE) met the target values for the Flow2 raw data; the Flow2 monitor may not provide a reliable measure of $PM_{2.5}$.

Performance over time. Because the performance of the PurpleAir seemed to degrade over time and was not consistent with the AQ-SPEC testing results in California, we performed additional analyses of the monitor's performance over time.

Figures 4 and 5 compare measurements of the PurpleAir during the first two months of testing (12/1/2021–1/31/2022) to those from the last two months of testing (6/1/2022–7/31/2022). Table 5 provides the coefficient of determination (R^2) for a linear regression of the PurpleAir data versus the reference data for progressive two-month periods over the 8 months of testing. It is clear from these figures and table that the performance degraded over time during the testing period. During the first two months of testing, the performance was strong (indicated by an R^2 of 0.82) for both of the PurpleAir devices tested during this period. This is a little less than the EPA AQ-SPEC testing result ($R^2 > 0.92$). However, R^2 progressively decreased over time, to approximately 0.35 during that last two months of tests, for each of the installed monitors. For the calibrated data, R^2 also decreased from 0.86 to 0.40.

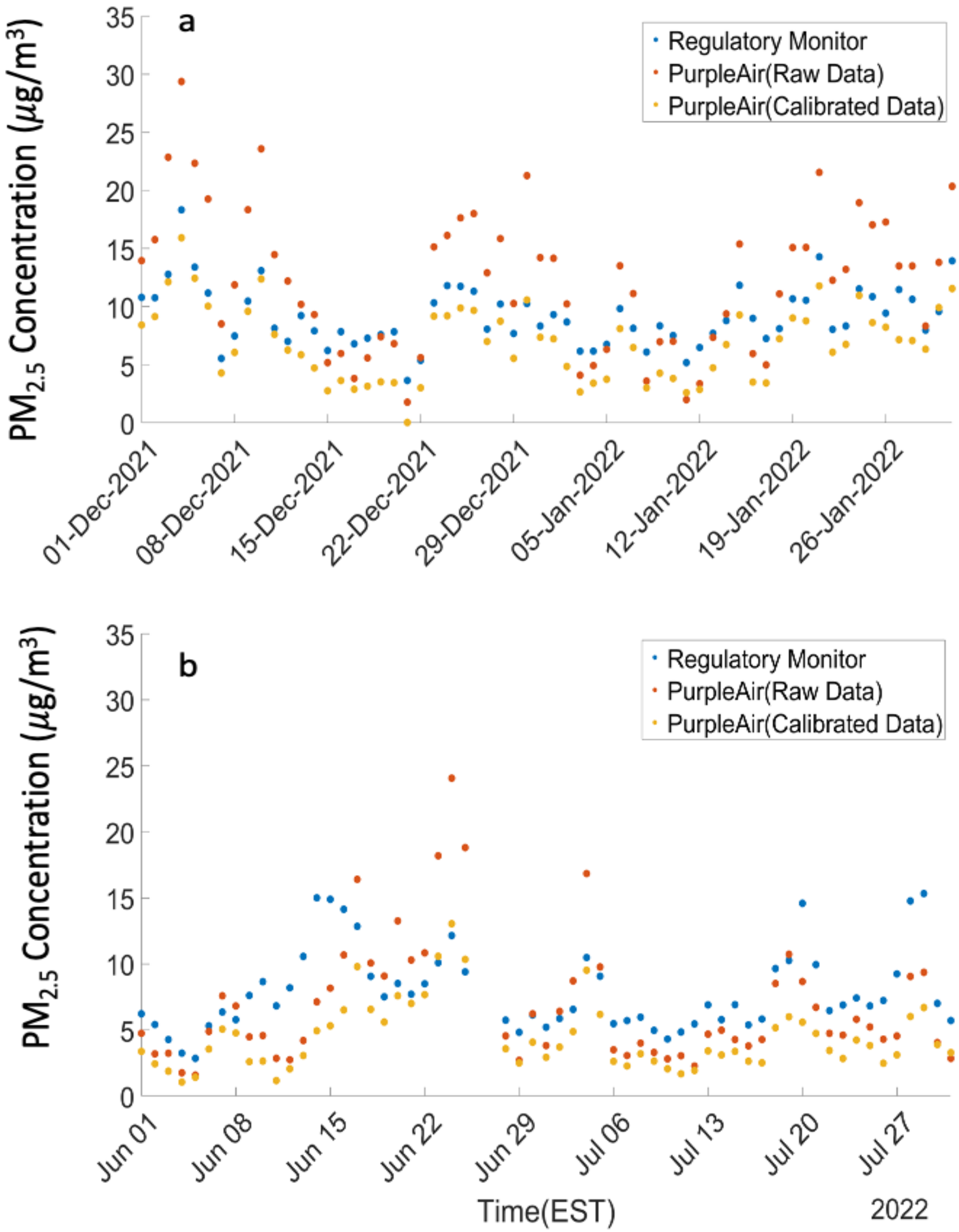


Figure 4. Trends in time in 24-hr average $PM_{2.5}$ concentration level measured by the PurpleAir monitor and the reference monitor during the 1st two months of testing (a) versus the last two months of testing (b).

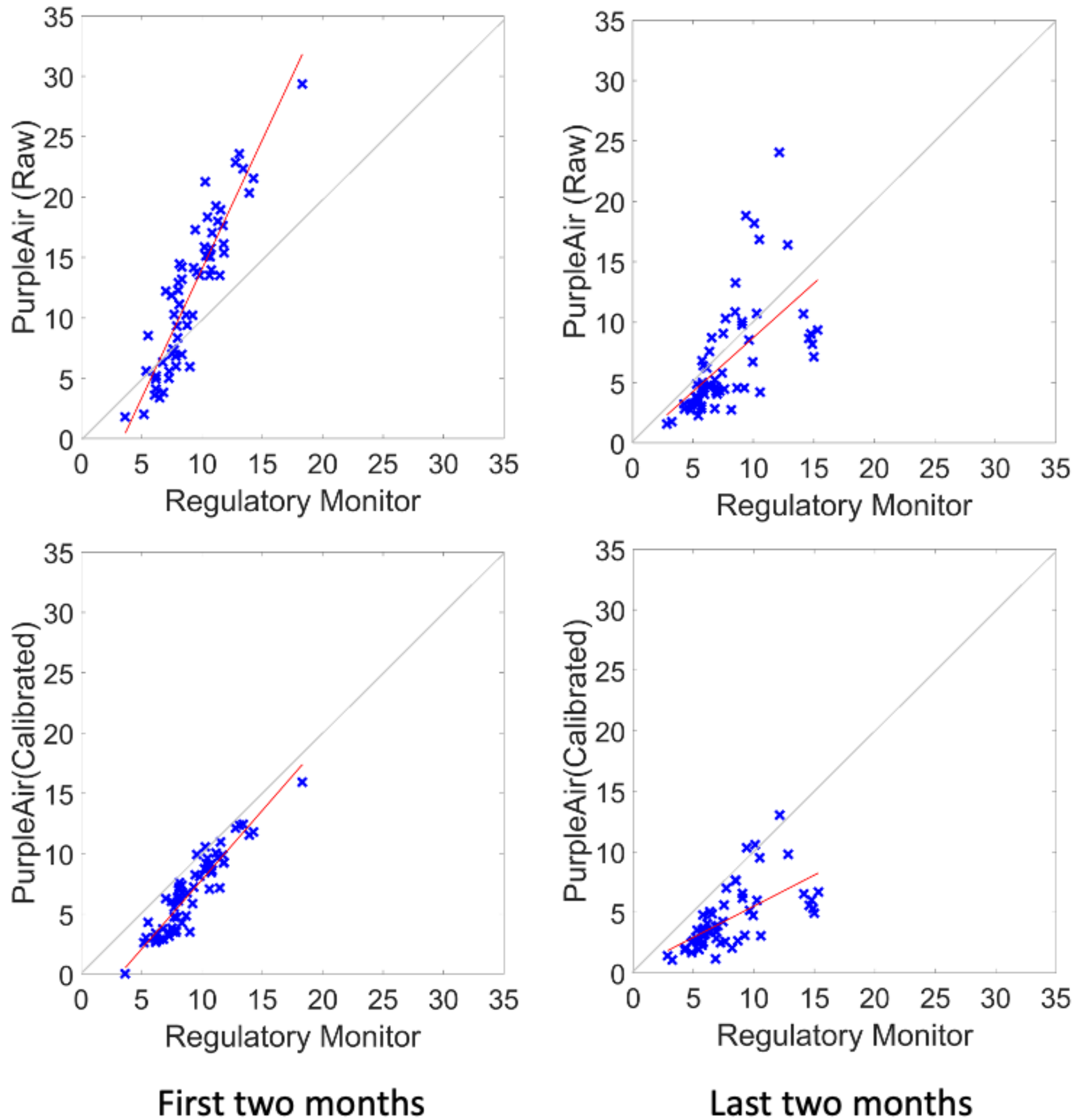


Figure 5. Bivariate scatter plots of co-located 24-hr average $PM_{2.5}$ concentrations (μg/m^3) measured by the PurpleAir 1 monitor compared with the reference monitor for the 1st two months of testing (left column) and last two months of testing (right column). Raw PurpleAir data are shown for the 1st row of graphs, while calibrated data are shown in the 2nd row. The red lines provide the regression lines, while the grey diagonal lines provide the 1:1 benchmark.

Table 5. Linearity performance (R^2) for 24h-average raw $PM_{2.5}$ concentration measured by the PurpleAir II versus the reference data for each two months of testing.

Monitor	12/01/2021 – 01/31/2022	02/01/2022 – 03/31/2022	04/01/2022 – 05/31/2022	06/01/2022 – 07/31/2022
PurpleAir 1 (raw)	0.82	0.68	0.44	0.36
PurpleAir 2 (raw)	0.82	0.70	0.46	0.36
PurpleAir 3 (raw)	-[a]	-[a]	0.46[a]	0.35
PurpleAir 1 (calibrated)	0.86	0.71	0.40	0.40
PurpleAir 2 (calibrated)	0.86	0.72	0.42	0.35
PurpleAir 3 (calibrated)	-[a]	-[a]	0.38[a]	0.39

[a]The third PurpleAir monitor was not installed until 04/08/2022. Hence no results are shown for the first two periods and data for the third period is limited to after installation.

We suspect two reasons for the change in performance. First, the instrument components may become dirty or degrade over time as it is exposed to ambient conditions for a longer period of time. Maintaining cleanliness is a particular problem with optical fine particle monitors (Sousan et al., 2016), such as the PurpleAir. Degradation in performance over time suggests that regular maintenance (cleaning) or replacement of the monitors may be required to maintain the accuracy of the reported community data. However, the PurpleAir manufacturer does not recommend regular cleaning or maintenance. They suggest that a vacuum cleaner or compressed air can be used to clean out debris, if needed (community.purpleair.com/t/sensor-maintenance/1531). The PurpleAir lifetime is approximately two years, but the laser counters may need to be replaced over time (community.purpleair.com/t/purpleair-sensors-functional-overview/150). A second reason for the observed change in performance during the testing period may be changes in meteorological conditions. Ambient temperature and relative humidity are known to impact $PM_{2.5}$ measurements (Robinson, 2020; Wallace et al., 2021), and during the testing period the temperature in Tampa increased from 71 °F (high) / 53 °F (low) in January 2022 to 91 °F (high) / 77 °F (low) in July 2022. (The relative humidity remained variable between 60% to 80%.) Because the performance during the last four months of testing was similar for the monitor installed in April 2022 to that for the monitors installed in December 2021, despite the difference in operating period, we strongly suspect the influence of meteorological conditions on performance, with better performance during the cold winter months than during the warm summer months. If this hypothesis is correct, it suggests that the USEPA recommended calibration model, which only considers changes in relative humidity, may not be appropriate for the local context. Instead, a model that uses temperature as a predictor may be needed. Additionally, these results suggest a need to systematically recalibrate the PurpleAir II data over time.

Precision. Results from precision testing of the PurpleAir II and AirBeam 2 monitors are shown in Figure 6 and Table 6. We note that the PurpleAir and AirBeam are expected to have similar data quality because they use similar sensor models from the same manufacturer (the Plantower PMS-5003 vs Plantower PMS-7003). It is clear from Figure 6 that the measurements from each device are similar and have very similar variations and trends. The standard deviation (SD) in the replicate PurpleAir data over the testing period (4/9/2022–7/31/2022) is within the

USEPA target value (Duvall et al, 2021a), while the coefficient of variation (CV) is slightly higher than its target. However, because only one of these statistics must be within the target, the PurpleAir passes this qualification. For the AirBeam, the SD and CV both meet the individual target values. However, data completeness was worse for the AirBeam than the PurpleAir. Of the 47 days during the collection period, two AirBeam had 35 days of complete enough records of data to calculate 24-hour mean values. One AirBeam had 29 days of complete enough records of data.

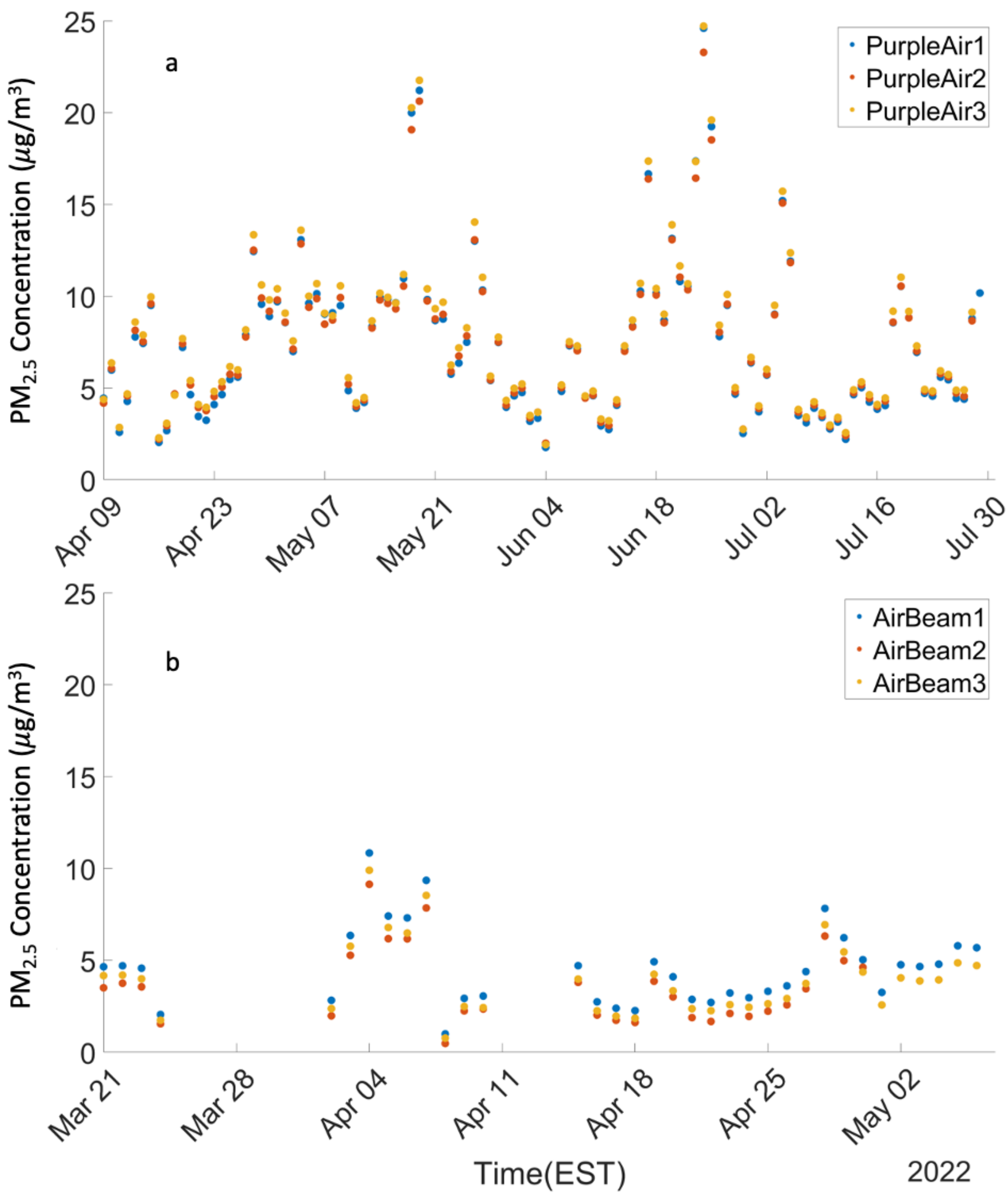


Figure 6. Trends in 24-hr average $PM_{2.5}$ concentration (μg/m^3) for co-located replicate PurpleAir (left subplot) and AirBeam (right) devices.

Table 6. Precision performance statistics for 24-hr average $PM_{2.5}$ measurement by the PurpleAir and AirBeam monitors.

Monitor	Completeness[b] (%)	Standard deviation ($\mu g/m^3$)	Coefficient of variation (%)
Target value[a]	≥ 75	≤ 5	≤ 30
PurpleAir	100	2.1	32
AirBeam	62 - 74	1.1	28

[a]Target values for all but data completeness are based on the USEPA Testing Guidance (Duvall et al., 2021a). Values in grey do not meet the target.
[b]Refers to the percent of days during the testing period that have enough valid data to calculate a 24-hr average.

3.4.4 Performance of novel monitors for NO_2 measurement

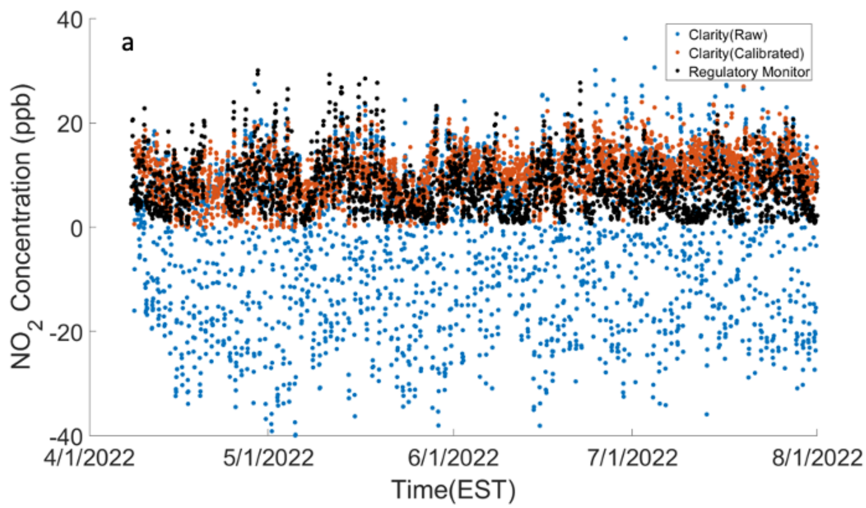
Three monitors tested in this project measure NO_2: the Clarity, Cairsens, and Flow2. Trends in NO_2 hourly concentrations from each monitor compared with the reference monitor are shown in Figure 7, with paired bivariate scatter plots showing performance against the reference monitor presented in Figure 8. Accuracy performance statistics are listed in Table 7. We note that none of the monitors have undergone precision testing for NO_2 measurement at this time.

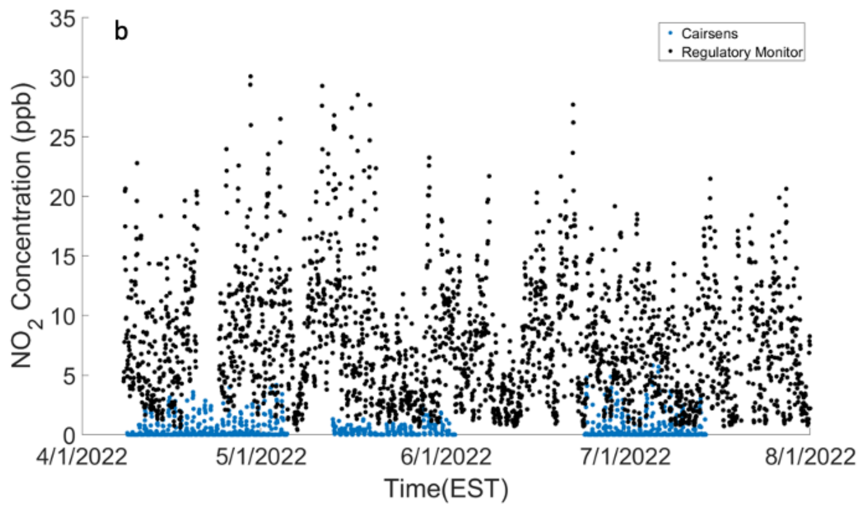
Table 7. Accuracy performance statistics for 1-hr average NO_2 measurement by novel monitors.

Monitor	Completeness (%)	Linearity R^2	Bias Intercept (ppb)	Bias Slope	RMSE (ppb)
Ideal target[a]	100	1	0	1	0
Clarity (Raw)	100	0.17	-8.37	1.16	13.1
Clarity (Calibrated)	100	0.20	7.34	0.39	3.92
Cairsens	52	0.02	0.60	-0.02	0.85
Flow2	35	0.01	11.7	-0.29	17.9

[a]There is no evaluation guidance for realistic performance statistics for NO_2 measurement with novel monitors, hence only the ideal values are listed here.

Figure 7 shows that the values measured by all monitors except the Flow2 (and the uncalibrated Clarity data) were in a similar range between 0 and 30 ppbv. The uncalibrated Clarity data show many unrealistic values below zero, that are largely corrected via calibration. It is not possible to discern whether variations are similar between monitors based on this plot; a more detailed look at each trend against the reference data is needed. Figure 8 shows that the Clarity NO_2 data are positively correlated with the reference data, and the calibration improves the correspondence with the reference data, as also seen in the improvement in intercept value and error (Table 7). However, the slope performance degraded with calibration, leading to underprediction of high values. Further, the R^2 value remains weak at 0.20. The Cairsens and Flow2 measurements show a very small, slightly negative, correlation with the reference monitor, indicating their accuracy is poor. This performance is worse than that found in previous testing with these monitors (www.aqmd.gov/docs/default-source/aq-spec/field-evaluations/plume-labs-flow-2---field-evaluation.pdf?sfvrsn=8; Duvall et al., 2016).





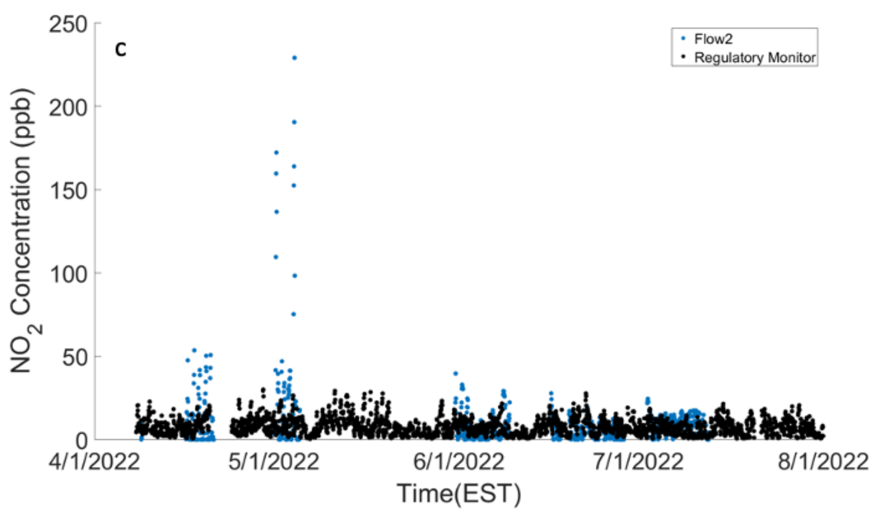


Figure 7. Trends in 1-hr mean NO_2 concentration for each novel monitor compared with the reference monitor. (a) compares data from the Clarity, (b) shows Cairsens data, and (c) shows Flow2 data.

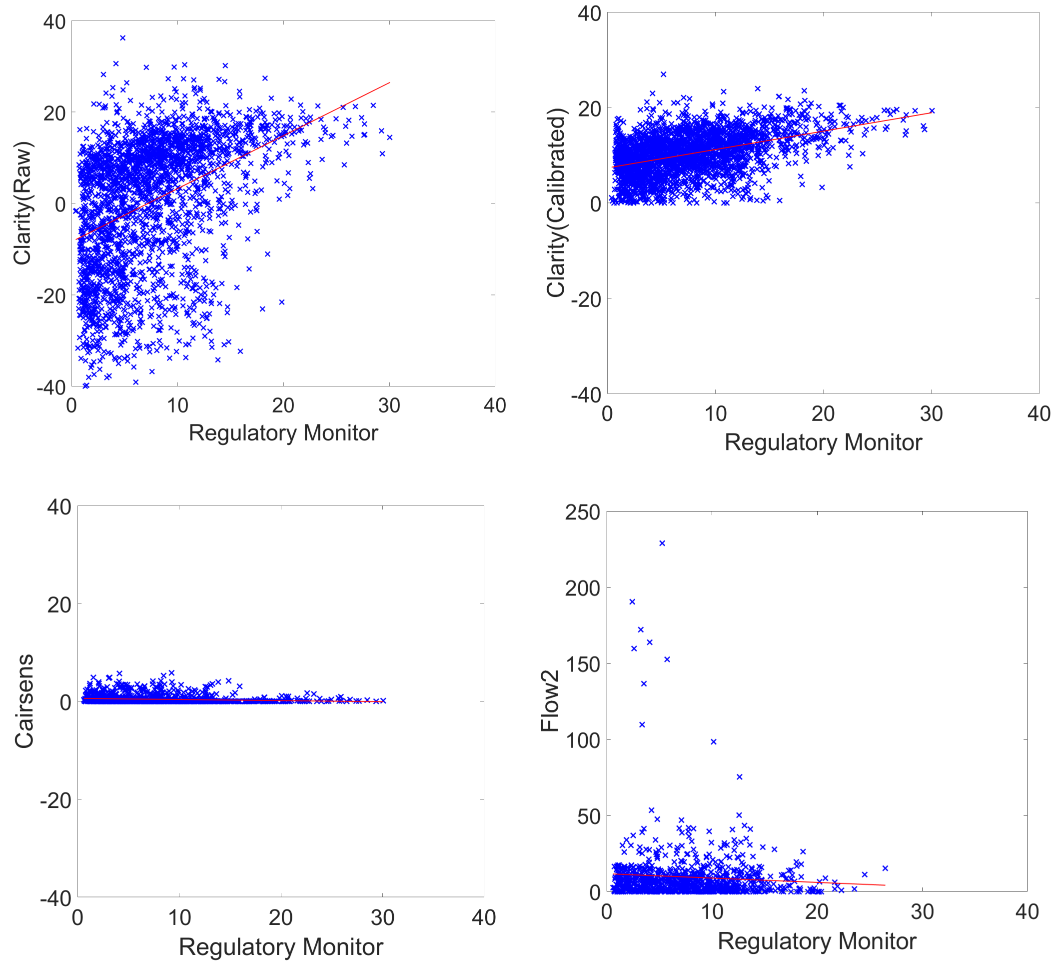


Figure 8. Bivariate scatter plots of co-located 1-hr average NO_2 concentrations (ppb) measured by each novel monitor compared with the reference monitor data for the period 4/9/2022 –7/31/2022.

Overall, the accuracy of the NO_2 monitoring data from the monitors tested here is much worse than that for $PM_{2.5}$. Even for the Clarity data, which were calibrated using temperature and relative humidity by the manufacturer, values remain only weakly correlated with the reference data. Additionally, neither of the other NO_2 monitors tested show any correlation with the reference data. Hence, other monitors or improved calibration methods may be needed. For now, data should be regarded as uncertain; only rough comparative analyses between locations are suggested.

3.4.5 Summary of monitor selection and performance

Based on a review of the available literature and efforts to purchase possible monitors, 7 novel 'low-cost' monitors were identified as promising for evaluation for community air quality monitoring in Hillsborough County. These included two stand-alone particle monitors (PurpleAir II and AirBeam2), two stand-alone NO_2 monitors (the Cairsens and Liveable Cities monitors), one multipollutant fixed-site monitor (the Clarity Node-S), and two wearable personal multipollutant monitors (Atmotube Pro, Flow2). During the project period, six of these monitors (all but the Liveable Cities device) were obtained and tested for usability and performance. Useability testing involved setting up the monitor and data collection to determine installation and use requirements, issues in use and maintenance, and facility of obtaining and using the device's data. Performance testing included graphic and statistical evaluation of completeness, accuracy, and precision of measurement of $PM_{2.5}$ and NO_2 by each tested monitor. Although the evaluation process is not complete, preliminary results from several months of testing suggest a few findings regarding monitors appropriate for community use.

Two fixed monitors, the Clarity and PurpleAir II, emerged as potentially the most appropriate for community monitoring. The Clarity monitor is the most versatile of the fixed-site monitors studied, with an integrated solar panel and cellular connection, substantially facilitating installation and use in community settings for which access to power and Wi-Fi is often limiting. Data from the devices can also be automatically uploaded to a publicly-shared website, facilitating community involvement. The Clarity measures both multiple size cuts of particles (including $PM_{2.5}$) and NO_2 along with temperature and relative humidity. Measurement of multiple pollutants and meteorological parameters may allow for better calibration, and ultimately more accurate measurements. Indeed, the Clarity had the best accuracy performance for $PM_{2.5}$ measurement. The Clarity is purchased through an annual service contract that also includes some calibration, data analysis support, and maintenance service. The one drawback of the Clarity is that an initial two-month colocation with a reference monitor is required for calibration and useability of the NO_2 measurements. This requirement is logistically difficult to achieve and taxing on the regulatory monitoring site operators and the community site installation process. However, we note that even with co-location calibration, performance for NO_2 monitoring of the Clarity was weak (e.g., $R^2 = 0.2$), but better than the other monitors tested. This weak performance for NO_2 indicates a need for further investigation of calibration protocols, including potentially considering additional pollutant predictors in the calibration model.

The PurpleAir II monitor also is promising for some community sites. It has the longest record of use for community monitoring in many locations throughout the US and the World. It is also very inexpensive and has a well-established public data sharing and mapping website to which device data can be automatically uploaded and shared. However, it requires a continuous plug-in power (either through a connection to the electric grid or using a battery and solar panel set-up) and reliable continuous Wi-Fi access allowing data upload. These have proven to be problematic requirements for many community sites, such as community centers, libraries, and parks, limiting the possible installation locations substantially. Hence, the PurpleAir may be most appropriate for home use by individuals willing to host a community monitor. However, this could possibly limit the sense of access and involvement of other community members. The PurpleAir measures multiple size cuts of particles (including $PM_{2.5}$), as well as temperature, relative humidity, and pressure. Although the accuracy of the PurpleAir measurement of $PM_{2.5}$ was initially very good, accuracy performance appears to degrade over time or vary based on meteorological conditions. Further analysis of performance over a longer period is needed to confirm these hypotheses, but current findings suggest that regular maintenance (cleaning), replacement, and re-calibration may be needed to maintain adequate accuracy.

Finally, the wearable monitor, Atmotube, may be appropriate for community-involvement and outreach campaigns involving supplemental personal mobile monitoring to characterize resident air quality and exposure. The Atmotube measures multiple size cuts of particles (including $PM_{2.5}$) and VOCs, along with meteorological parameters. $PM_{2.5}$ measurements from the devices are correlated with the reference measurements, although accuracy performance is mixed overall.

The other devices we have tested thus far have useability and/or performance issues that limit their usefulness for community monitoring. Further work is needed continue performance analysis for a longer period of time, to assess precision of devices not yet tested for precision, to develop and apply appropriate ongoing data quality and calibration approaches, to develop protocols for monitor maintenance by the community, and to test other devices that emerge on the market (such as the Liveable Cities device).

4 Establishment of pilot community monitoring sites

In parallel with selecting and testing monitors for potential community site use, several pilot community monitoring sites were established in collaboration with community organizations and agencies. This included work to identify, prioritize, and select sites for initial installations; install monitors at the pilot sites; and analyze air quality data from these installations.

4.1 Identification of potential community sites

Identification of potential community sites was a collaborative activity of the project team. This included setting criteria for site identification and selection, using mapping applications and a spreadsheet to discuss and rank potential sites, hosting a focus group with community stakeholders to solicit community input on these criteria and potential sites, and site scoping visits to identify and ensure appropriate locations for installing monitors.

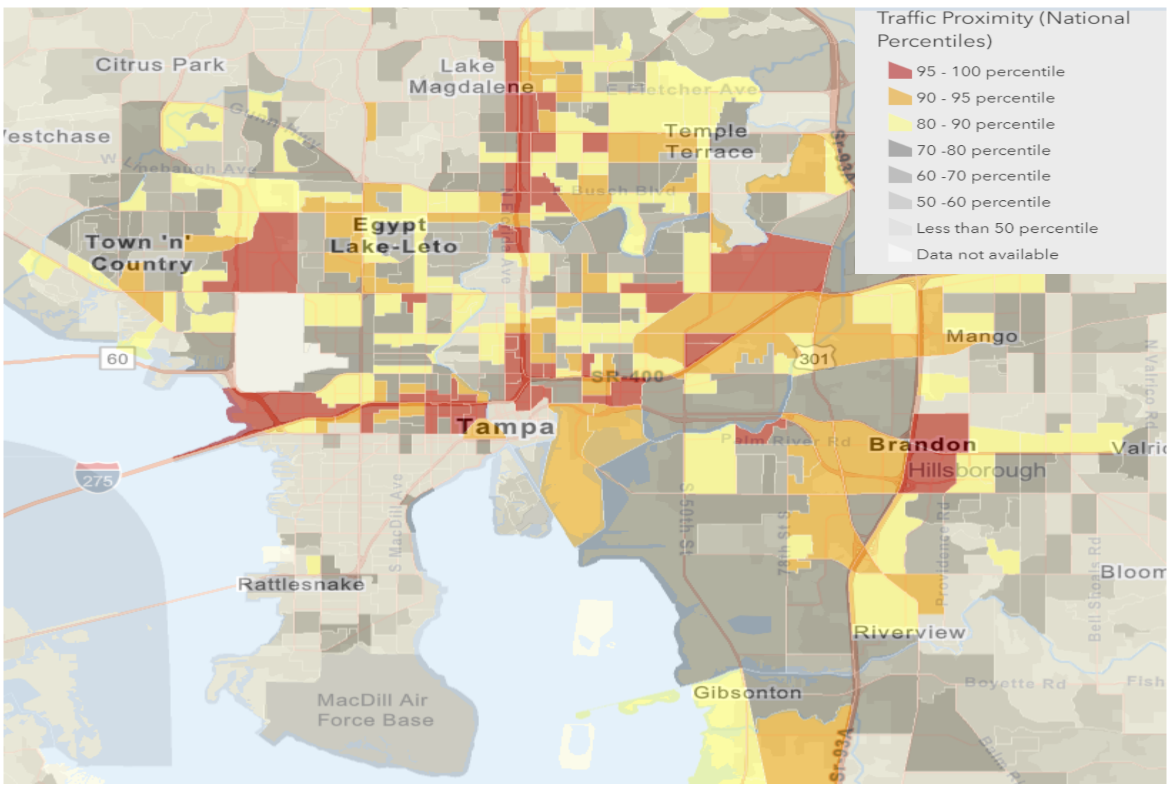


Figure 9. Map indicating proximity to traffic by area for Hillsborough County, Florida. The colors visualize traffic proximity based on the percentile on the overall distribution of proximity in the U.S., with the highest values of proximity indicated by red and the lowest indicated by light grey (see key). Source: EPA EJSCREEN

The main criteria for selecting priority air monitoring sites were a neighborhood's proximity to the I-4/I-75 interchange and other high-traffic roadways (freeways, freeway interchanges, and/or major highways), as well as the density of marginalized populations with historically disproportionate levels of TRAP exposure (people of color and low-income populations). We used EPA's EJScreen tool (see Figure 9 as an example map) to identify areas where measures of traffic proximity intersected with high densities of both low-income populations (including populations eligible for free and reduced lunch assistance at school) and people of color (considering both race and ethnicity). Three main target areas were ultimately identified: Tampa Heights/V.M. Ybor, and Encore/South Nebraska, and Sulphur Springs.

Within the target neighborhoods, further factors were used for the identification of specific community sites most appropriate for hosting air monitors. These factors included openness and accessibility to the public, degree of local civic engagement, installation location within approximately 500 meters of the roadway, and power and Wi-Fi access. Public sites such as government buildings, parks, libraries, and schools were targeted. Churches and other community gathering places were also considered.

Possible monitoring sites were identified and initially prioritized by ranking their degree of traffic exposure and percentage of populations of concern. Sites that were ranked highest satisfied the criteria of being within 0.5 miles of a freeway, major highway, or interchange and fell within the 95th percentile of exposure to diesel emissions and high traffic volumes. Sites with higher proportions of minority populations (African American, Hispanic, and total people of color) and low-income populations (less than $25,000 and less than $15,000) also ranked higher in the prioritization. This initial ranking was discussed with the broader project team to come up with a semi-ranked draft priority list of candidate sites.

To engage community input, a virtual focus group meeting for community members in the target neighborhoods was facilitated and hosted by a TPO and USF team members. During this focus group, attendees were asked to participate in a mapping activity (see Figure 10) during which they placed markers on locations where they would like to have the air monitored. Participants were also engaged in an activity to provide comments on the site selection criteria and site selection process more generally. Including input from the public in identifying community monitoring locations and site selection criteria introduced us to more locations than we'd previously considered and helped us to understand the communities' priorities. From these activities, the potential sites selected as pilot community monitoring sites were Tampa Heights Junior Civic Association, Booker T. Washington Elementary School (adjoining Robert J. Saunders Library), Seminole Elementary School, New Mount Zion Missionary Baptist Church, Robles Park, Perry Harvey Park, and Sulphur Springs Park.

Before the monitors could be installed, the project team needed to confirm the sites met the logistical requirements to install and support the monitor. An initial survey about power, internet, and building access and security was distributed to the potential sites. The project team members from USF, TPO, and EPC visited each potential community site to determine possible monitor installation locations and to build relationships with the potential hosts. This step was significant in determining logistical requirements for monitor installation. For instance, Booker T. Washington Elementary School did not have accessible power or a secure location, so after the site evaluation, the primary location for the monitor was, instead, placed at the adjoining Robert J. Saunders Library. As discussed in section 3.4.2, operation of some monitors requires locations within range of both Wi-Fi and power sources, while also fulfilling the requirement of being visible to the public and having nearby areas for engagement signage to be placed. Site visits allowed the team to take inventory of locations monitors could be placed, to identify ancillary installation or operational equipment needed, and to gain needed input from site managers and supervisors.

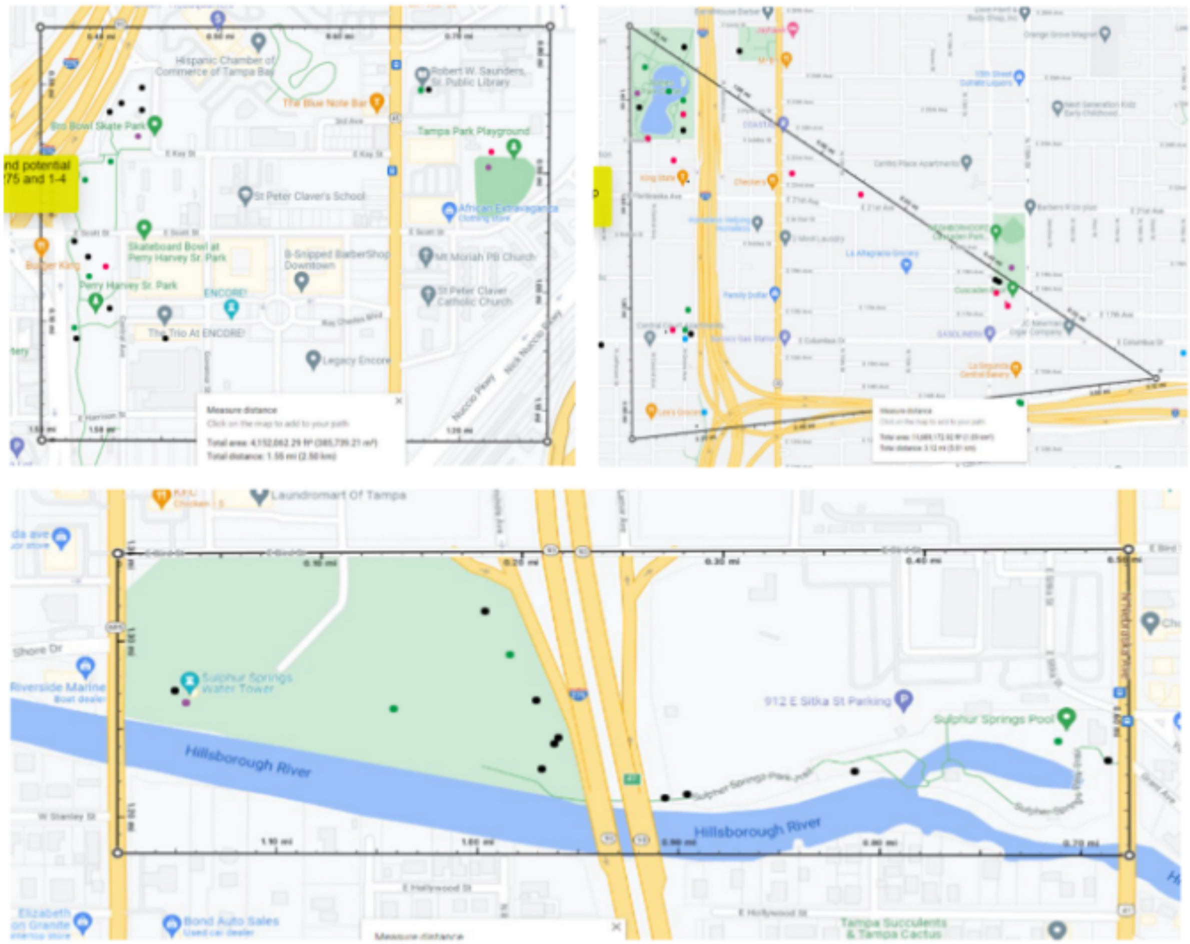


Figure 10. Neighborhood maps annotated during the online focus group meeting. Dots of all colors indicate areas that participants would like to see air monitors installed in Encore/South Nebraska (upper left), Tampa Heights/V.M. Ybor (upper right), and Sulphur Springs (bottom).

4.2 Community site installations

Table 7 lists the sites identified for initial pilot community installations, while Figure 11 provides a map of the location of the sites. Multiple initial field visits were performed to identify locations at each site appropriate for installation and coordinate with site hosts. After approvals from the appropriate directors and jurisdictions for each site, monitors were installed at community sites starting in April 2022. Figure 12 provides pictures of several installations. A PurpleAir II monitor was first installed at the New Mount Zion Baptist Church on April 15, 2022. Then, a PurpleAir was installed at the Tampa Heights Junior Civic Association on May 19, 2022. Due to issues with the Wi-Fi connectively, the initial monitor was replaced on May 22, 2022, for ongoing use. A Clarity monitor was also installed on a nearby pedestrian crossing post near the Tampa Heights Junior Civic Association on July 21, 2022. A PurpleAir monitor and a Clarity were installed at the Seminole Elementary School on May 19, 2022. Finally, a Clarity device was installed at the Robert J. Saunders Sr. Public Library on August 2, 2022. Three additional Clarity installations are planned at three county parks for fall 2022, at the locations shown in Figure 11.

Table 8 List of initial pilot community monitoring sites with monitor installed.

	Site Location	Map Code	Monitor(s)
1	Tampa Heights Junior Civic Association. 2005 N Lamar Ave, Tampa, FL 33602	THJCA	PurpleAir II, Clarity Node-S
2	New Mount Zion Baptist Church 2511 E Columbus Dr, Tampa, FL 33605	NMZ	PurpleAir II
3	Seminole Elementary School 6201 N Central Ave, Tampa, FL 33604	SES	Clarity Node-S
4	Robert W. Saunders, Sr. Public Library 1505 N Nebraska Ave, Tampa, FL 33602	Saunders	Clarity Node-S
5	Robles Park 3305 N Avon Ave #5906, Tampa, FL 33603	na	Clarity Node-S (planned)
6	Perry Harvey Park 1000 E Harrison St, Tampa, FL 33602	na	Clarity Node-S (planned)
7	Sulfur Springs Park 701 E Bird St, Tampa, FL 33604	na	Clarity Node-S (planned)

Note: na is used to indicated ‘Not applicable’.

Following installation, the air quality data reported by each device was monitored by USF team members to ensure that the device and data transfer connection were working correctly. Once this was confirmed, the websites housing data for each device were made publicly accessible. Data from the PurpleAir devices can be visualized and downloaded through the PurpleAir website (map.purpleair.com/). $PM_{2.5}$ measurement data for the Clarity devices can be visualized at the Clarity open map site (openmap.clarity.io/). We note that no measurements for NO_2 are currently publicly available from the Clarity website due to their internal policies. A two-month co-location calibration procedure also will need to be performed prior to sharing of the Clarity NO_2 data. Finally, USF team members created a mockup page for access to these links for the TPO project website (planhillsborough.org/low-cost-air-quality-monitoring-pilot-study/) to enable easy access for all to community site air quality data.

Figure 11. A map of the locations of monitoring sites, including the installed sites and planned sites. The long names for each site location are provided in Table 8.

Figure 12. Installations at community sites. The top row, from left to right, shows installations at the New Mount Zion Baptist Church, Tampa Heights Junior Civic Association, and on a Rectangular Rapid Flashing Beacon post along the Tampa Heights trail. The bottom row shows installations, from left to right, at Seminole Elementary School (the left image is the PurpleAir II, and the center image is the Clarity Node-S), and Robert J. Saunders Sr. Public Library.

4.3 Community air quality

Figure 13 shows the 24-h average $PM_{2.5}$ concentrations trends over time at the four community sites with monitors active long enough for analysis. Trends are shown from April through August 2022. (The first monitor was installed in April.) Raw and calibrated data from both the PurpleAir and Clarity monitors are shown. Only the raw concentrations from the PurpleAir monitor at the Tampa Heights Junior Civic Association is shown because the monitor did not capture ambient relative humidity necessary for the calibration for unknown reasons (see sections 3.4.1 and 3.4.2).

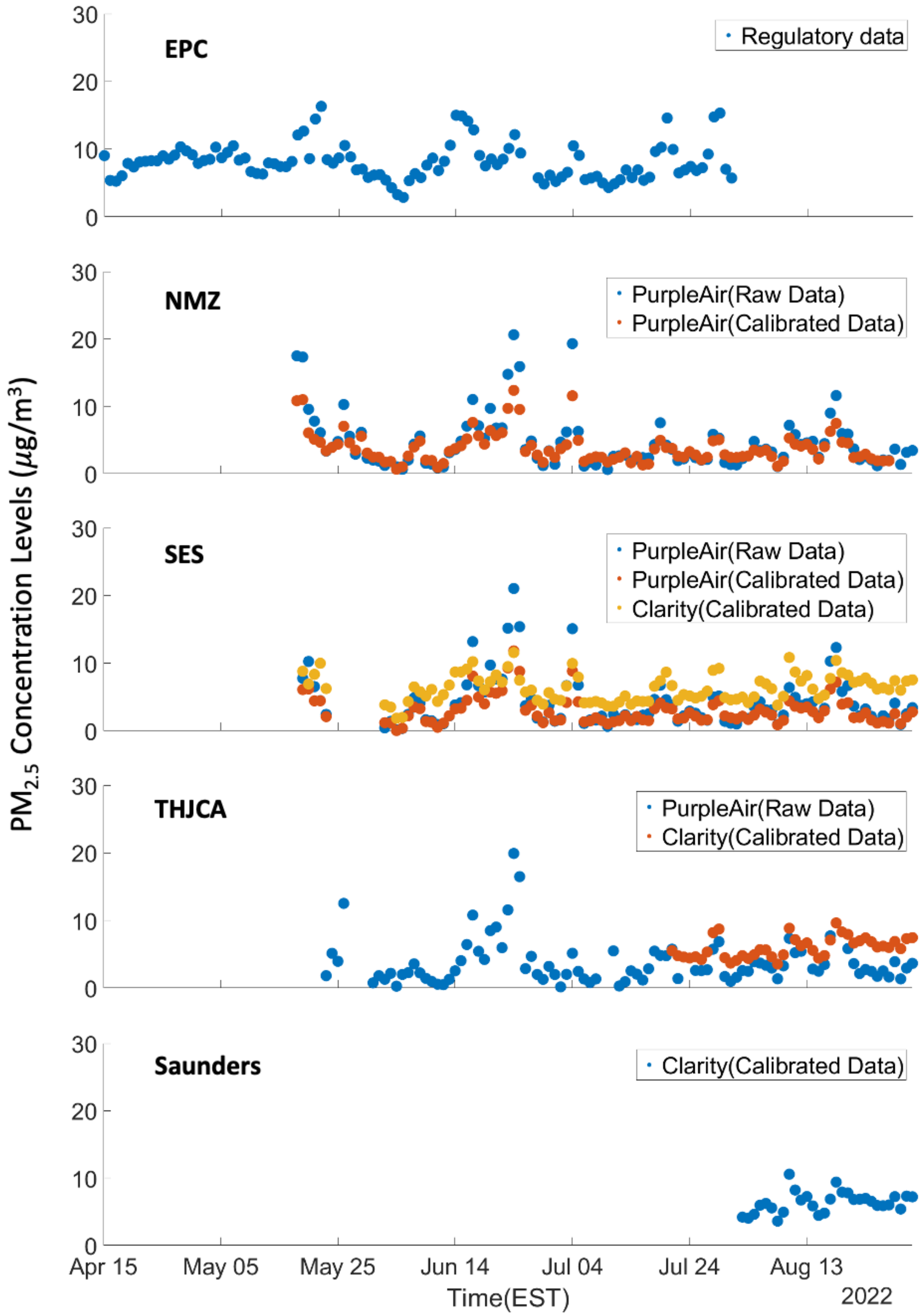


Figure 13. 24-hr average $PM_{2.5}$ concentration at community sites from April 1 to August 31, 2022. Community site names for the codes listed here (NMZ, SES, THJCA, Saunders) are provided in Table 8. The top graph provides the reference data from the EPC regulatory monitor at the Munro site. Note that the community monitors were installed on different dates, leading to different periods of data shown.

To interpret this data, it is helpful to note a few things. First, background levels of $PM_{2.5}$ (i.e., levels in a clean atmosphere) are typically a few (< 5) $\mu g/m^3$. Second, the U.S. National Ambient Air Quality Standard (NAAQS) daily primary standard level, designed to be generally protective of health for short-term exposures, is 35 $\mu g/m^3$, while the annual primary NAAQS level, designed to be protective of health for long term exposures, is 12 $\mu g/m^3$. Third, the World Health Organization (WHO) guideline levels for $PM_{2.5}$ are 15 $\mu g/m^3$ on a daily basis and 5 $\mu g/m^3$ on an annual basis.

We can see from Figure 13 that all 24-hr values measured at the community sites and the EPC regulatory site are below the primary daily NAAQS of 35 $\mu g/m^3$, indicating air quality is acceptable, i.e., there are no regulatory concerns for the periods of time studied. Most data values are also below the more stringent WHO 24-hr guideline level of 15 $\mu g/m^3$. A few days with average levels above 15 $\mu g/m^3$ can be seen in the raw data for all sites, while none of the calibrated daily values from community sites exceed this level. Data from at least a full year are needed to compare measured concentrations directly to the annual standard. This is because averaging of data from days with high and low concentrations can result in an annual mean that meets (falls below) the annual standard level, even when several daily concentrations exceed that level. However, it is notable that we see several days at most sites (including the regulatory site) when measured daily values exceeded the annual NAAQS level of 12 $\mu g/m^3$. Additionally, there is evidence in the literature that detrimental health effects can occur at values below the NAAQS for some populations, such as those unusually sensitive to air pollution (Hesterberg et al., 2009). In Figure 13, we see many days that the average concentration exceeds 5 $\mu g/m^3$, with some spikes that reach about 20 $\mu g/m^3$. This suggests the need for continued monitoring to ensure the protection of health for all people.

One analysis that can help to understand how concentrations vary over time is to look at the average concentration for each hour of the day or day of the week. Figure 14 shows the diurnal cycle of $PM_{2.5}$ levels based on raw data from the PurpleAir device at each of the community sites for the period 4/18/2022 – 8/22/2022 for THJCA and NMZ, and 5/18/2022 – 8/22/2022 for SES. The blue line in each graph indicates the average value for each hour throughout the day, while a cumulative distribution box plot of the measured values for the sample of days considered is also shown. (Each box plot provides the interquartile range (IQR) of values, the red line segment shows the median, whiskers indicate the most extreme value within 1.5 times the IQR, and red dots shows data values outside the IQR.) The highest values appear to typically occur at about 7 AM, which may be due to morning rush hour traffic coupled with low atmospheric mixing heights typical of early mornings. We also see peaks in the late afternoon at the Tampa Heights Junior Civic Association, which may be due to evening rush hour. The maximum values reported for each hour at the community sites were larger than EPC's maximum value, with the largest peaks reported at Seminole Elementary School and New Mount Zion Church. Comparison of values and trends at the community sites to those measured at the regulatory site (EPC) provides insight into how representative the regulatory data may be for air quality in community neighborhoods. Although more analysis is needed in future work, we see hourly values at the near-road regulatory site that are in a similar range, and often somewhat elevated, compared with those at most community sites. However, the trend shown at the regulatory site does not capture the degree of diurnal variation seen at some of the community sites. To understand the weekly cycle, Figure 15 shows the average $PM_{2.5}$ level measured at each site for each day of the week during the same periods of time. The highest concentrations during the week were generally measured on Thursdays, while levels over the weekend were lower on average compared to weekdays.

Further work will be needed to investigate what conditions, including times of day, week, season, and local source conditions, such as traffic density, correspond to peak measured levels, as well as whether these highs occur more frequently at some sites than others, and whether the EPC data represent the community data. Additionally, community 'background' sites that measure pollutant concentrations within the community, but further from traffic sources, and installation of local wind measurement instruments (anemometers), would be helpful to discern the potential impact of traffic sources and roadways on the community's air quality.

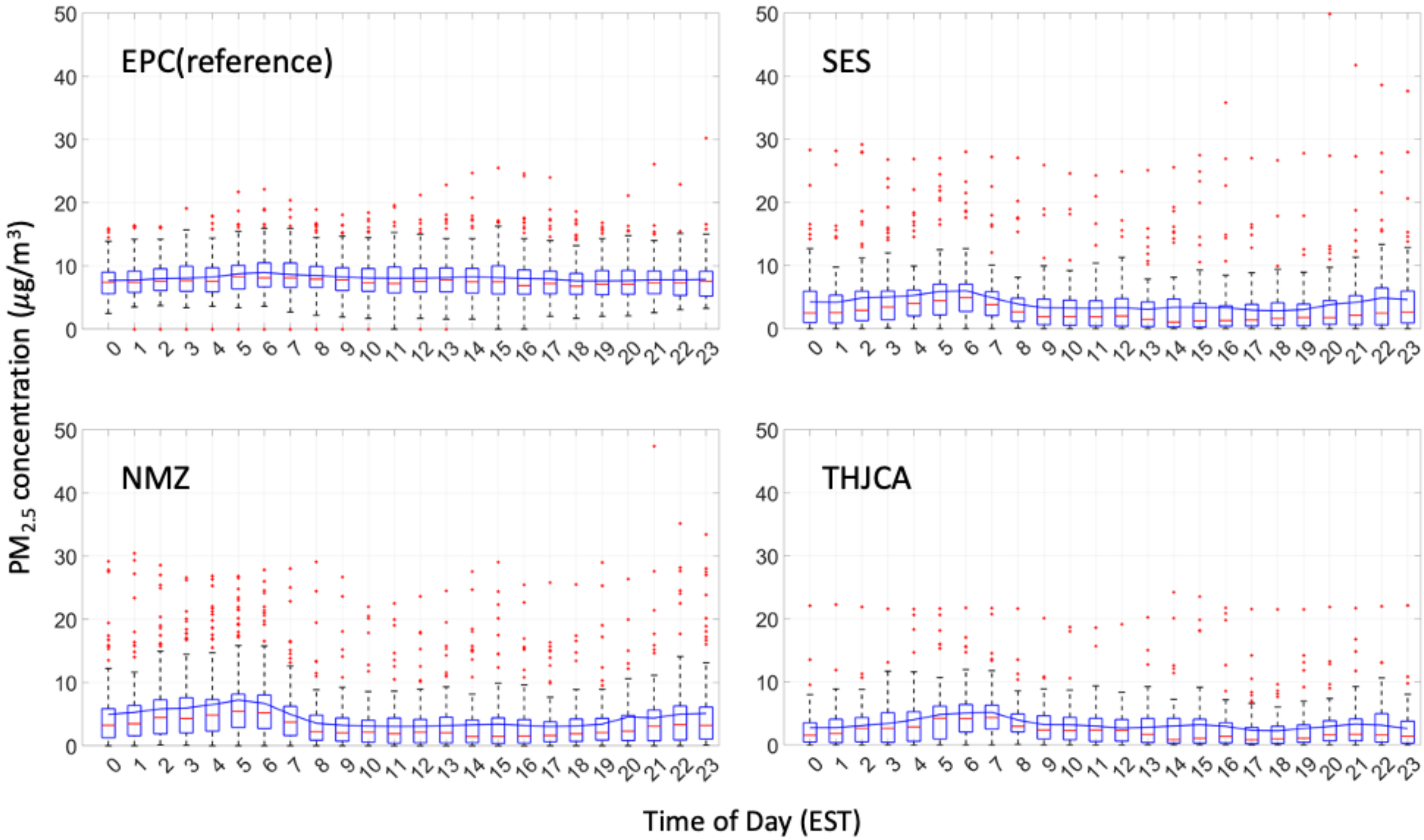


Figure 14. Diurnal cycle for raw $PM_{2.5}$ levels from the PurpleAir device at each of the community sites for the periods 4/18/2022 – 8/22/2022 at THJCA and NMZ and 5/18/2022 – 8/22/2022 at SES. Data labeled EPC is from the regulatory reference monitor at the Munro EPC site. An extreme value of 137 $\mu g/m^3$, observed on July 4 for the 20:00 hourly average at the NMZ site, is outside the scale shown.

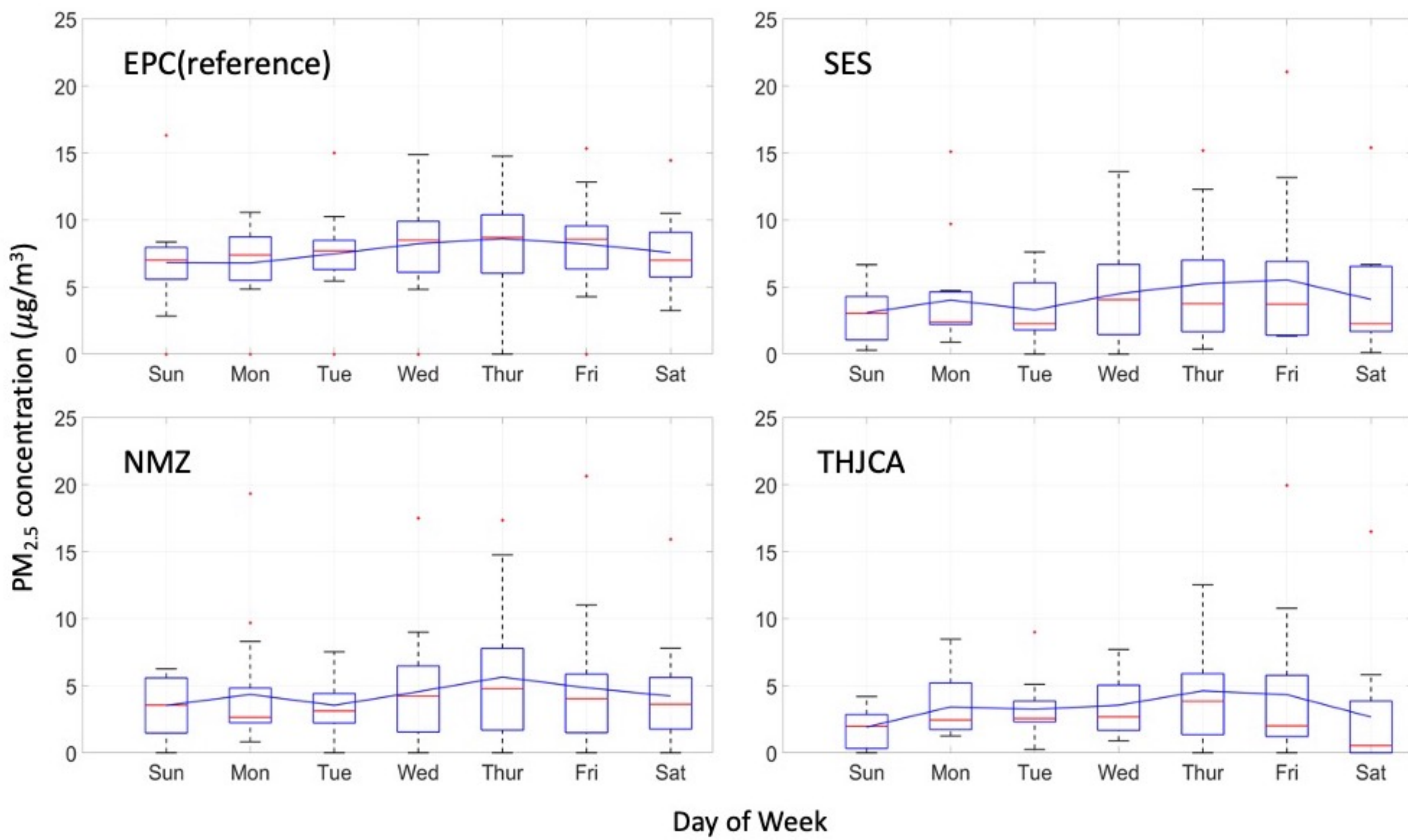


Figure 15. Weekly cycle of raw $PM_{2.5}$ level measured at each site for each day of the week during the same period of time as Figure 14. Data labeled EPC is from the regulatory reference monitor at the Munro EPC site.

5 Community engagement and education

In addition to monitor selection, testing, and collaboration with the community to select and install monitors at community sites, community education and participation activities were performed during the project period. These activities are discussed below.

A primary mechanism for engagement of the general public in this community air quality monitoring project was the installation of posters at each community monitoring site. To this end, we developed the poster shown in Figure 16 to enable passers-by to learn more, access the air pollution data, and explore the TPO project website. After the installation of a monitor at each site, a poster was affixed near to the installed monitor at each site. Example poster installations are shown in Figure 17.

Figure 16. Community engagement poster installed at each community monitoring site.

Figure 17. Examples installation of the community engagement poster at the New Mount Zion Baptist Church, Seminole Elementary School, and the Robert W. Saunders Public Library/Booker T. Washington Elementary School sites (from left to right).

Additionally, the USF team were involved in two student education events as a part of the TPO Future Leaders in Planning (FLiP) and FLiP junior programs. For these events the USF team created and presented materials and interacted with the program participants in order to engage and inform students about air pollution and its measurement as well as impacts of community design, transportation, and personal activities on air pollution emissions and exposures. Figure 18 shows an image of USF's presentation for the FLiP program on 5/31/2022. This was approximately an hour-long activity involving a slide presentation, students seeing and touching example monitors, and a question-and-answer session. Students ranging in age from middle school to high school were very engaged and interactive throughout the event. Several students indicated the need to consider transportation related air pollution in urban planning by the end of the event. For the FLiP junior program, on 7/13/2022, USF team members and TPO staff led groups of primarily elementary and middle school students on a walking tour from the Tampa Heights Junior Civic Association monitoring site to the nearby community garden. Each group carried a wearable low-cost monitoring device to visualize changes in air quality through a connected cell phone app. Students answered a set of prepared questions. Many expressed excitement by asking their own questions about the reasons the data values changed and their meaning.

Figure 18. Images of the FLiP (left one) and FLiP Junior (right two) program events.

Presentations were also made to the project collaborative team and to community participants to educate the community about air pollution and monitoring. Examples involving community members are discussed here. For the Plan Hillsborough Informational Brown Bag Quarterly lunch and learn session on 8/17/2022, TPO, USF, EPC, and Tampa Heights Junior Civic Association gave an overview of the project; educational information about air monitoring, TRAP, and health effects; and their respective roles and involvement. USF talked about the motivations for involvement in the project, USF's role and tasks, and led participants through use of the online PurpleAir map and data access tool to help them better understand the community air quality data and its interpretation. Participants included community members, city stakeholders, and people who are interested in the project. For the project update meeting on 09/08/2022, we reported on outcomes of the project. This included the current and planned methods of monitor identification and selection, sensing data and community analysis, identified monitors, monitor installation at the community sites, data and project information outreach, a map walk through, and educational material development. Participants included the community site hosts, city stakeholders, and other organizations and community members. In addition, members of the project team attended the EPC annual Clean Air Fair and EcoFest to display and discuss the project with attendees. USF students on the project team also presented jointly authored posters on the work at a few conferences for scholars and practitioners, including the 2002 AEESP Research and Education Conference (at Washington University in St. Louis), the 2022 Air Quality Workshop (at the University of Florida), USF Health Research Day, and the USF Undergraduate Research Conference. Finally, the project was highlighted in Newsletter publications by Hillsborough Soil and Water Conservation District's Hillsborough 100 Conservation Challenge (issuu.com/timescreative/docs/hillsborough _100_2022/25), a Tampa Bay Times publication, and the Plan Hillsborough's Newsletter, Connections to Tomorrow.

6 Summary and conclusions

In this project, USF worked with the TPO, EPC, and community members to select tools, perform testing, and engage the community toward improved air quality through neighborhood-scale monitoring of transportation related air pollution in vulnerable neighborhoods near I-275 and I-4 in Hillsborough County, Florida. This work involved the establishment of a university-government-community collaborative relationship that facilitated the project goals, with each organization contributing their expertise.

Through the project, several potential community monitoring devices were identified via literature review and tested for useability and performance. This testing resulted in the selection of two monitors, the Clarity Node-S and PurpleAir II, that showed the most promise for fixed community site installation, and one monitor, the Atmotube Pro, that may be useful for supplemental mobile personal monitoring and outreach. Based on this testing, the Clarity and/or PurpleAir monitors were installed at four community pilot sites, and the Atmotube was used for K-12 community engagement activity.

Findings of this work indicate that truly low-cost and easy to use monitors that provide public data on transportation related air pollution remain limited. Of the monitors identified, both the Clarity Node-S and PurpleAir II are relatively easy to use, though the PurpleAir II's useability is limited by the need for plug-in power and continuous high-quality Wi-Fi. (Locations without these available would require ancillary equipment including a solar panel, battery, and cellular node for automated collection and transfer of data; these would substantially increase the complexity and cost of site installation and maintenance.) Long-term data quality also remains a concern, but measurements of $PM_{2.5}$ from both of these monitors showed reasonable quality in initial testing analyses. However, appropriate calibration approaches, community host-site maintenance protocols, and replacement plans will need to be developed and tested because the data quality appears to decrease with time and/or change with weather conditions. Measurements of NO_2 showed weak performance and may only be suited for comparative analysis rather than for interpretation as absolute pollutant level. Calibration procedures for NO_2 levels (from the Clarity monitor) are cumbersome and performance improvement from the calibration applied here was limited. Hence, alternative models for calibration that consider co-pollutant predictors that can affect sensor response, such as ozone, are likely needed. Finally, although monitors that can measure traffic-related toxic organic pollutants were not our primary focus during this initial project period, we did find the selection of possible devices very limited and expensive. However, some low-cost monitors do measure VOCs, but little performance data are available; more work is needed in this area.

Levels measured at the pilot community sites for the period of time available after installation indicate that the air quality was adequate for the pollutants measured at all locations and does not raise regulatory concerns. However, a longer period of data and additional analyses are needed to confirm this finding, to determine whether the EPC regulatory data represent community exposures, to determine whether levels are a concern for the health of sensitive individuals, and to understand short-term spikes seen at some sites. Placement of monitors at additional 'background' community sites and installation of meteorological equipment could also help to determine the influence of traffic and roadway sources on community air quality.

One of the goals of this project was to engage members of marginalized communities in the process of community air quality monitoring in order to build trust and involvement in public decision-making affecting air quality. This engagement was achieved by reaching out to community organizations and involving their members in the selection of monitoring sites, coordination of installations, and discussion of progress and data. Posters accompanying each site and the project website were also used to raise awareness and engage involvement of the general public. Finally, dedicated interaction activities with K-12 students were used to educate and inspire community youth on air pollution, urban design, and health disparities.

Overall, this pilot project has shown that a community monitoring network using low-cost monitors may be a promising approach for characterizing traffic-related air pollution at high resolution in marginalized neighborhoods of Hillsborough County, while engaging community members in transportation decision-making processes. Next steps will involve continued monitor testing, data calibration and analysis, community education, expansion of the network, and development of protocols and processes to involve community members in the installation and maintenance of the network, as well as interpretation of network data.

Acknowledgements

This work would not have been possible without the participation of all collaborative team members at the TPO, EPC, community site hosts, and other community participants. We thank all project partners for providing their expertise and assistance throughout the project. We also thank the City of Tampa and Hillsborough County staff for enabling selection, siting, and installation of monitors at public facilities. Drs. Dinah Martinez-Tyson and Jason Beckstead at the USF College of Public Health also provided valuable insights and expertise on the project work.

In addition to the funding for this work through this research agreement, funding for the USF team's work described here was also provided by the USF College of Public Health (COPH). This included support through an internal grant titled "Pilot study and methods development on the use of low-cost sensors and citizen science to reduce air pollution exposure inequality and empower vulnerable communities", which funded time for undergraduate and masters level student workers and additional project equipment and supplies. Supplemental support for doctoral student and faculty time was provided by the COPH. Additional funds for low-cost monitoring equipment were provided by the Federal Highway Administration through a State Transportation Innovation Council (STIC) grant.

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