Development of Aerosol Black Carbon Detector Network in West Oakland

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ABSTRACT

Black carbon (BC) is a small light-absorbing aerosol that accelerates climate change and negatively impacts exposed communities. BC concentrations are typically measured using optical techniques implemented in commercially available aethalometers. Independent sensor development is on the rise because of increasing availability of inexpensive hardware. The goal of my study is to investigate concentration gradients in West Oakland measured by a cost-minimizing design of Aerosol Black Carbon Detectors (ABCDs) built at Lawrence Berkeley National Lab (LBNL). West Oakland is a local hotspot because it is surrounded by three major freeways and the Port of Oakland. The cost-minimizing BC sensor cells include an Arduino, a pump, a flow meter, and a sensor. Applying a new calibration curve to determine the optimum voltage to achieve a certain flow rate decreased the percent error from 6% to 1%. Analyzing the hourly averages by day of the week, Sunday had the most variation, with a large peak at 8-10 am, while other days had smaller peaks at similar times. The weekday peaks can be attributed to diesel truck emissions, while the weekend peaks appear to be anomalies due to external factors such as fires or weather conditions. ABCDs exposed to air closer to I-880 had higher BC concentrations because most diesel trucks travel on I-880.

KEYWORDS

Aethalometer, Arduino, black carbon, ABCD, concentration gradient

INTRODUCTION

Black carbon (BC) is a small light-absorbing aerosol that accelerates climate change and negatively impacts exposed communities. BC emitted into the air in the form of particulate matter ($PM_{2.5}$) and comes from incomplete combustion of fossil fuels, biofuel, and biomass. It is the solid form of mostly pure carbon that absorbs solar radiation at all wavelengths (Flanner et al. 2007, EPA 2012). Diesel PM is the primary source of BC emissions, accounting for 52% of all U.S. PM emissions (EPA 2012). By mass, BC is the most effective form of $PM_{2.5}$ at absorbing solar energy and can absorb up to a million times more solar energy than carbon dioxide, the most plentiful greenhouse gas (EPA 2012). Temperature rise can be partially attributed to BC because it is the most effective energy absorber. Aside from climate change, BC also impacts human health. It has a relatively short life-time of days to weeks in the atmosphere, which creates an uneven distribution and results in exposed communities that are more likely to suffer from BC's health impacts (EPA 2012). Because BC is less than 2.5μm in diameter, it can go deep into human lung tissue and increases the risk of death (Krzyżanowski et al. 2005, HEI 2010, Li et al. 2016). Decreasing BC emissions will generate considerable co-benefits for both human health and climate mitigation. It is essential to understand BC exposure because it affects both climate change and health.

BC concentrations are typically measured using optical techniques implemented in commercially available aethalometers. These meters work by pulling in air samples from the surrounding environment and running these samples through a filter that collects BC while the attenuation of a light emitting diode (LED) is calculated using the measured transmittance (Hansen et al. 1984). The attenuation calculation correlates with the amount of BC that has accumulated on the filters. Commercially available aethalometers use these techniques. These aethalometers are often used because they have been widely-tested (Arnott et al. 2005, Drinovec et al. 2015). However, the cost of these instruments, which average around $25,000, prevents studies of spatial variation in BC concentrations. West Oakland currently has only two aethalometers monitoring BC concentrations (Preble et al. 2015). These two aethalometers are located far from the local port, where most emissions are thought to occur. The BC concentrations measured at the two aethalometer sites did not decrease despite decreases in BC emissions at the port (Preble et al. 2015). This indicates a need for highly spatially resolved measurements of BC concentrations to understand local-scale concentration gradients, exposure levels, and sources. Developing inexpensive sensors is essential because the measurements needed for spatially resolved BC concentrations require sensors at many locations.

Independent sensor development is on the rise as a result of increasing availability of inexpensive hardware. Arduino provides a platform for electronic development that is ideal for making inexpensive environmental sensors. Arduino-based environmental sensors are advantageous because once developed, they are exponentially cheaper to produce than purchasing commercially available devices. However, they can be time-consuming, expensive to develop, and require verification of their precision. Although development of inexpensive devices has its drawbacks, these cost effective sensors can provide monitoring to developing countries that could not otherwise afford it, or can create spatial resolution that can only be achieved with many devices. Prototypes of Arduino-based multiple environmental monitors including hydrocarbon, carbon monoxide, and nitrogen oxide sensors have been developed and tested in India (Abraham and Pandian 2013). These sensors cost only $200 to build and can be kept in a car to provide mobile monitoring for developing countries. The number of research studies that employ Arduinos or similar hardware systems have increased in recent years (Berntzen et al. 2016, Kunjumon et al. 2016). A prototype of independently developed sensor network used to analyze highly spatially resolved BC concentrations throughout cities is needed. Increased monitoring would provide knowledge to policy makers about spatial BC distribution, allowing the appropriate measures to be taken to mitigate climate change and reduce human health impacts.

The goal of my study is to investigate the accuracy of a cost-minimizing design of Aerosol Black Carbon Detectors (ABCDs) built at Lawrence Berkeley National Lab (LBNL) and their effectiveness compared to commercially available aethalometers. My research is part of a broader program that aims to develop a network of BC sensors, deploy them throughout West Oakland, and monitor BC exposure for 100 days. First, I tested the pumps used to pull air into the sensors and created a calibration curved that was used to determine an accurate flow rate. Then I calculated ABCD concentrations throughout each day of the week to determine BC concentrations throughout West Oakland.

METHODS

Cost-Minimizing BC sensors

The cost-minimizing BC sensor cells include an Arduino, a pump, a flow meter, and a sensor. The sensor unit was developed by Julien Caubel, Troy Cados, and Tom Kirchstetter and works based on aethalometry. In basic aethalometry, air is pulled into the sensor through the inlet, through a filter on which BC collects and then pulled through a second reference filter. Light from a light-emitted diode (LED) is shone through a filter and a photodiode detects the voltage corresponding to the attenuation of light. As more BC accumulates on the filter, more light is attenuated and the photodiode records a smaller voltage. These sensors work by pulling air in through the pump, which then goes through the flow meter, into the sensor, then through the outlet of the sensor cell. An Arduino Nano mounted on a circuit board is connected to the sensor unit, the pump and the flow meter. The Arduino is programmed to set a pulse-width modulation (PWM) switching frequency, which corresponds to the voltage at which the pump operates and, in turn, sets the flow rate. The accuracy of ABCDs were tested against the permanent aethalometers in the field to ensure the ABCDs provide quality data prior to deployment and continued to compare measurements from the two instruments on an ongoing basis to ensure quality data throughout the trial period.

Pump Testing in Cost-Minimizing BC Sensor

To determine the optimal voltages to apply to the pumps (Schwarzer, Essen, Germany) to achieve accurate flow rates, I collected voltages and corresponding flow rates of five different pumps and created calibration curves. Determining the calibration curve will ensure that the optimal voltage is applied to the pumps to maintain the desired flow rate. An accurate flow rate is essential because the flow rate is used in converting attenuation measurements to BC concentrations. To collect voltages and corresponding flow rates from each pump, I connected the pumps to an external bubble flow meter. The pumps, which are controlled by an Arduino, are connected to a computer where I entered in different PWM switching frequencies ranging between zero and 255. I collected the voltage data beginning at a PWM of 10 and measured in increments of 10. The voltage that data collection starts at differs between pumps because PWM switching frequencies correspond to different voltages, depending on the condition of that particular pump. At each PWM, ambient air is pulled into the system and a 10-bit voltage number and flow rate, measured in cubic centimeters per minute (ccm), are recorded from the bubble flow meter and Arduino program. In this way, voltage acts as the controlled variable and measures how hard the pump works.

To determine the accuracy of the pumps, I analyzed the calibration curve. I created calibration curves with the 10-bit voltage as the independent variable and the voltage as the dependent variable. I made these calibration curves with four Schwarzer pumps and then created an average calibration curve. From the average calibration curve, I found the maximum percent error at each flow rate and each voltage. This error represents the percent that the resulting flow rate could vary from the flow rate expected from applying a certain voltage.

Field Test

Study Site

The field test site is West Oakland because it has historically been a local hot spot for BC concentrations (Bay Area Air Quality Management District 2014). West Oakland is surrounded by three major freeways and the Port of Oakland, all of which emit BC. Because the main source of BC is diesel combustion, the Port of Oakland is thought of as a major BC emitter. After implementation of the Drayage Truck Regulations, BC emissions were cut dramatically, however, BC concentrations at the current West Oakland monitoring site failed to change (Bay Area Air Quality Management District 2014, Preble et al. 2015). To understand the spatial and temporal distribution of BC and its sources, we deployed 100 sensors throughout West Oakland: in people's homes, at BAAQMD's West Oakland Monitoring Site, and in the Port of Oakland.

Temporal Variation

To determine how BC concentrations vary temporally, the 100 sensors in West Oakland collected data over a 3 week time period from March 21st to April 16th, 2017. The data reported from the sensors includes a time stamp, flow rate, attenuation, reference voltage, signal voltage, BC concentration, relative humidity, temperature and battery voltage. The data is collected within the sensor cell and stored on a mini SD card, but is also be sent to a database by SMS. The sensor data is collected every two seconds. To examine the concentrations over the entire test period, I took hourly averaged BC concentrations from each sensor at Laney college and plotted the BC concentration of each sensor. I used only the sensors at one location because there was not enough data to analyze the sensor network. To analyze the average daily concentrations, I took the daily average of the BC concentrations. Next, I separated the data according to which day of the week it was recorded and found the hourly averaged BC concentrations. I then made box plots of this data. After, I separated the data according to day of the week and hour of the day and plotted the results, with time of the day on one axis and BC concentration on the other. This graph contained a plot for each day of the week.

Spatial Variation

To determine how BC concentrations vary spatially, I plotted hourly averaged data and I made a map of concentration gradients. I plotted the hourly averaged data from a sensor that was located close to I-880 and one that was located in the middle of West Oakland, far from any freeway. Next, I made a map of the deployed sensor network on April 12^{th}, 2017 to look at the general trends associated with distance from freeways.

RESULTS

Pump Testing

The optimal pump voltage to achieve accurate flow rates is determined by the average of four pump calibration curves. The flow rate increases approximately quadratically with the voltage after both calibrations (Figure 1). The percent error decreases with increasing voltage, meaning the set voltage will result in more accurate flow rates at higher flow rates. We run the sensors at 110 ccm, so my results focus on the flow rate. Using an outdated calibration curve, the pumps resulted in a 6% error rate when set at 110 ccm. After applying the calibration curve, percent error dropped to about 1%. The improved accuracy of the set voltage to flow rate increased the accuracy of BC concentration calculations because the calculations are dependent on flow rate.

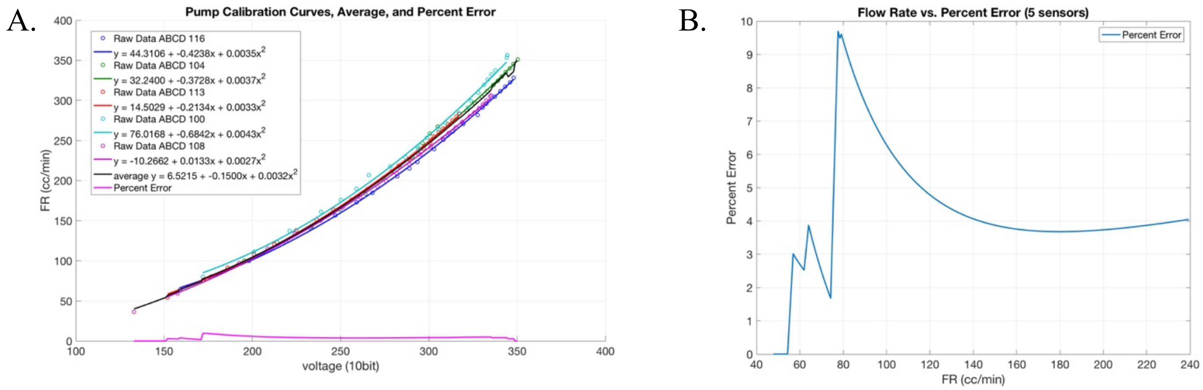

Figure 1. Pump Calibration Curve and Percent Error. A) Calibration curve from made from five complete ABCDs. B) Percent error of the five ABCDs used to make the calibration curves.

Field Test

Temporal Variation

The hourly averaged BC concentrations taken from sensors at Laney college indicate diurnal patterns to BC concentrations (Figure 2). Moderate peaks of about 1 to 1.5 μg/m^3 occur daily. These peaks tend to occur from 7 am to 9 am each day. Larger peaks of 4 to 10 μg/m^3 appear less frequently. BC concentrations reach a background level of 0.5 μg/m^3 at around 12pm each day.

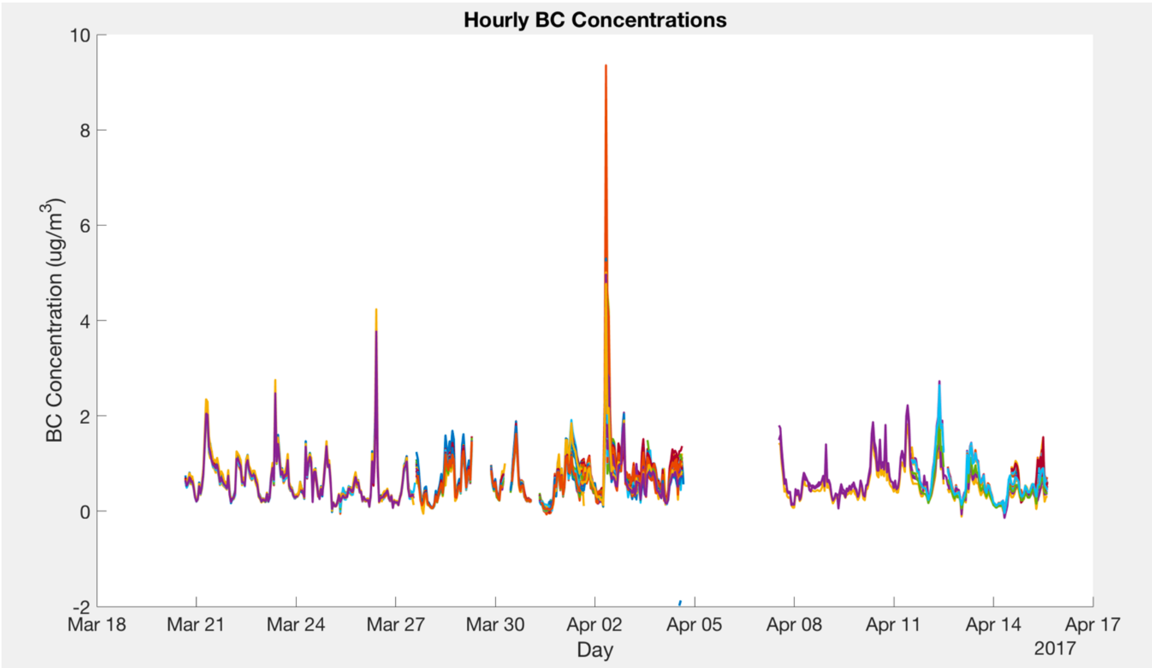

Figure 2. Hourly averaged BC concentrations. Hourly averaged concentrations taken from sensors located at Laney College in Oakland.

Average BC concentrations vary over the three week test period (Figure 2). At the beginning of the test period, average daily concentrations of each ABCD were relatively similar. The variation within each day increased as the test period continued. Throughout the test period, the average amount of BC varied depending on the day. There are cycles of high and low BC concentrations throughout the test period.

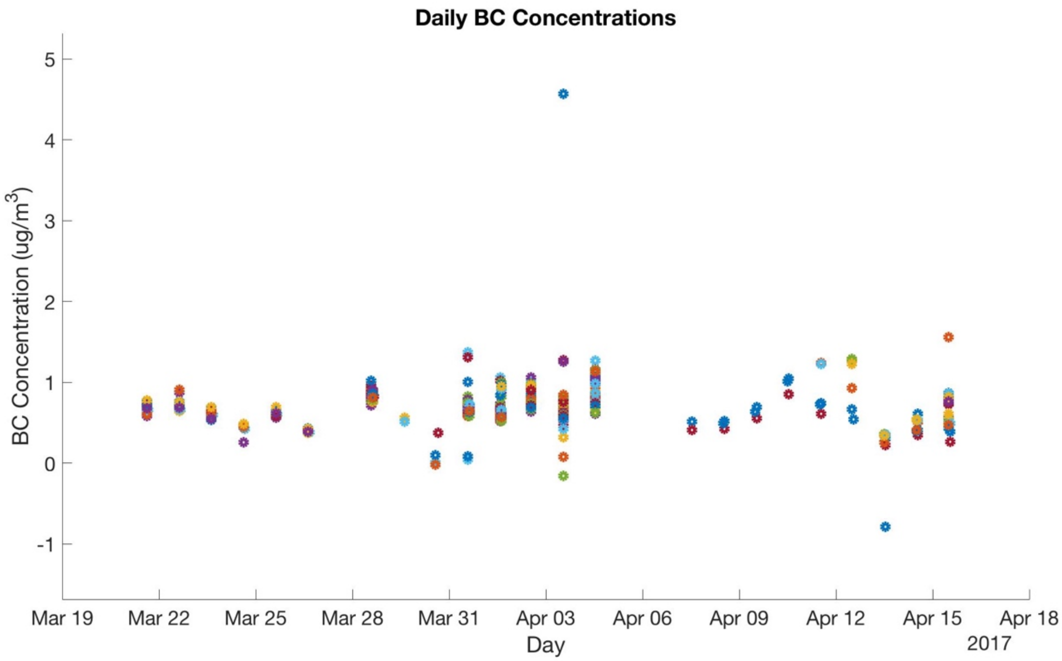

Figure 3. Daily Averaged BC concentrations. Daily averaged BC concentrations from ABCDs at Laney College. Each dot marks the daily average of a different ABCD.

To determine if the average concentrations correlate to the day of the week, I separated the data by which day of the week it was collected. The median is relatively stable for Sunday, Monday, and Tuesday, increases on Wednesday and decreases through Friday (Figure 4). The median for Saturday increases again. The variation in concentrations for Sunday are much higher than the variation for the other days of the week.

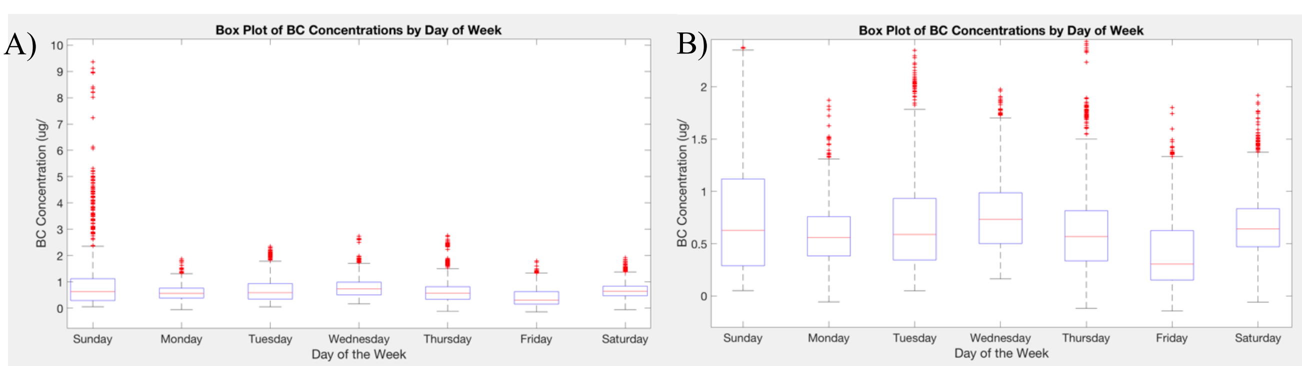

Figure 4. Box plot of BC concentrations. A) Box plot of BC concentrations by day of week, showing all outliers. B) Box plot of BC concentrations by day of week, zoomed in to show median values.

The hourly averaged BC concentrations by day of week indicate that there is an increase in concentration in the morning beginning at 6 am (Figure 5). There is a large peak on Sundays at 8 am and 10 am, with an average concentration of 4 μg/m^3. A third peak occurs on Sundays at 9 pm. There is a peak on Thursdays at 9 am, with an average of 2 μg/m^3. The concentrations generally decrease as the day goes on and stabilize around the background concentration of 0.5 μg/m^3. The concentrations on Friday tend to be lower than the other days of the week.

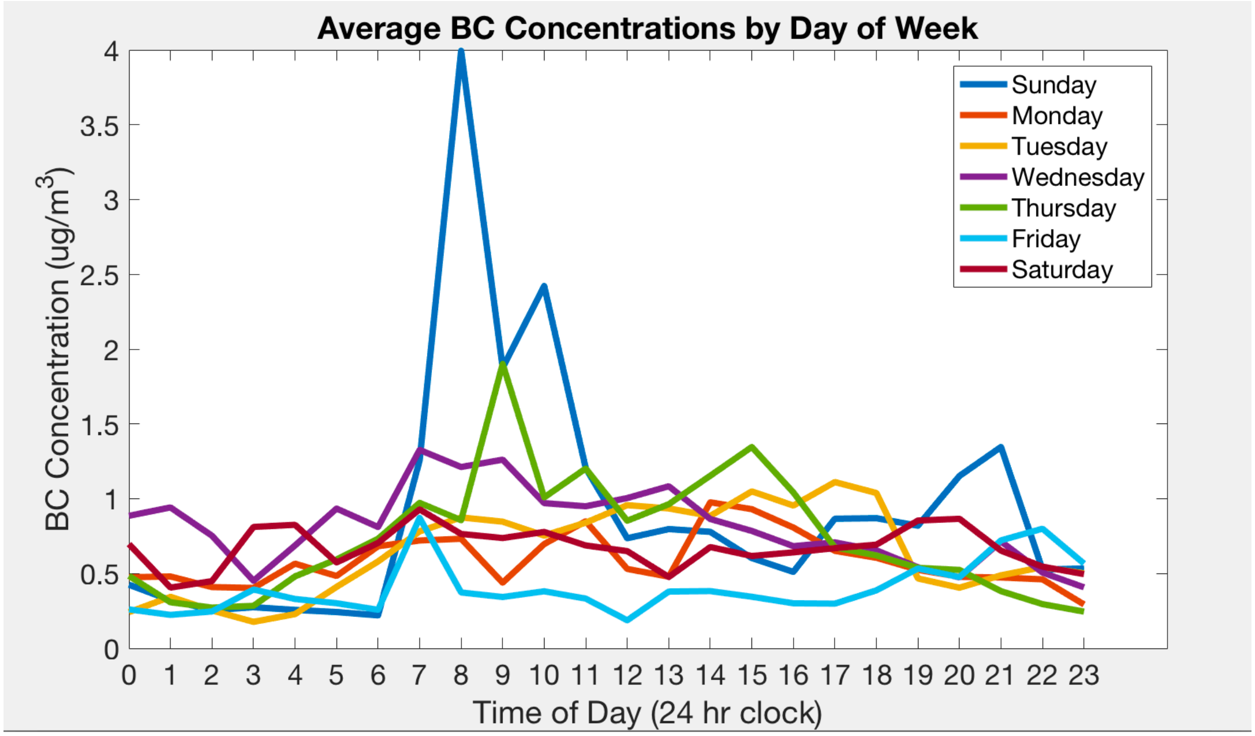

Figure 5. Average BC Concentrations by Day of Week.

Spatial Variation

To evaluate spatial variation, I analyzed the concentrations of ABCD 71 located at 1789 Goss Street in Oakland and ABCD 87 located at 2842 Magnolia Street from April 11th to April 12th (Figure 6). ABCD 71's location is directly next to I-880, while ABCD 81 is located closer to the center of West Oakland. Concentrations near the freeway are up to double the concentrations away from the I-880. ABCD 71 and 87 both follow the same general trend of lower concentrations on the night of April 11th and a peak around 8 am the following morning and then a decrease in concentration. The map of ABCDs deployed on April 12th at 11am indicates that there are higher concentrations near the intersection of I-980 and I-880 than in the rest of the area (Figure 7). Concentrations are lower farther from I-880.

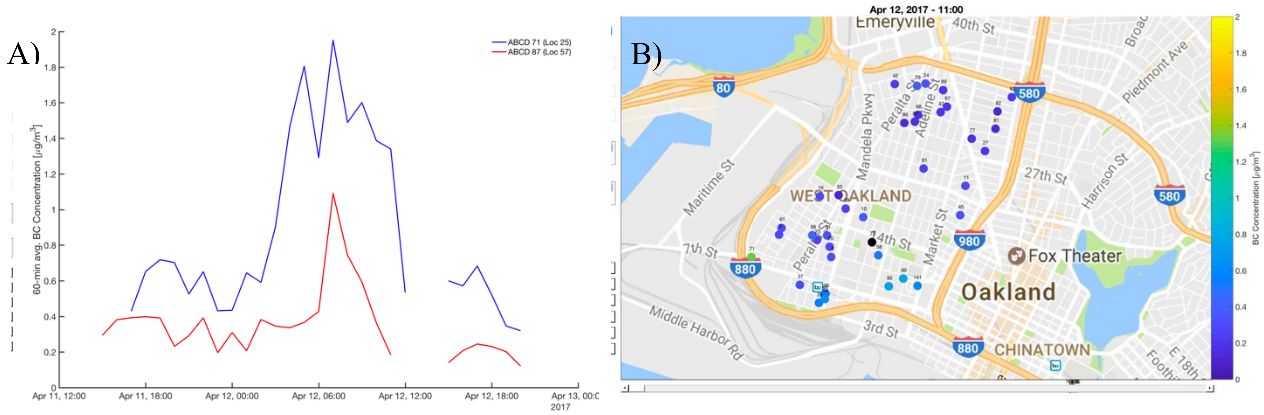

Figure 6. Spatial Variation of ABCDs. A) BC concentrations of ABCD 71, which is close to I-880, and ABCD 87, which is in the middle of West Oakland. B) BC concentrations of the sensor network as of April 12th.

DISCUSSION

West Oakland is a local hot spot for BC because of emissions from the Port of Oakland and from the three major highways surrounding it. Average BC concentrations were highest in the morning and evening. BC concentrations are often correlated with inversion layers. Inversion layers occur when a warmer layer of air sits on top of a cooler layer of air and stops atmospheric mixing. Inversion layers that are closer to the ground generally increase concentrations because BC cannot mix with air higher up, and is therefore contained in the air below the inversion layer. BC has a short atmospheric lifetime, which indicates that BC concentrations are likely to stay near their emission sources and therefore affect nearby residents disproportionately. High BC concentrations are correlated with cardiac and respiratory health issues; consequently, understanding emission sources and concentration gradients has the potential to improve the health of affected communities.

Pump Testing

Pump testing improved the BC concentration data and increased the accuracy of the flow rate, therefore increasing the accuracy of BC concentration calculations The ABCD pumps cost

$113 each, contributing substantially to the overall cost of $372 for each unit. The pump is a significant portion of the cost of the unit. Achieving accurate flow readings ensured accurate BC concentrations measured by the low-cost unit and aided in creating a high quality, low-cost sensor network. This sensor network allows for highly spatially resolved data at a cost-efficient price, which is essential in understanding concentration gradients and how to decrease harmful exposure. Improving the accuracy of the pumps facilitated the implementation of the ABCD network, which reveals spatial and temporal concentration gradients and informs both citizens and policy makers of how to avoid and limit exposure.

Field Test

Temporal Variation

BC concentrations are often higher at night than during the day because of inversion layers. Inversion layers occur when a cool layer of air is trapped under a warm layer of air, preventing mixing between the two layers, which limits the amount of air that pollutants can mix with and increases their concentration. Inversion layers remain if the colder air does not heat to the same temperature as the warmer air on top and traps the particles. Therefore colder weather increases the concentration of BC particles. In the early weekday mornings, there are peaks in concentration, which are due to a combination of factors including inversion layers and emissions (Figure 1, Figure 5). Because it is early in the morning and temperatures are cold, inversion layers are persistent. In addition, emissions from diesel trucks that bring shipping containers to the port begin around 7am on weekdays (Bay Area Air Quality Management District 2009). These two factors likely account for peaks in concentrations in the early mornings on weekdays. There tend to be secondary peaks later in the afternoon each day (Figure 2, Figure 5). These peaks can be attributed to several factors as well: inversion layers begin to form when Earth's surface cools after the sun reaches its highest point during the day, BC is accumulated in the air throughout the day, and commuting brings lots of traffic through West Oakland. After this peak, concentrations decrease to the normal background level of 0.5 $\mu g/m^3$ because emissions decrease and BC begins to settle out of the atmosphere (Figure 5). Studies in the Central Indo-Gangetic Plain, Gorakhpur, show similar results. Concentrations are higher in the early morning before the inversion layers have broken and later in the evening, after BC has been emitted throughout the entire day, which is consistent with my data (Vaishya et al. 2017). Because there are higher concentrations in the evening and during the early morning, West Oakland residents should be cautious of the amount of outdoor air exposure during peak times.

Stable medians for Sunday, Monday, and Tuesday indicate that average exposure during these days is similar (Figure 4). The median concentration increases on Wednesday and then decreases through Friday (Figure 4). However, Sunday concentrations have much more variation and all outliers are above the box plot, which imply that certain times on Sundays have very high peak concentrations compared to the other days of the week. In addition, the median concentration for Saturday are higher than the medians for Thursday and Friday. Because trucks are less prevalent on weekends, other external factors must be considered, such as increased traffic due to sporting events, fires, or interactions with weather (Viidanoja et al. 2002, Bay Area Air Quality Management District 2009). My results show an increase in median concentrations despite findings that indicate significantly lower weekend concentrations (Kirchstetter et al. 2008). These differences may be due to differences in study sites. The previous study included sites from across the Bay Area, while my study focused solely on West Oakland. Another possible explanation is the proximity to the freeways. My data was collected directly next to the freeway. The last and most likely explanation is that my data was taken over a very short time period of 3-weeks. In contrast, Kirchstetter et al. collected data from 1967-2003.

Spatial Variation

ABCD 71, which is close to I-880, shows higher concentrations than ABCD 87, which is farther from freeways (Figure 6). This indicates that locations near I-880 are exposed to up to double the BC concentrations compared to other areas of West Oakland. Locations in the Southeastern area of West Oakland have the highest concentration. These ABCDs are located close to the intersection of I-880 and I-980 (Figure 6). Because more than triple the amount of diesel trucks travel on I-880 than on I-980 and I-580 combined, ABCDs positioned near I-880 have higher concentrations than in the rest of the area (Bay Area Air Quality Management District 2009). Of these positioned near I-880, the highest concentrations are in the Southeast corner because I-880 loops around West Oakland and because the wind generally travels East, meaning

ABCDs that are farther East can be exposed to BC emitted on freeways and streets near the sensor and from further away. Understanding these emissions will influence which regulations to pursue to decrease West Oakland residents exposure to BC.

Limitations

One of the major limitations on my project was the time it took to develop the sensors. This project began a couple semesters before I joined, during which time the team was testing hardware and software that would accurately capture BC concentrations as compared to the established AE33 values. After determining the best hardware and software to use, validation tests began. Another drawback was the lack of labor needed to build the sensors. Because the sensors are low-cost, the parts were ordered in bulk and often needed modification before they could be incorporated into each unit. These modifications required a significant amount of time because we built 150 units. These limitations could have been overcome if more money was spent on ordering each piece to its exact specification, however, this would have increased the cost of the sensors. Because sensor development took much longer than expected, I didn't collect much data. Another limitation is the inability to differentiate between biomass and diesel combustion. This differentiation was not possible because one wavelength is used to measure the BC concentrations in ABCDs, but could be implemented in future versions of the sensors.

Future Directions

There are many future directions for this project. One possible direction is to analyze the data based on its distance from freeways or from other hotspots. This would determine how each emission source affects the rest of the area and how far the emissions travel. Another possible direction is to collect data throughout many different seasons to analyze the effect that seasonal weather patterns have on BC concentrations. Data such as precipitation levels, temperature, and boundary layer height could be incorporated into the analysis. This type of analysis would more accurately reflect the BC concentrations and the variables that effect it. In terms of sensor development, additional wavelengths could be used to determine BC emitted from biomass and from diesel combustion. BC emitted from biomass has higher absorption in the UV range, so by comparing the absorption in the UV range to other wavelengths, the proportion of BC emitted from different sources can be determined.

Broader Implications

West Oakland is a BC hot spot because diesel trucks and ships emit BC from the three surrounding freeways and the Port of Oakland. The highest BC concentrations occur during the evening and the early morning, before inversion layers have mixed. Because BC can cause serious health problems, it is advised to avoid to exposure to excess outdoor air during peak concentration times. This new low-cost technology will help researchers determine the most effective ways of reducing black carbon emissions in affected neighborhoods and affect policy change going forward. This low-cost of this network creates a more feasible opportunity to understand BC concentration gradients with higher resolution. Low-cost sensor networks will allow other hotspots to monitor their emissions, advise residents on when to avoid outdoor air, and inform policymakers on how they can limit exposure. This study follows the new trend of low-cost hardware and shows the endless possibilities that this new technology can accomplish. Hopefully it inspires others to rethink costly research strategies and encourages more innovative and cost-effective methods of data collection.

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