Analysis of Spatial and Temporal Trends of Black Carbon in Boston

George Allen

Prepared by
NESCAUM

January, 2014

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Acknowledgments

NESCAUM gratefully acknowledges the funding support provided by the Massachusetts Department of Environmental Protection (MassDEP) and the U.S. Environmental Protection Agency. BC Data from the Countway Library Brigham Circle site was provided by the Harvard School of Public Health.

This report was a joint effort between staff at NESCAUM and MassDEP. NESCAUM is an association of the eight northeast state air pollution control programs. NESCAUM provides technical guidance and policy advice to its member states.

NESCAUM also thanks the following individuals for providing review and comments on this report:

C. Mark Smith, Office of Research and Standards, MassDEP
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Printed: January 2014

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Executive Summary

NESCAUM, with funding from MassDEP and the U.S. EPA, conducted a study to evaluate spatial patterns and temporal trends of black carbon soot (BC) in Boston.

Key Findings

1. Concentrations of black carbon (BC, or soot) in Boston decreased substantially between 2002 and 2004. During this time period, diesel bus retrofit and State diesel Inspection and Maintenance (I/M) programs were implemented in Boston. The observed decrease in BC is likely due to these programs, and demonstrates the effectiveness and benefit of such programs.
2. From 2005 to 2012, BC concentrations in Boston have not dropped at two of the three long-term monitoring sites.
3. BC was substantially higher in the urban area where there are more mobile sources.
4. Urban BC was associated with time of day and day of week traffic patterns.
5. Within the urban area, there was substantial local scale heterogeneity.
6. Of the four BC sites in operation since 2009, the highest annual mean BC was observed at the NESCAUM office South St. site. Wind analysis suggests traffic emissions from the Southeast Expressway as the likely cause of the higher BC concentrations at this location.
7. Point sources of BC (e.g., emergency diesel gensets) can produce very large short-term (~20 minute) spikes of BC.

ES-1. Introduction

This report presents an analysis of spatial and temporal trends of black carbon soot (BC) in Boston, Massachusetts. BC is an optical measurement of how dark an aerosol is, and has been shown to be well correlated with elemental carbon (EC) measurements. BC is a useful indicator of local mobile source aerosol emissions in urban areas.

Local mobile sources in large urban areas contribute to elevated levels of a wide range of air pollutants associated with adverse health effects reported in a wide range of epidemiological studies. More recently, BC has been cited as a factor in near-road health effects.

From a policy perspective, an improved understanding of the spatial patterns (gradients) and long-term temporal trends of mobile source-related PM in large urban areas, as represented by BC, can inform control strategy assessment and implementation. It can also aid in understanding exposure dynamics of potential environmental justice-related hot-spots, such as the Dudley Square area of Roxbury (Boston) and can contribute to better understanding and improving estimates of exposures used in health effect studies. This project analyzed BC in the metropolitan Boston area, with the goal of better understanding urban gradients and temporal trends of BC (i.e., locally generated mobile source aerosols, including diesel PM) over the last decade.

In December 2002, NESCAUM started a one-year exploratory study to investigate the spatial extent of elevated BC from traffic, using two existing long-term BC monitoring sites (Roxbury and Brigham Circle) and four new sites. This project reanalyzed these data, using the full year of data and with improved data processing techniques. Site locations spanned from downtown Boston to the town of Stow, which is just inside the I-495 loop. Sites were located to be representative of neighborhood-scale concentrations, and avoid influence from heavily trafficked roads. Table ES-1 lists the six sites and the MassDEP North End site that started taking BC measurements in July 2003. Distance from the Joy Street Beacon Hill site, considered the centrally located site, and a general description of site characteristics are presented.

Table ES-1. Description of Core Monitoring Sites.

7 Core Site Locations	**Km from Beacon Hill Site**	**Site Description**
Joy Street, Beacon Hill (Boston)	0.0	Urban Residential (near State House)
North End (Boston)	1.1	Urban Residential/Commercial
Roxbury (Boston)	3.5	Urban Residential/Commercial; EJ
Brigham Circle (Boston)	4.1	Urban Residential/Commercial
Brighton (Boston)	7.0	Semi-Urban Residential
Waltham	14.9	Suburban Residential/Light Commercial
Stow	35.3	Semi-rural, open land, Regional Background Site for Metro Boston

Figure ES-1 presents the distribution of hourly BC for periods noted. BC concentrations at the four urban sites (Joy Street, North End, Roxbury, and Brigham Circle) were all higher than the two suburban and one background sites. The North End and Roxbury sites were similar to each other. As expected, the Stow semi-rural background site was the lowest, with mean BC being roughly one-fourth of the North End and Roxbury sites.

Figure ES-1. Distribution of 2003 Hourly BC for Seven Core Sites.

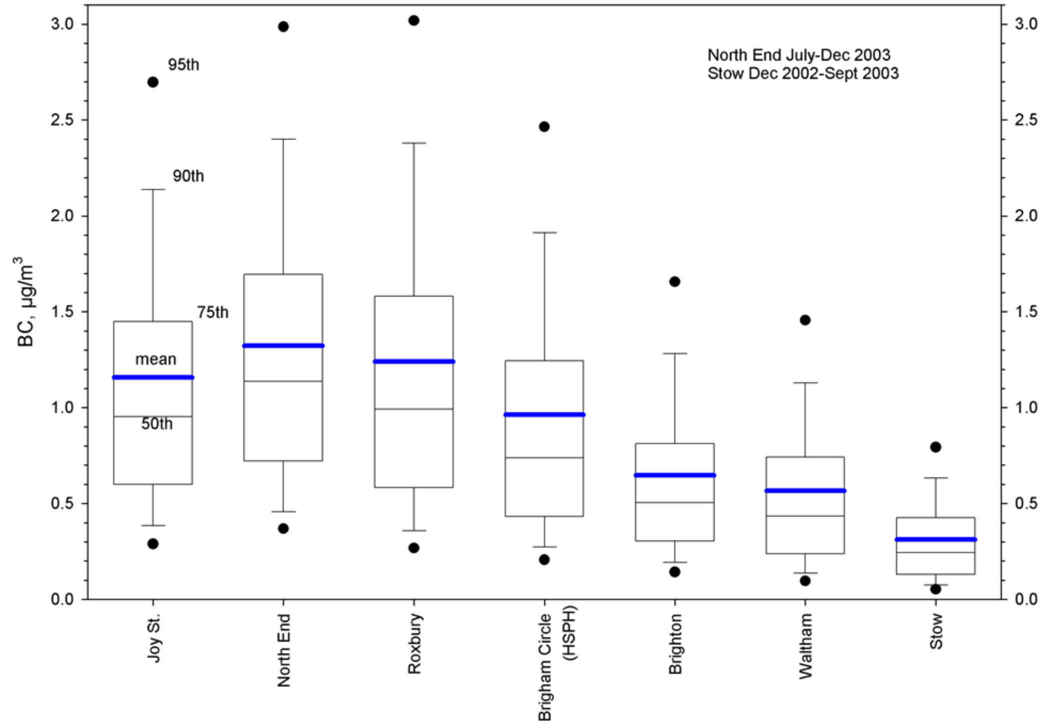
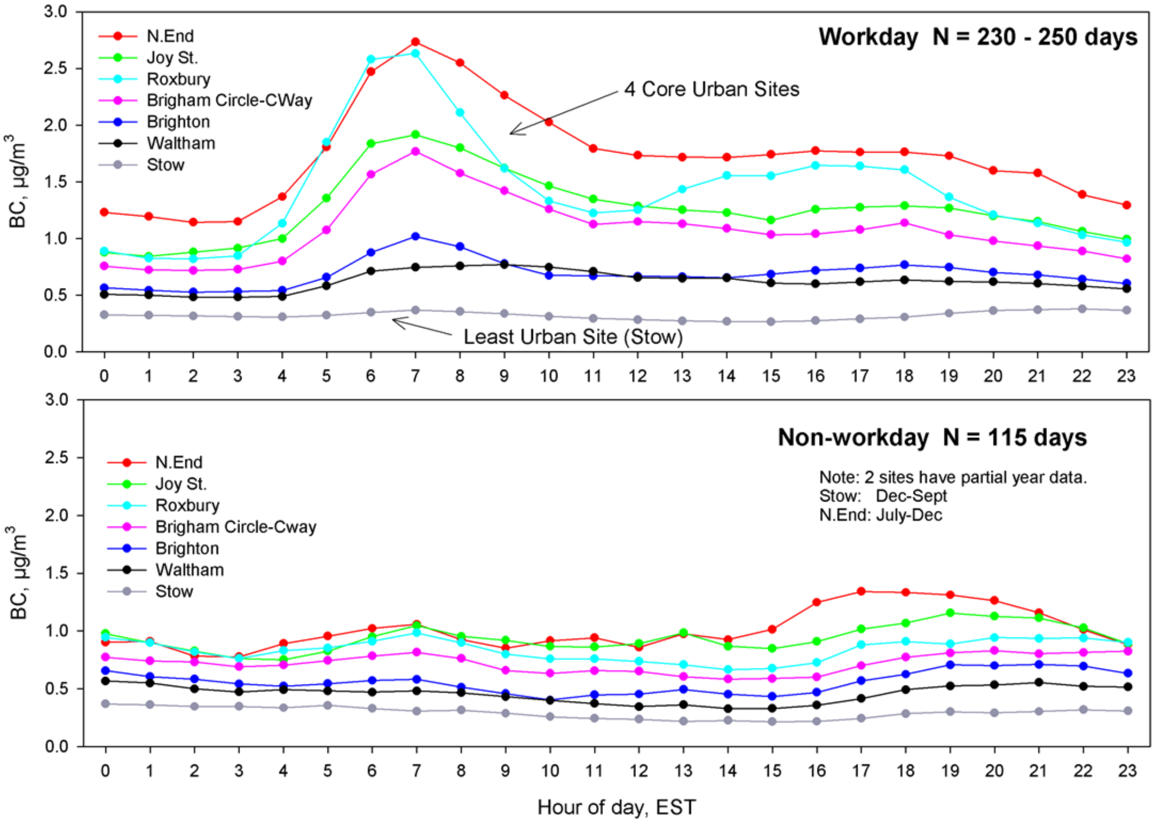


Figure ES-2 shows the diurnal BC pattern for the seven sites, with work days plotted separately from weekend days and holidays. For the weekday plot, the Roxbury and the North End sites had the highest morning rush-hour BC concentrations; the Joy Street and Brigham Circle sites were somewhat lower. The two suburban sites (Brighton and Waltham) showed a smaller morning rush hour peak relative to the rest of the day. The background site (Stow) showed no strong BC pattern for the entire day, consistent with its semi-rural location upwind of Boston.

For the non-weekday plot, there was no strong diurnal pattern, even for the core urban sites. This is consistent with expected non-weekday traffic patterns. The North End site showed its daily maximum in the early evening, from 5:00 to 7:00 pm. The multi-season weekday/non-weekday diurnal analysis provides increased confidence that BC is reasonably specific to local mobile source aerosol at these sites, minimizing concerns related to potential interferences at these sites from other sources of BC, such as oil-fired space heating and woodsmoke.

Figure ES-2. 2003 Diurnal Plot of Seven Core Sites.



A Boston Neighborhood Scale study was conducted for two months during the summer of 2003. Five additional sites were added to explore BC gradients within the urban core of Boston. Of all 12 sites, 10 were in Boston; 9 of which were within a radius of 2.5 km and in very urban settings. The Brighton site, while in the City of Boston, is in a semi-urban setting. Siting was representative of neighborhood scale (rather than hotspot/microscale) exposures. Table ES-2 presents, for each of the 10 Boston sites, their distance from the Joy Street site and general site characteristics.

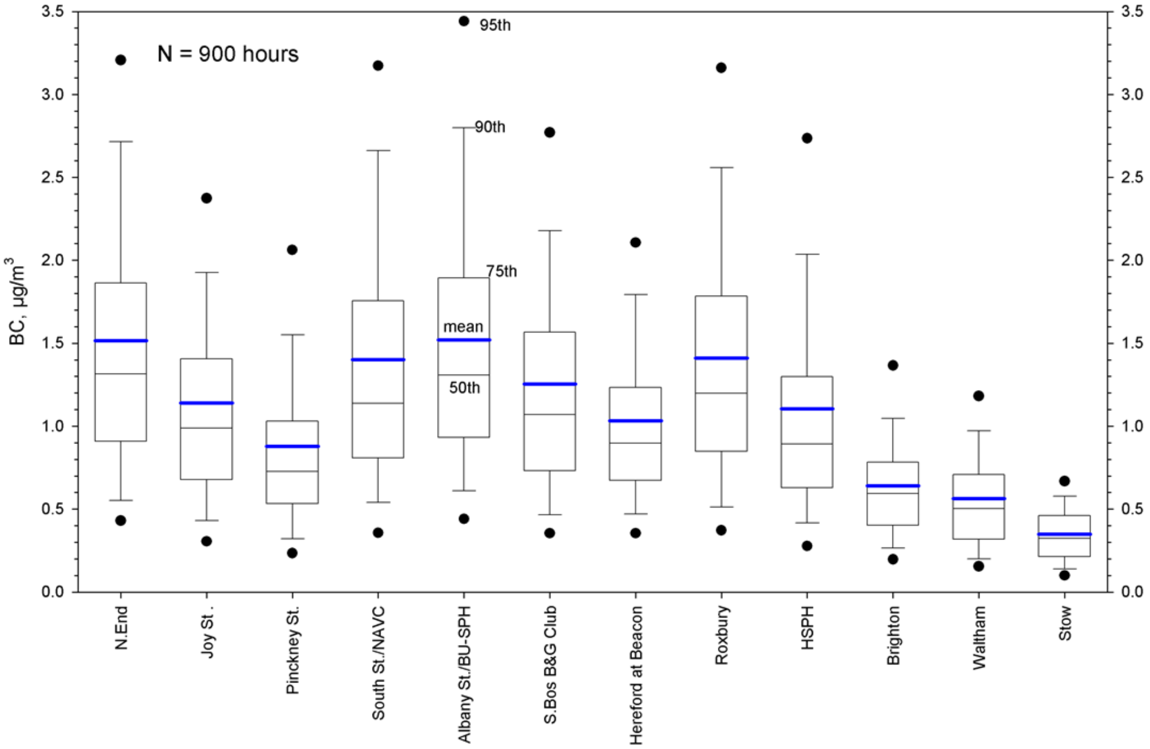
Table ES-2. Description of Sites for Summer Intensive.

Site Locations	Km	Site Description
Joy Street	0.0	Urban Residential/Commercial. (Beacon Hill, near State House)
Pinckney Street	0.3	Urban Residential (Beacon Hill)
North End	1.1	Urban Residential/Commercial (near the I-93 Expressway)
South Street	1.0	Urban Commercial (near South Station bus and train terminals)
Hereford Street	1.9	Urban Residential (Back Bay)
Albany Street	2.4	Urban Commercial (BU School of Public Health)

South Boston	2.9	Urban Residential
Roxbury	3.5	Urban Residential/Commercial
HSPH	4.0	Urban Residential/Commercial (urban scale)
Brighton	7.0	Semi-Urban Residential

Figure ES-3 shows the BC distributions for all 12 monitoring sites, limited to days where all sites had data. Approximately 20 days were excluded because two sites each had a 10-day period of missing data attributable to equipment malfunction and/or data loss attributable to sample collection and processing issues.

Figure ES-3. BC Distributions of 12 Summer Intensive Sites.

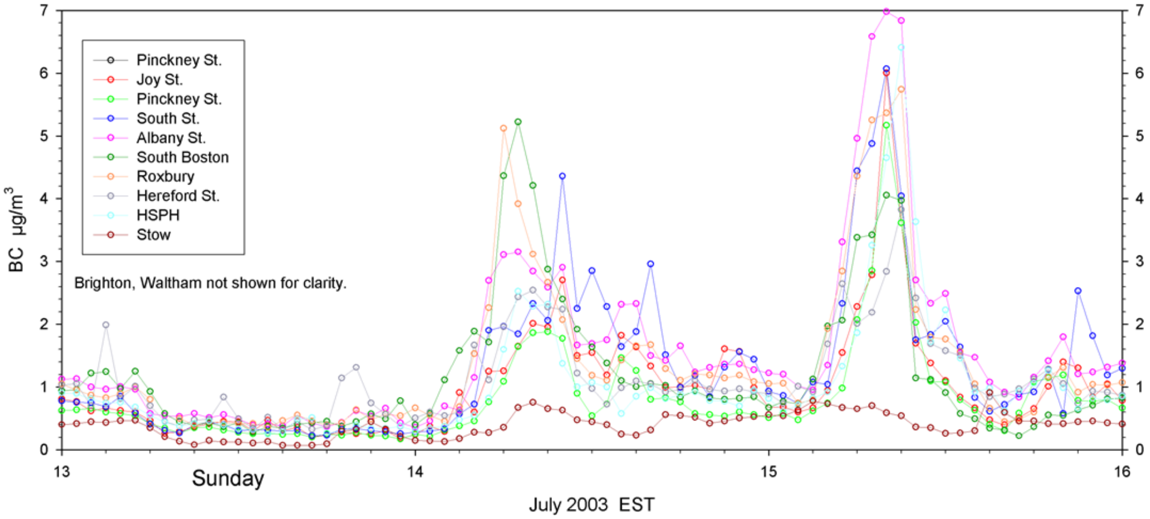


There were substantial gradients for mean BC at neighborhood scale-oriented sites in Boston. The observed variation across sites may be attributable to variability in monitor siting, mobile source strength gradients, and microscale meteorology. The North End and Albany Street sites were the highest, and the Roxbury and South Street (near South Station) sites were slightly lower. The urban Boston sites with the highest and lowest BC were North End and Pinckney Street (on Beacon Hill) locations. Although these sites are only 1.3 km (0.8 miles) apart, they exhibited a BC ratio of 1.7. The measured BC at the Hereford Street site was also relatively low, as it is near both Storrow Drive, where truck traffic is prohibited, and the Charles River.

Figure ES-4 is a time series plot that shows short-term patterns and gradients of hourly BC across the Boston area for July 13-15, 2003. A distinct “clean Sunday and dirty work-day” effect was observed. Tuesday, July 15, 2003 was one of the dirtier BC days of the summer;

several sites exceeded 4 micrograms per cubic meter (µg/m^3) BC for several hours during the morning. The ratio of these sites to the Stow background site for this peak period was approximately 10.

Figure ES-4. July 13-15, 2003 Event.



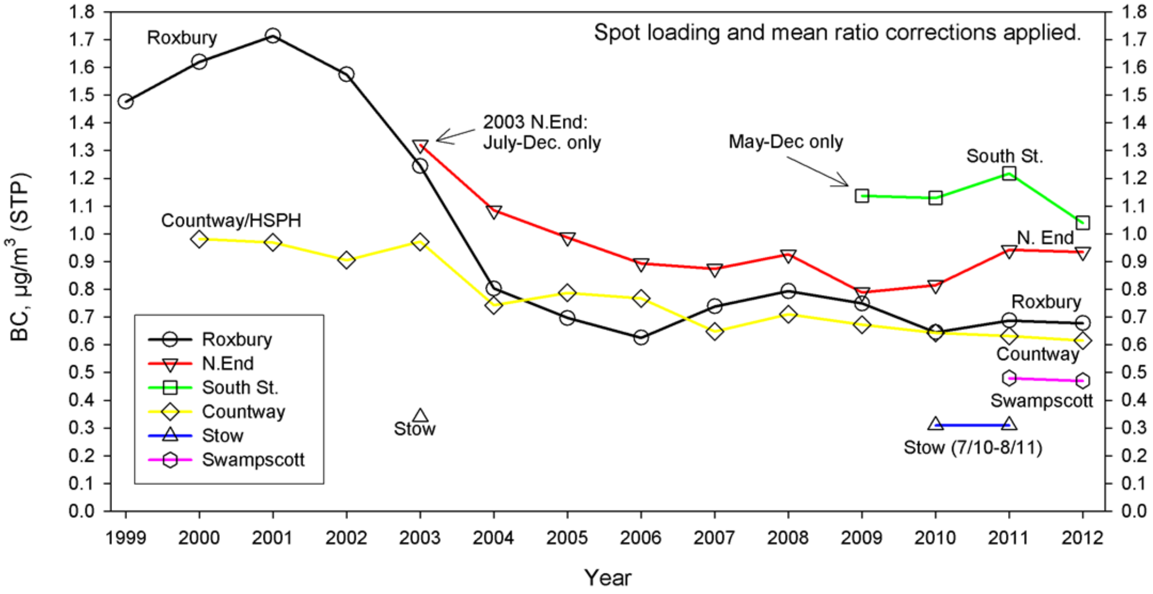
ES-2. Updated BC Spatial Analysis

The 2003 Spatial Study was conducted during a year when substantial reductions in heavy-duty diesel PM occurred due to the installation of PM control technologies on the MBTA and Boston school bus fleet. By spring 2005, both these fleets were entirely controlled for PM emissions. Trend analysis has shown a substantial drop in BC at the two long-term sites, and these changes may have affected the spatial patterns of BC.

From 2009 to 2012, additional BC monitoring sites were run specifically for this study to provide an updated assessment of the spatial scale of Boston BC. The Stow regional background site was run for two years (July 2009-August 2011), a permanent site at NESCAUM's South Street offices started in May 2009, and BC was monitored in Swampscott (21 km northeast of Boston) for the period 2011 through 2012.

Figure ES-5 shows the trend for the four Boston BC sites, along with the Stow 2003 and 2010 to 2011 means, and the 2011 to 2012 BC means for Swampscott. BC at the Stow regional background site dropped from 0.34 to 0.31 µg/m^3 over seven to eight years, consistent with reduced heavy-duty diesel PM emissions on a regional basis. Swampscott BC concentrations were lower than the Boston sites, but higher than the Stow site. Swampscott is downwind of Boston, and Stow is upwind; this may explain the relative BC concentrations at these two non-urban sites.

Figure ES-5. Trend for Four Boston BC Sites, Stow, and Swampscott.



The NESCAUM South Street site measured the highest BC of all Boston sites for 2009 to 2012 (Figure ES-5). Mean BC was 1.13 µg/m^3. The means for the other Boston BC sites ranged from 0.64 (HSPH) to 0.87 (North End) µg/m^3. The mean for Springfield was 0.87 µg/m^3. South Station, a major transportation hub for rail and intercity buses, is 300 meters to the southeast of the South Street monitoring site, and was considered to be a potential source of the BC at South Street. However, analysis of BC and wind direction data clearly showed that winds from the south-southwest and southwest accounted for more BC on average than any other direction, and winds from South Station (southeast) contributed a relatively small amount of BC measured at the site. The lack of influence from South Station diesel sources may be due in part to the use of an active ventilation system for commuter rail engines and the bus depot that vents their exhaust at high velocity through four stacks above the roof of the bus depot parking garage. The exhaust is diluted and dispersed approximately 37 meters above street level. The Massachusetts Turnpike (I-90), the Southeast Expressway (I-93), and the large interchange between the two, are all to the south-southwest and southwest of the South Street site by approximately 650 meters. The large amount of traffic activity from this area and the first kilometer of the I-93 Expressway above ground to the south-southwest is a likely reason for the high mobile source-related BC observed at this site.

The South Street site used in 2003 (located at the rear of 112 South Street) and the NESCAUM site at 89 South Street site are 65 meters apart, and thus close enough to be compared over time. Figure ES-6 shows that the summer spatial intensive BC distribution for the 2003 site, along with the 2009-2012 BC data from the NESCAUM South Street site, matched for the same days of the year. The 2009 to 2010 BC distributions were similar to the 2003 data. The 95th percentiles were higher for 2009 to 2010, in part due to a local source.[1]

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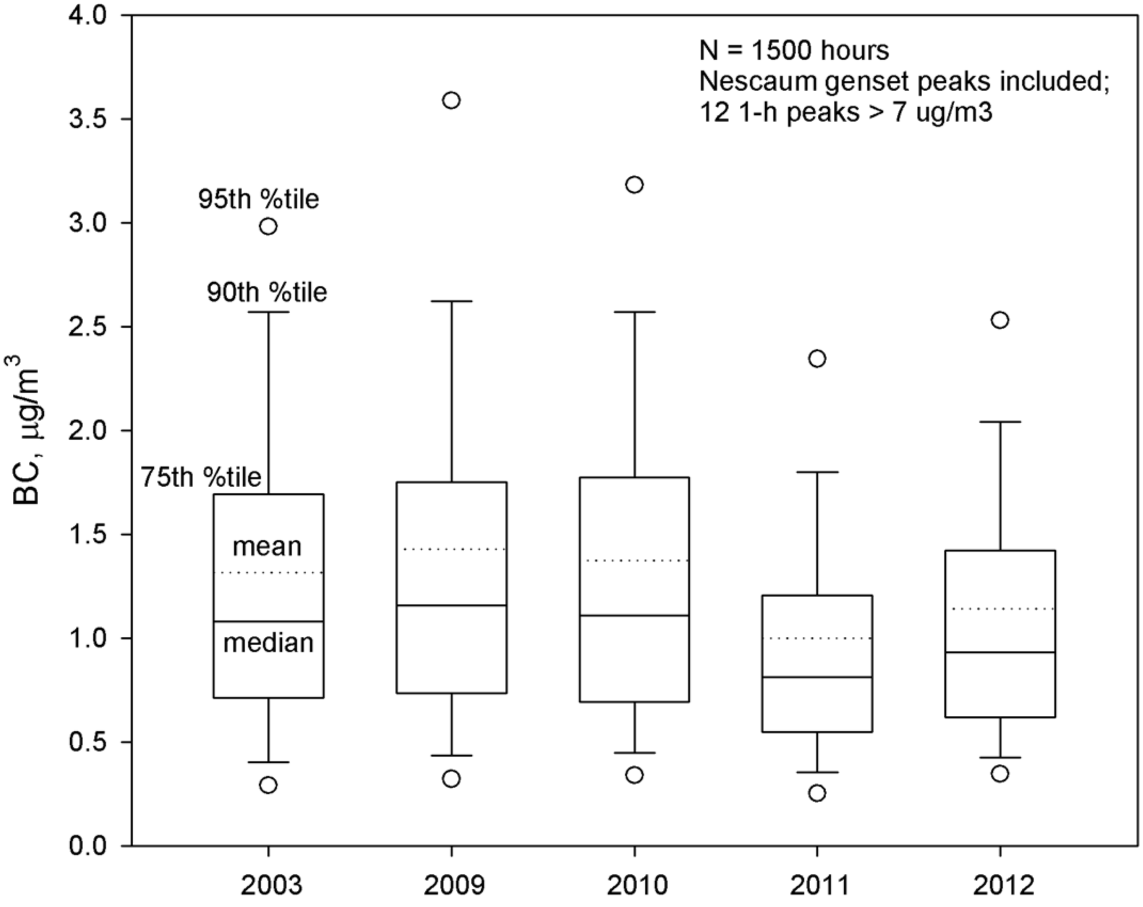
[1] A diesel genset weekly test produced very high BC, up to > 100 µg/m^3 for one-minute concentrations, once a week for approximately 15 minutes.

Figure ES-6. Summer 2003 and 2009-2012 South St. BC.

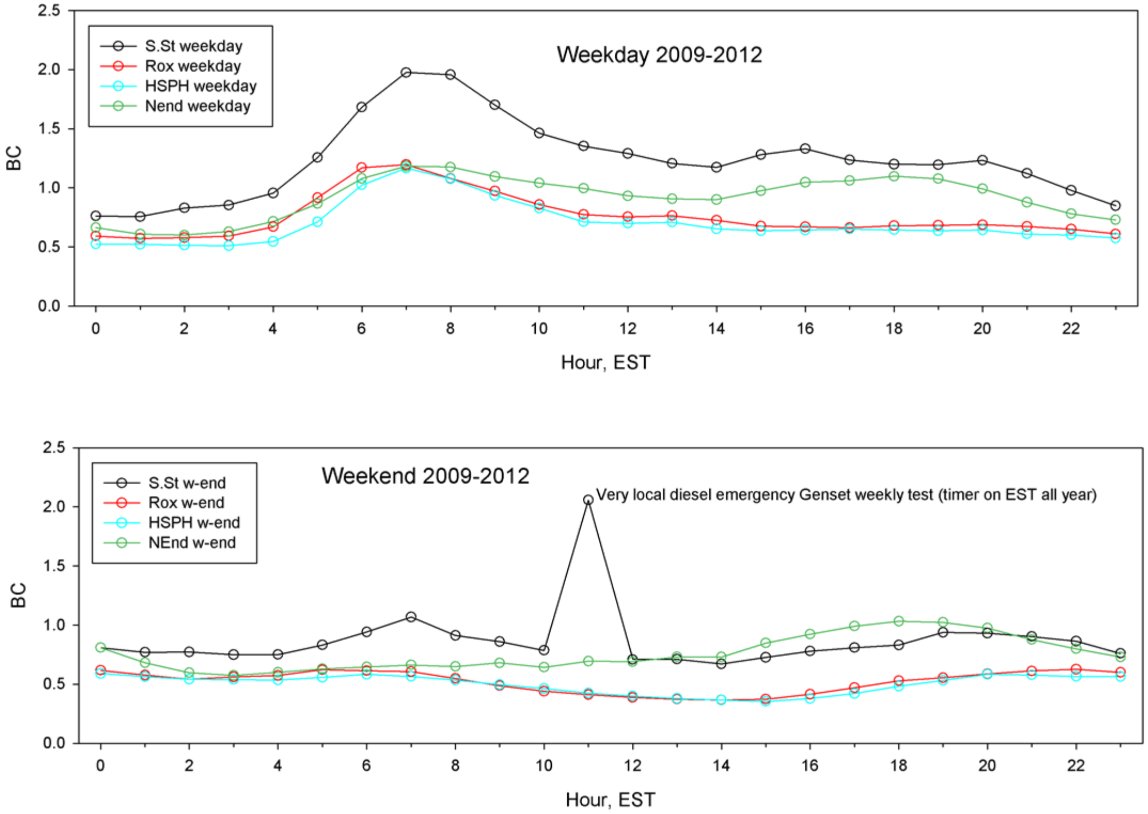


ES-2.1. Diurnal plots for 2009-2012, four Boston sites.

The weekday and weekend diurnal BC plots shown in Figure ES-7 have been updated for data from 2009 through 2012 for three of the Boston sites used in 2003. The NESCAUM South Street site was also added. The general patterns were unchanged, but as expected, the Roxbury site appeared to behave more like the HSPH site, with a smoother and less pronounced morning rush-hour peak that is characteristic of an urban-scale site.

The South Street site was highest for all hours during weekdays and weekends. The North End site was higher than Roxbury and HSPH for most hours of the day. As with the 2003 diurnal plots, there was a clear morning rush hour peak on weekdays, and no peak on weekends, except at South Street. That site also showed the effect of the weekly test of an emergency diesel genset on Saturdays at hour 11:00 a.m. EST.

Figure ES-7. Updated Diurnal Plots.

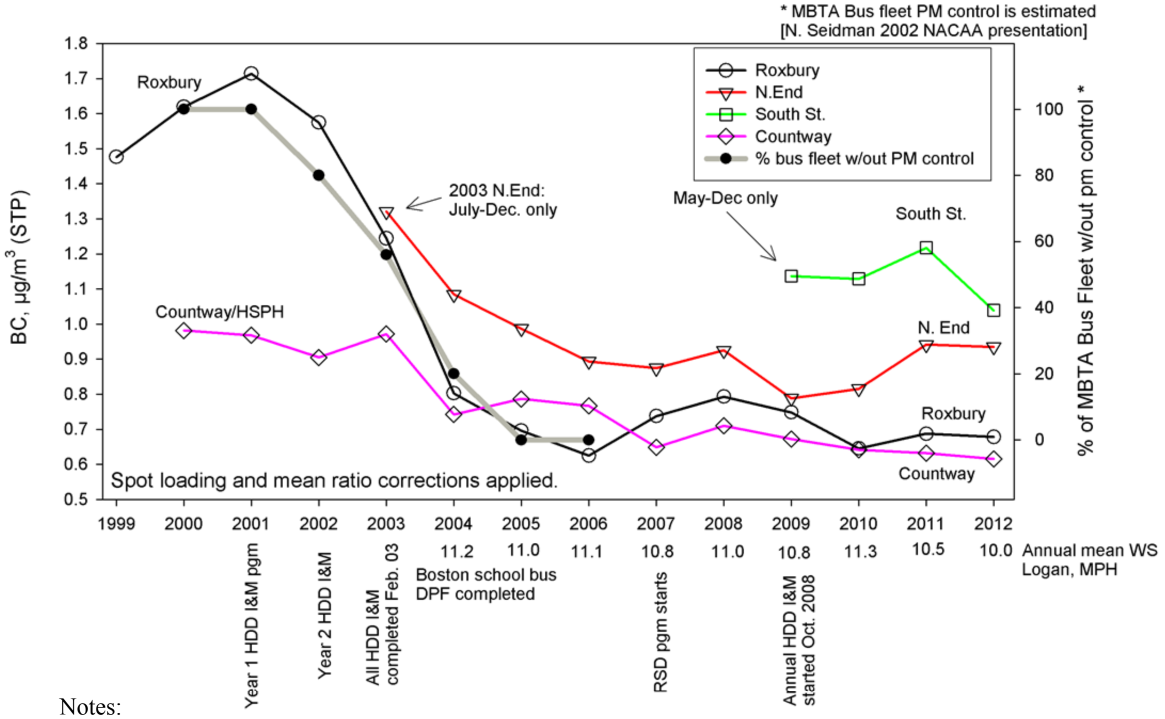


ES-3. Temporal Trends of Boston BC

There are several sites with multiple years of BC measurements in Boston. The Roxbury site started in February 1999, and the HSPH site started in October 1999. BC measurements were added to the MassDEP's North End site in July 2003. As part of this project, BC measurements commenced at NESCAUM's South Street, sixth-floor office (overlooking Tufts Street) in May 2009. Note that this is not the same South Street location used in the 2003 Boston Neighborhood Scale spatial summer intensive study.

Trend analysis was based primarily on annual mean BC concentrations. Figure ES-8 shows the BC trend data for the four Boston sites that had multiple years of data. Dates of the MassDEP's heavy-duty diesel control programs and the MBTA and Boston school bus fleet control programs are also indicated.

Figure ES-8. BC Trend Data for Boston Long-term Sites.



Notes:
"HDD I&M" is the MassDEP heavy duty diesel inspection and maintenance program.
"DPF" is diesel particulate filter
"RSD program" is the MBTA's bus garage Remote Sensing Device program for bus emissions.
"Spot loading and mean ratio corrections" are measurement method artifacts that varied over time and could affect trend analysis if not controlled for.

There was a striking drop in Roxbury BC over the three-year period 2002 through 2004. This correlates with the progress of the MBTA's bus fleet PM emission control program (the grey line from 2000 to 2006 in Figure ES-8), which resulted in the clean-up of 100% of the fleet between late 2002 and the end of 2004 (Seidman, 2002). The percentage of buses without PM controls is shown on the right axis of Figure ES-8. The entire Boston school bus fleet was also retrofitted with PM controls between 2003 and spring of 2005. Another factor in the reduction of Roxbury BC may have been the closing of the MBTA's Bartlett Street bus garage near Dudley Square at the end of 2003.

ES-3.1. Post-retrofit Progress.

Starting in 2005 after heavy-duty diesel PM emissions from the MBTA bus and the Boston school bus fleets were fully controlled and the Roxbury Bartlett Street MBTA bus garage was closed, there was no clear trend in BC indicated at the North End and Roxbury sites. The annual mean BC concentrations for 2005 and 2012 for these two sites were essentially identical, at 0.70 and 0.68 µg/m^3 for Roxbury, and 0.99 and 0.94 µg/m^3 at the North End. Figure ES-9 shows the regression of annual mean BC versus year at the North End from 2005 through 2012. It shows no clear trend. The Roxbury BC trend from 2007 through 2012 (Figure ES-10) had a downward trend, but the regression was not significant (p = 0.11). The trend from 2005-2012 was weaker (p = 0.8, not shown).

Figure ES-9. Regression of Annual Mean BC vs. Year 2005-2012 for North End.

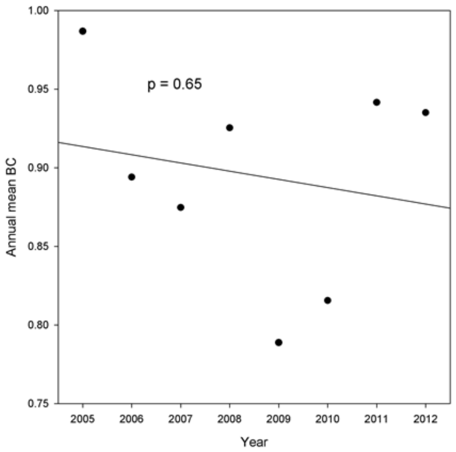
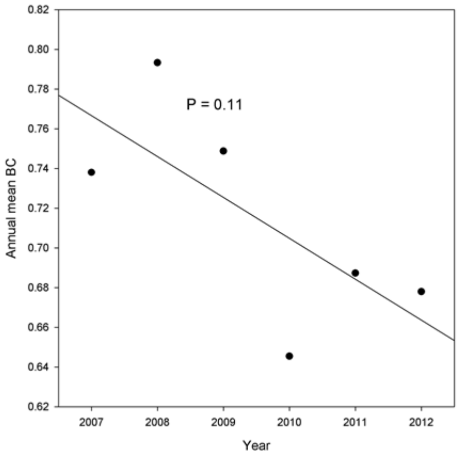
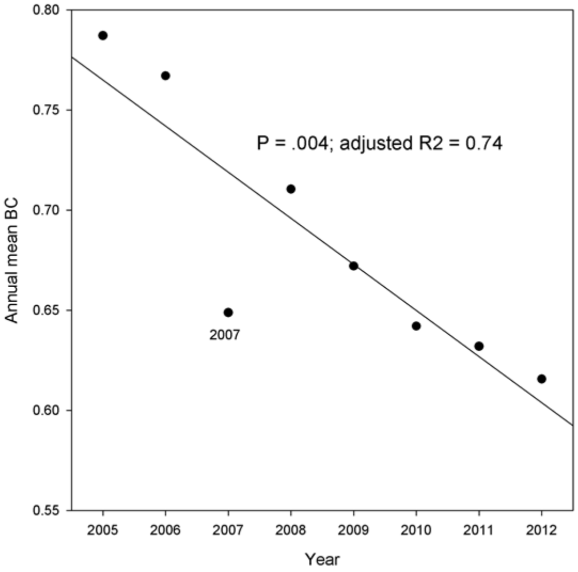


Figure ES-10. Regression of Annual Mean BC vs. Year 2007-2012 for Roxbury.



The same trend analysis for the HSPH Brigham Circle BC data showed a robust downward trend over time for 2005-2012 (Figure ES-11). It is not clear why the HSPH site showed a stronger trend for 2005-2012 than the Roxbury site. Both sites were urban scale over the 2005 to 2012 period, and had a similar mean BC (0.70 μg/m^3 for Roxbury and 0.68 μg/m^3 for HSPH).

Figure ES-11. HSPH Trend 2005-2012.



ES-4. Future work.

BC will continue to be monitored at four existing Boston sites, allowing assessment of future trends. The new MassDEP near-road monitoring site on the inbound Southeast Expressway, two kilometers east of the Roxbury site, includes BC measurements, for a total of five Boston BC monitoring sites. As mobile source BC emissions continue to be reduced, similar to the dramatic reduction of carbon monoxide over the last two decades, the utility of BC as a mobile source marker is also likely to decrease. While this is desirable from a health and exposure perspective, there are other mobile source pollutants of concern that may not be reduced, and it may be difficult to find another easily measured marker of mobile sources.

1. INTRODUCTION

This report presents an analysis of spatial and temporal trends of black carbon (BC) in Boston, Massachusetts. BC is an optical measurement of how dark an aerosol is, and has been shown to be well correlated with elemental carbon (EC) and coefficient of haze (COH) measurements (Allen et al., 1999). It is a useful indicator of local mobile source aerosol emissions in urban areas (Janssen et al., 1997). BC measurements were made at three long-term sites in Boston; these data were used to assess temporal trends and the impact of various diesel PM control strategies. Additional BC measurements made in 2003 and from 2009 through 2012 were assessed to evaluate spatial patterns across the metropolitan Boston area.

1.1. Sources and Health Effects of BC

Local mobile sources in large urban areas contribute to elevated levels of a wide range of air pollutants, including particulate matter (PM) from automotive (spark ignition) and diesel vehicles. PM from local mobile sources can be highly toxic, and is considered a major factor in the observed PM health effects reported by a wide range of epidemiological studies over the last decade (von Klot et al., 2011; Janssen et al., 2011). More recently, BC has been cited as a factor in near-road health effects (Brunekreef et al., 2009; Vette et al., 2013; Knibbs and Morawska, 2012).

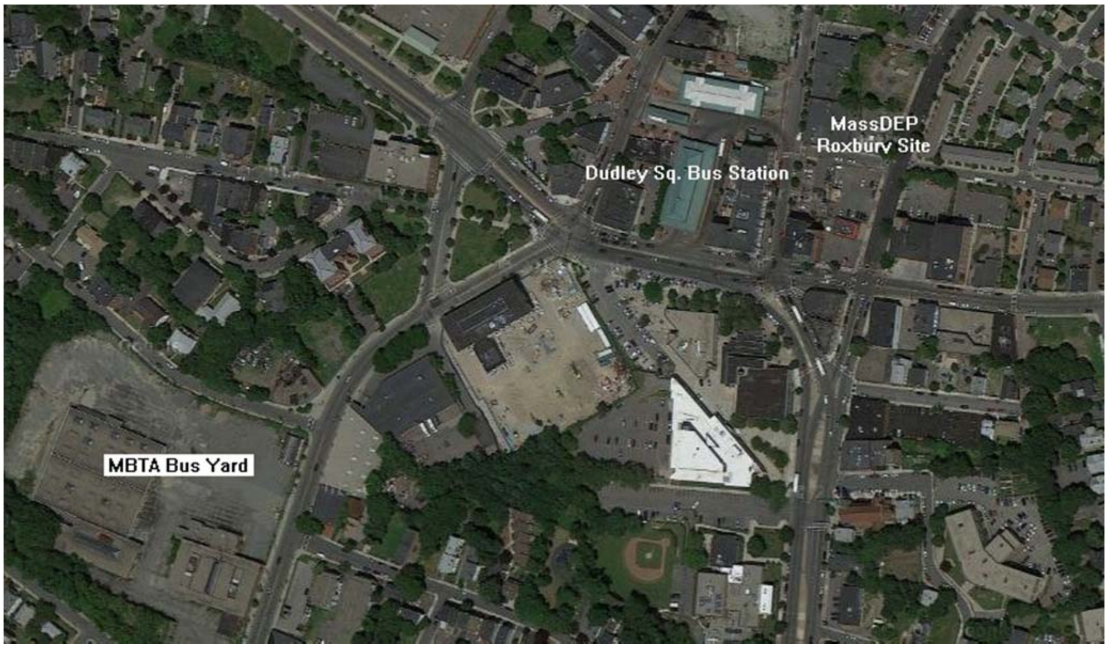
From a policy perspective, an improved understanding of the spatial patterns (gradients) and long-term temporal trends of mobile source-related PM in large urban areas, as represented by BC, can inform control strategy assessment and implementation. It can also aid in understanding exposure dynamics of potential environmental justice-related hot-spots, such as the Dudley Square area of Roxbury (Boston). Moreover, it is critical for better understanding and improving estimates of exposures used in health effect studies. For example, Harvard University's EPA Boston PM Center has used the Massachusetts Department of Environmental Protection's (MassDEP's) air pollution data in several studies over the last decade.

When data from a single monitoring site are used to represent concentrations of locally generated pollutants such as BC for a metropolitan area, exposure misclassification may occur since variation in pollutant concentrations can be substantial over the urban area. Unless the spatial component of exposures is taken into account, this error can bias estimates of health effects toward lower (less hazardous) values (Kunzli et al., 2005). This project analyzed BC in the metropolitan Boston area, with the goal of better understanding urban gradients and temporal trends of BC (i.e., locally generated mobile source aerosols, including diesel PM) over the last decade. Quantifying BC spatial gradients and temporal trends are related tasks, as both affect characterization of mobile-source aerosol exposures.

1.2. Previous Related Work in Boston.

Since 1999, BC measurements in Boston have been collected at two sites: (1) in Roxbury at the intersection of Harrison Ave. and Ziegler St. near Dudley Square by MassDEP (February 1999); and (2) near Brigham Circle on the roof of the Harvard University Countway Library by the Harvard School of Public Health (HSPH) (October 1999). When Roxbury measurement efforts started, the Dudley Square area was considered a hot-spot for diesel pollution from the Dudley Square Bus Station and the nearby Massachusetts Bay Transit Authority (MBTA) Bartlett Street bus yard and garage. At that time, the MBTA bus fleet was old. Much of the fleet dated back to the mid- and late-1980's, and included some two-stroke diesel engines. Buses had no emission controls, and thus contributed to high levels of pollution, including soot. Figure 1-1 shows an aerial view of Roxbury, with the bus yard, the Dudley Square Bus Station, and the MassDEP Roxbury monitoring site labeled.

Figure 1-1. Aerial View of Roxbury.



Beginning in 1999, local environmental justice (EJ) groups worked with MassDEP to install a comprehensive monitoring site one block from Dudley Square. The EJ groups, MassDEP, the Harvard School of Public Health, and NESCAUM received funding from the U.S. EPA for an EMPACT project (Environmental Monitoring for Public Access and Community Tracking) to develop outreach tools for the community (Loh, 2002). The resulting AIRBEAT project provided the public access to real-time ozone and PM data through a web site and telephone hotline. The AIRBEAT web site, which is hosted by NESCAUM, remains operational as of January 2014, and the project was chosen by EPA as a technology-transfer case study.[2]

In December 2002, NESCAUM started a one-year study to investigate the spatial extent of elevated BC from traffic, using the two existing monitoring sites and four new sites. Their locations spanned from downtown Boston to the town of Stow, which is just inside the I-495 loop. Sites were located to be representative of neighborhood-scale concentrations and avoid influence from heavily trafficked roads. Figure 1-2 shows the site locations of these six year-long sites plus the MassDEP North End site that started July 2003.

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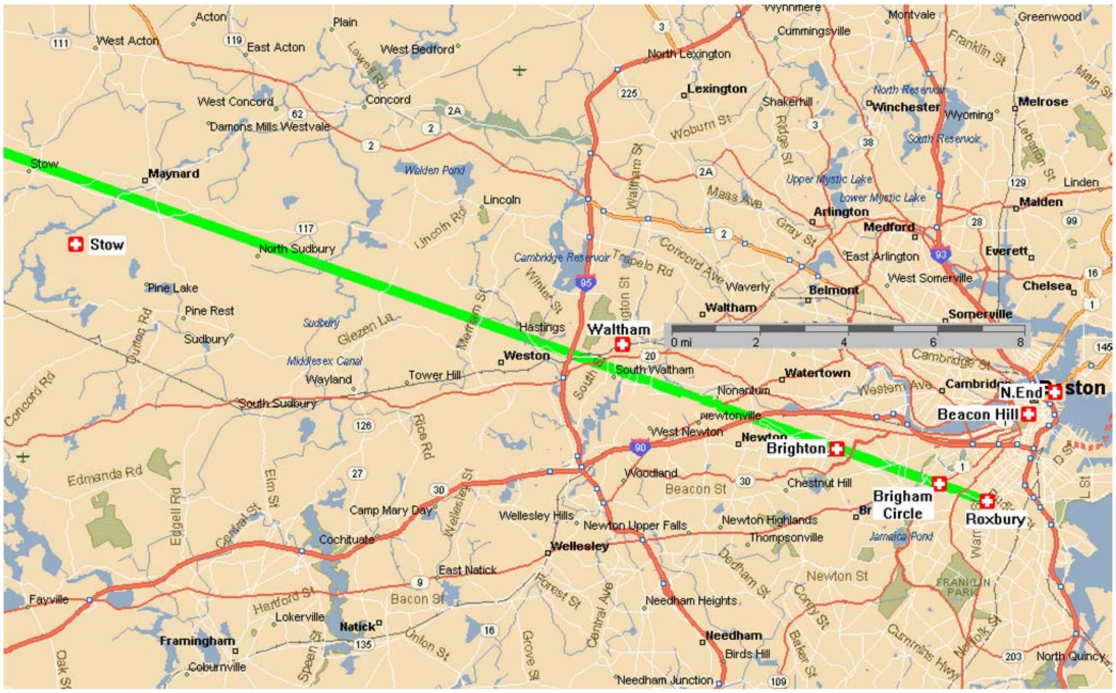
[2] United States EPA. Planning and Implementing a Real-time Air Pollution Monitoring and Outreach Program for Your Community The AirBeat Project of Roxbury, Massachusetts. 2002. Accessed May 21, 2013. http://airbeat.org/airbeat-tech-xfer-final.pdf.

Figure 1-2. Map of Seven Year-long Sites.



A related pilot study that included three additional monitoring sites ran for six weeks, from January 11 to February 26, 2003. Subsequently, during the summer of 2003, six additional sites were added in order to look at gradients within the Boston urban core, resulting in a total of ten urban core sites. Previous preliminary analyses for these efforts, conducted prior to this assessment, are included in Appendix A and B.

1.3. Limitations of Previous Work

There were several limitations to the previous preliminary analysis. The scope of the analysis was limited due to resource constraints. The lack of long-term data did not allow for proper seasonal analysis. The last four months of data were not analyzed, and the North End site was not included. Moreover, a substantial artifact to the BC measurement method was not accounted for.

The BC artifact produces a reduced instrument response at higher filter particle loadings. This error can vary from none to a factor of two for some hours. The error varies with filter loading, instrument configuration, and the aerosol composition, which may have strong seasonal and spatial components (Virkkula et al., 2007; Park et al., 2010; Turner et al., 2007; Coen et al., 2010). In 2003, this artifact was not understood. NESCAUM authored a report for MassDEP on Aethalometer BC artifacts in 2007, entitled "Evaluation of the Aethalometer BC Spot Matrix Effect" that characterized different aspects of BC measurement errors.[3] This artifact has been accounted for in the following assessment.

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[3] http://www.nescaum.org/documents/madep-aeth-spot-effect-12dec2007.pdf/view

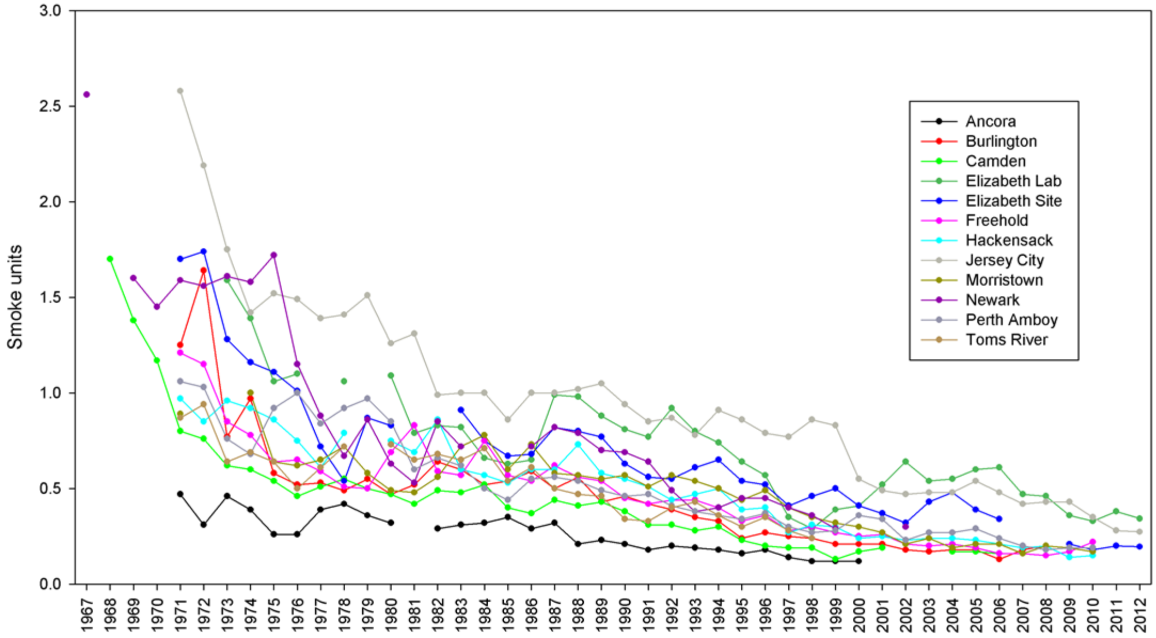
2. APPROACH AND METHODS

Data sources for this project included BC monitors at on-going MassDEP sites and at the HSPH's EPA PM-center, as well as BC measurements at sites that were run specifically for this project.

2.1. Aethalometer Method

The primary metric used for this analysis was BC from Aethalometers™ (Magee Scientific, Berkeley, CA), a measurement that is commonly used by the EPA National Air Toxics Trends Stations (NATTS) program. The Aethalometer measures how dark the aerosol is: the more sampled graphitic carbon soot (which comes primarily from diesel in urban areas as well as from spark ignition vehicles), the higher the reported BC concentration. Aethalometer BC has been shown to be highly correlated with thermal elemental carbon (EC) methods, such as those used in EPA's Chemical Speciation Network (CSN), and with the classic smoke shade coefficient of haze (COH) measurement that has been in use since the 1960's (Allen et al., 1999). One COH unit is approximately 5 micrograms per cubic meter ($\mu g/m^3$) BC. The New Jersey Department of Environmental Protection (NJDEP) has been measuring COH at multiple monitoring sites since 1967. Figure 2-1 shows COH trend data for New Jersey from 1967 through 2012, which demonstrates that, over the last several decades, there has been a dramatic reduction of COH (or BC), reflecting the cleanup of the on-road vehicle fleet (Kirchstetter et al., 2008).

Figure 2-1. NJ COH Long-term Trend.



2.2. Data Processing and Analysis

For the spatial BC analysis, annual means were used as the primary metric. Correlations of hourly concentration across sites were done for specific short-term periods of a few days.

Annual mean BC was also used for the temporal trend analysis. The monthly pattern of BC was examined for sites used in the trend analysis.

Data from the Roxbury and HSPH sites required evaluation of changes in instrument configuration and data handling over the 13 years of BC data. Most of these changes were taken into account by the data reprocessing technique that minimizes the filter spot loading artifact noted above. The reprocessing requires the original instrument data. For Roxbury, much of these original data were not available between 1999 and 2002, so BC data from the MassDEP data acquisition system (DAS) were used. There were periods in 1999 and 2000 when the original instrument data files were available; these were used to determine the relationship between the re-processed BC data and the MassDEP DAS data. Based on this analysis, a correction factor of 1.2 was applied to the DAS data, consistent with the bias expected from un-corrected BC data.

Instrument bias, the potential difference between two different Aethalometers even when operating properly (Müller et al., 2011), is another factor to be considered in trend analysis. At the North End site, the same instrument was used over the entire time-period used in this analysis (Springfield also used the same instrument) other than brief periods for repairs, removing this factor for trend analysis. The HSPH/Countway site used two different instruments over the 13 years; the change of instrument was evaluated, and there was minimal effect on trend data. The Roxbury site used several different instruments during the October 2004 to August 2007 period, and there was no evaluation (e.g., collocation) of possible effects of these changes on the reported BC data. These changes could introduce artifacts in the BC trend at this site. However, the Roxbury Aethalometer was not changed from the start of monitoring in 1999 to October 2004 (the period with a large decrease in BC concentrations) and since September 2007 other than for brief periods for repair. This and the observed decreases in BC at the HSPH and North End sites during 2003-2004 provides confidence that the BC trend during this period is not an artifact from using different instruments at the Roxbury site. Table 2-1 shows the dates and instrument serial numbers for the Aethalometers used for Roxbury BC measurements.

Table 2-1. Roxbury Aethalometer History (serial numbers)

Date	Instrument serial number
4/1/99-10/1/04	sn199
11/5/04-3/24/05	sn456
3/24/05-4/11/05	sn367
4/24/05-8/3/05	sn456
9/9/05-10/24/05	sn199
10/24/05-8/9/06	sn641
8/9/06-8/27/07	sn684
8/27/07-10/16/07	sn801
10/16/07-11/21/07	sn766
11/21/07-9/4/08	sn801
9/4/08-9/16/08	sn380
9/16/08-4/14/11	sn801
4/14/11-5/25/11	sn199
5/25/11-12/31/13	sn801

Another instrument factor that was controlled for was the "Mean Ratio" (MR) setting. Data from the MassDEP North End and Springfield sites used an MR value of 1.00 for the first several years, as that is how the instruments were originally configured by the Aethalometer manufacturer. Subsequently, the manufacturer determined that the MR value was approximately 0.85. This change was implemented in the instrument configuration in November 2009 for the North End site, and in March 2011 for the Springfield site. Data in this report before this change have thus been corrected by a factor of 0.85. The official MassDEP BC data do not reflect this change.

Similarly, the official HSPH data from the Countway Library site have not been corrected for the spot loading artifact. The data presented here were corrected, and therefore differ from the HSPH data. Appendices C and D provide examples of the differences between the reprocessed and original BC data sets for the HSPH and North End sites.

The original 2003 spatial analysis did not include the North End BC measurements, which started on July 1, 2003. For the re-analysis, reflectance measurements were performed on Federal Reference Method (FRM) sampler Teflon filters from the site to fill in BC data for the first half of 2003 (Heal and Quincy, 2012).

The reflectance data resulted in a mean BC concentration of 1.35 $\mu g/m^3$ for February through April 2003. The mean Aethalometer BC concentration for July through December 2003 was 1.32 $\mu g/m^3$, which was used as the annual mean for the North End site. Originally, we expected to be able to fill in BC data back to 2001 using this method, but the FRM filters for 2001-2002 could not be located. Additional details on the reflectance method are in Appendix E.

There are several sites in Boston for which there are many years of BC measurements. Roxbury started in 1999, and HSPH in 2000. BC measurements were added to the MassDEP's North End monitoring site in July 2003. As part of this project, BC measurements were started at NESCAUM's South Street (South St.), sixth-floor office (overlooking Tufts Street) in May 2009. Note that this is not the same South St. location used in the 2003 spatial summer intensive analysis. This report's trend analysis was based primarily on annual mean BC concentrations (with reflectance data fill in for the North End 2003 BC mean).

3. RE-ANALYSIS OF 2003 SPATIAL BC DATA.

Since the initial analysis in 2003, substantial effort has been put into improving data post-processing techniques to reduce the Aethalometer data artifact. This has resulted in a "binned" correction method. This correction method is described in a presentation from the 2012 National Air Monitoring Conference.[4]

All BC data used for this project were corrected for filter loading errors with this method in a consistent manner. Additional details on the binned correction method and examples of its effect are in Appendix D and Turner 2011, Appendix F.

3.1. Seven Site One-Year Re-Analysis.

For this study, the preliminary analysis conducted in 2003 was repeated, using a full year of corrected BC data from the six original sites and with data from the MassDEP's North End site.

The Stow background site has data from December 2002 through mid-September 2003, and the North End site started July 1, 2003. The other sites have a full year of data, with reasonable data capture. Table 3-1 lists the seven sites, their distance from the Joy Street site, and a description of the land use.

Table 3-1. Description of Seven 2003 Year-long Sites.

7 Core Site Locations	Km	Site Description
Joy Street (Boston)	0.0	Urban Residential (near State House)
North End (Boston)	1.1	Urban Residential/Commercial
Roxbury (Boston)	3.5	Urban Residential/Commercial; Environmental Justice
HSPH (Boston)	4.1	Urban Residential/Commercial (urban scale)
Brighton (Boston)	7.0	Semi-Urban Residential
Waltham	14.9	Suburban Residential/Light Commercial
Stow	35.3	Semi-rural, Open Land; (Regional Background site for Metro Boston)

Figure 3-1 shows the distribution of hourly BC for the study period for each site. The four urban sites (Joy Street, North End, Roxbury, and HSPH-Brigham Circle) were all higher than the three suburban and background sites. The North End and Roxbury sites were similar.

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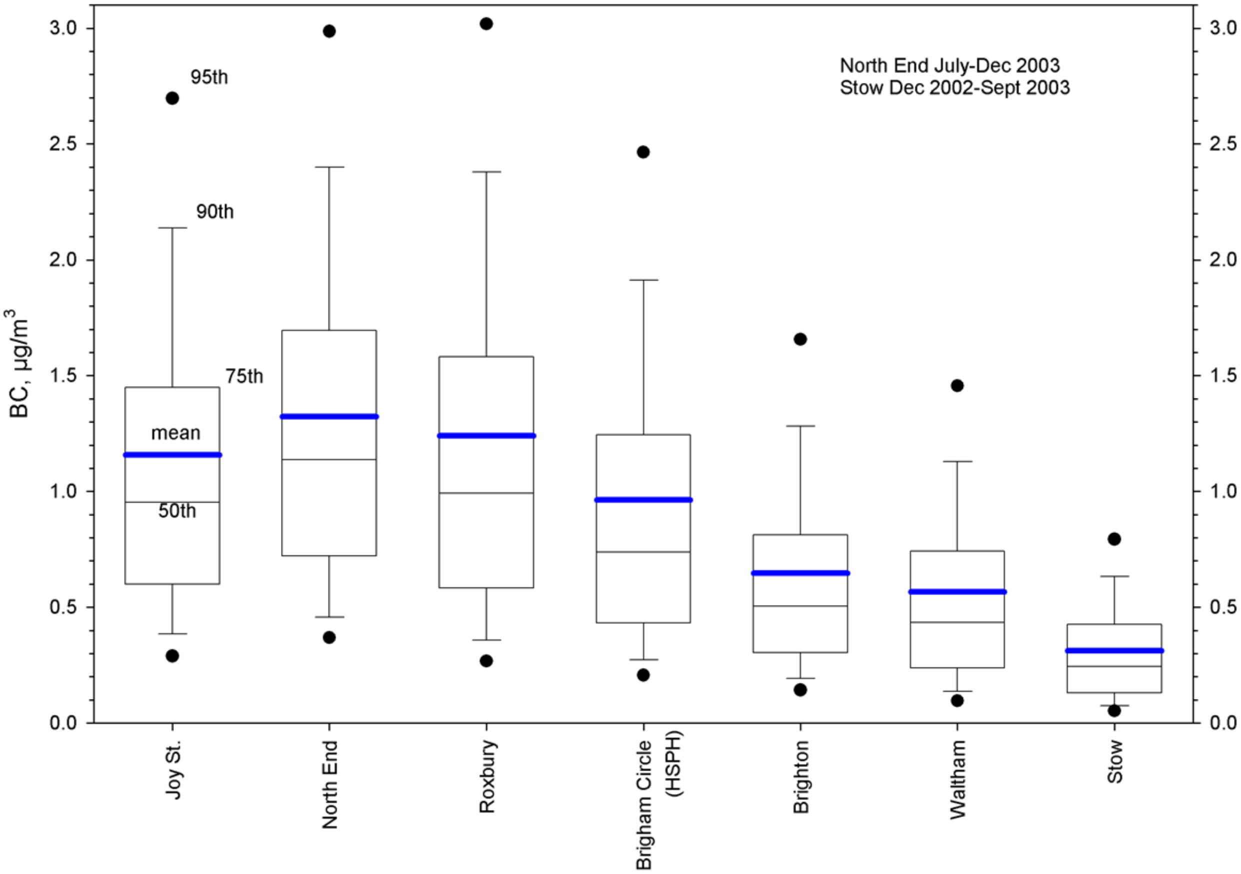
[4] Allen, George, and J. Turner. "Aethalometer Data Post Processor ('Masher;) Update: Spot Loading Correction." Presentation, National Air Monitoring Conference, Denver, CO, May 16, 2012. Accessed May 21, 2013, http://www.epa.gov/ttnamti1/files/2012conference/3C01Allen.pdf .

As expected, the Stow background site was the lowest, with mean BC about one-fourth of the North End and Roxbury sites.

Figure 3-1. Distribution of 2003 Hourly BC for Seven Core Sites.



Note that tests for significant differences in mean BC across sites were not performed, since the very large sample size typically shows all means to be different at $p = 0.05$.[5] This result is misleading for these data since the between instrument bias for the Aethalometer is typically between 10 and 20%. Thus, any difference less than approximately 15 to 20% could be an artifact of the measurement.

Figure 3-2 shows the diurnal pattern for the seven sites, with work-days plotted separately from weekend days and holidays. For the weekday plot, Roxbury and the North End site had the highest morning rush-hour BC concentrations; Joy Street and HSPH were somewhat lower. The two non-urban core sites, Brighton and Waltham, showed a smaller morning rush hour peak relative to the rest of the day. Stow, the background site, showed no strong BC pattern for the entire day, consistent with its semi-rural location upwind of Boston.

For the non-weekday plot, there was no strong diurnal pattern even for the core urban sites. This is consistent with the expected different non-weekday traffic patterns. The North End site showed a daily maximum in the early evening from 5:00 to 7:00 pm. This multi-season

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[5] Normally ANOVA on ranks followed with an all Pairwise Multiple Comparison Procedure would be used for this purpose.

weekday/non-weekday diurnal analysis provides increased confidence that BC is reasonably specific to local mobile source aerosol, minimizing concerns related to potential interferences at these sites from other sources of BC, such as oil-fired space heating and woodsmoke.

Figure 3-2. 2003 Diurnal Plots of Seven Core Sites.

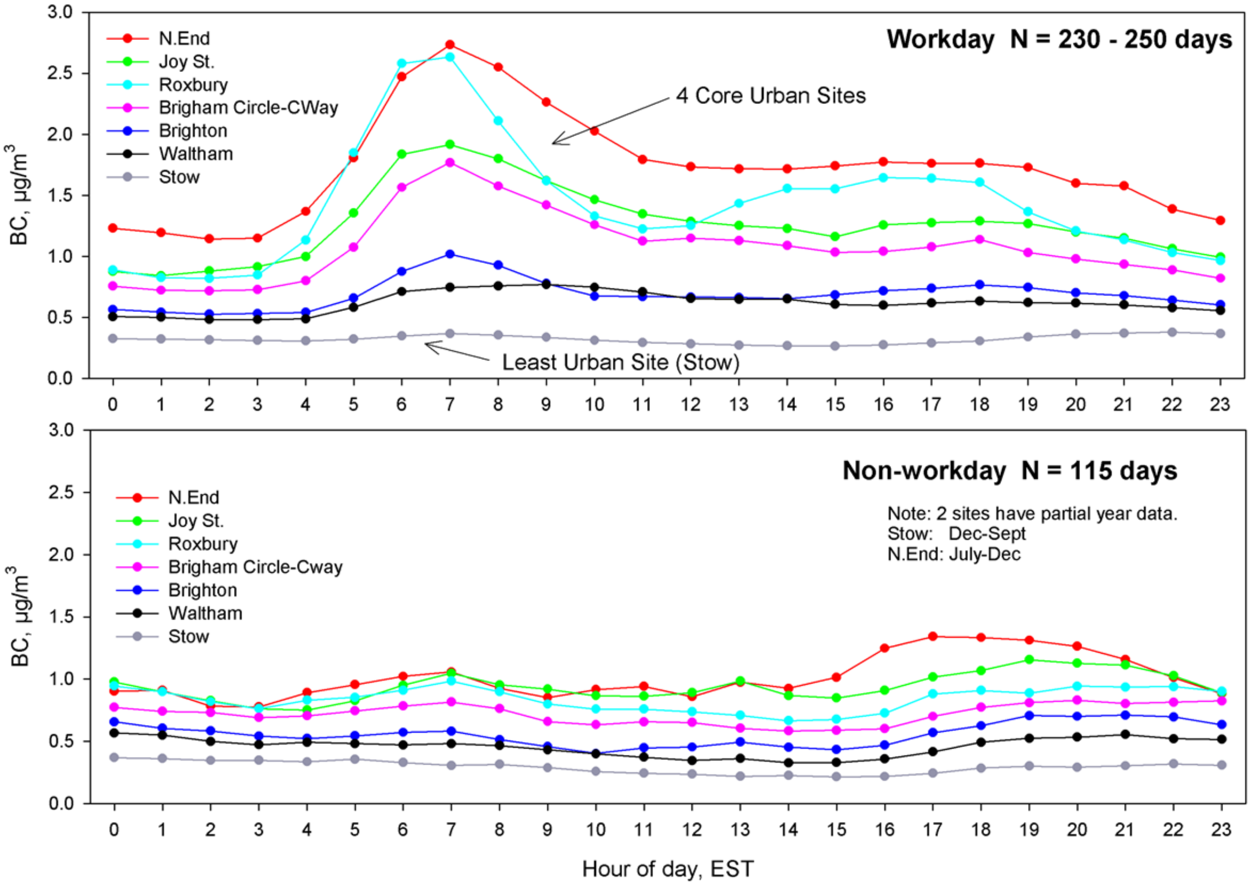
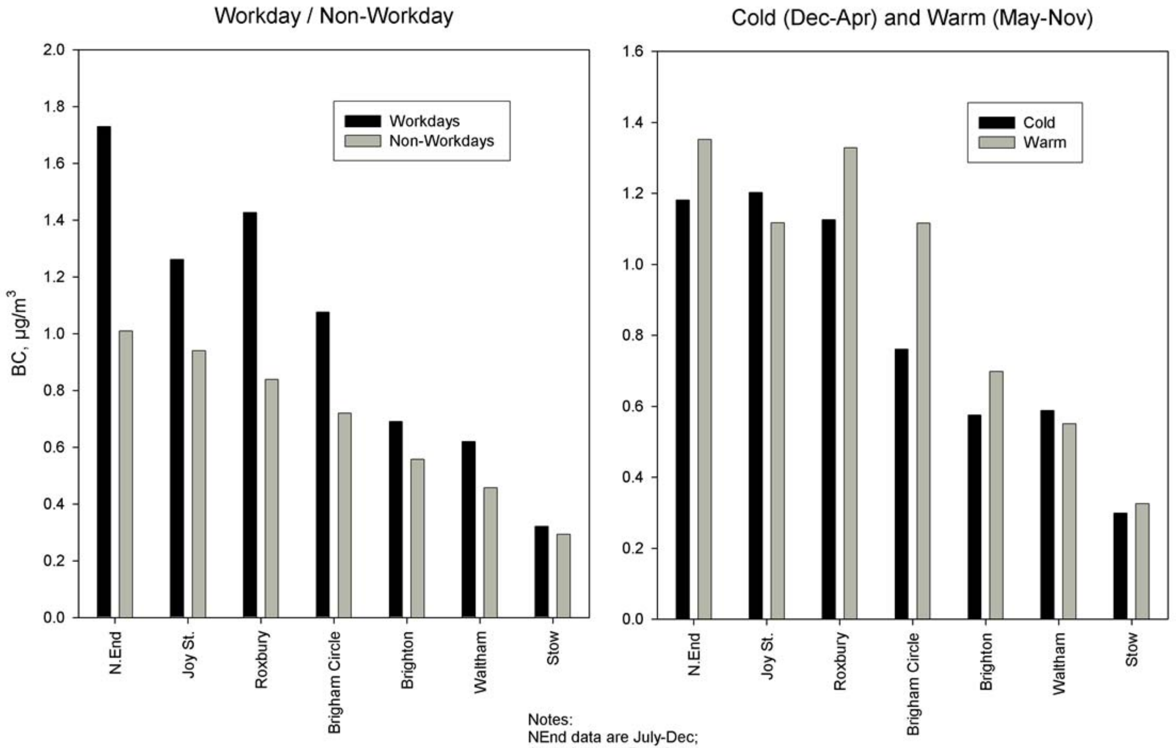


Figure 3-3a shows the average BC for these seven sites on work- and non-workdays. The relative difference decreased as the sites become less urban, with minimal difference for the Stow background site. Figure 3-3b shows the average BC for cold (i.e., December-April) and warm (i.e., May-November) months. There was no clear seasonal pattern. Joy St. was slightly higher than the other urban sites during the winter.

Figure 3-3a and 3-3b. BC for Work/Non-Workdays and Warm/Cold Season.



Notes:
NEnd data are July-Dec;
Stow data are Dec-Sept

The long-term trend data, which are discussed in Section 5, Temporal Trends, provide more detail than the simple warm versus cold-season mean BC shown above.

3.2. Twelve Site Summer Study.

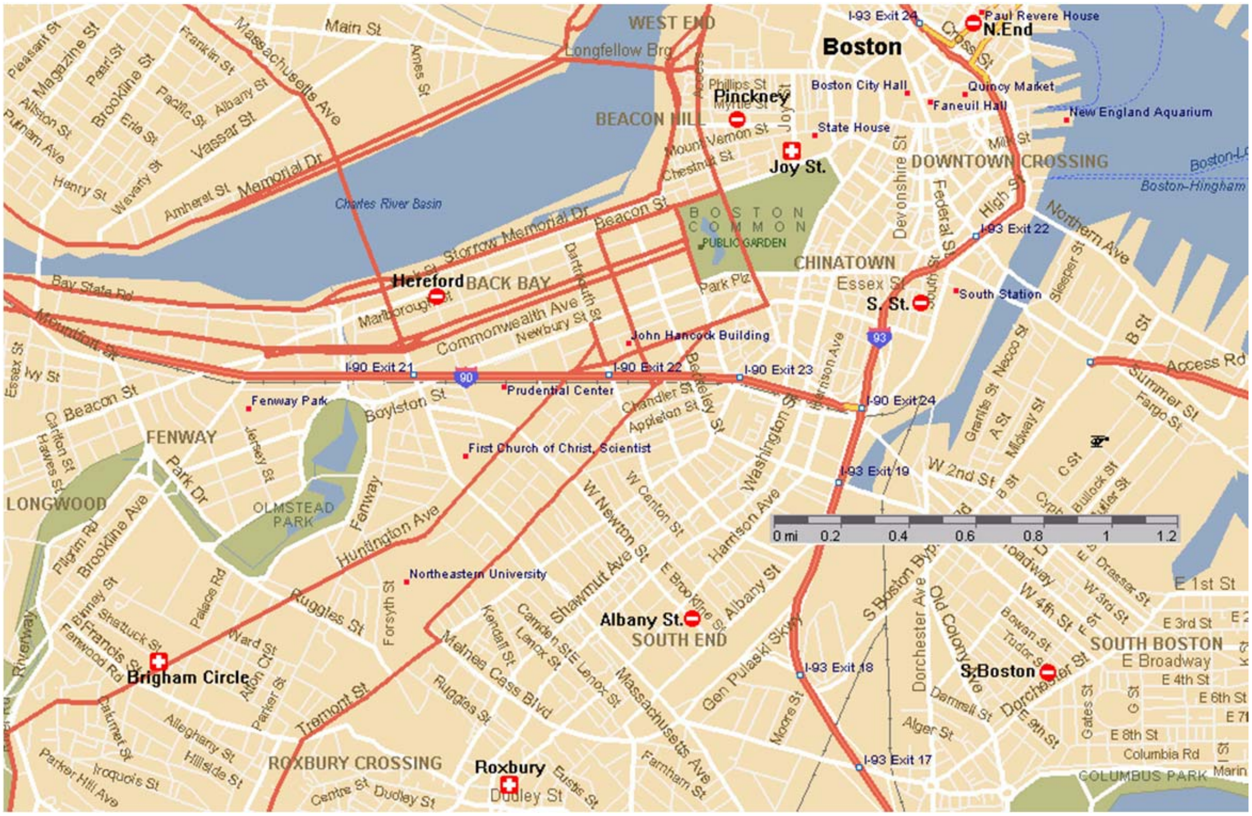
During the summer of 2003, a neighborhood scale study was conducted by NESCAUM in Boston for two months to explore gradients within the urban core. Ten of the twelve sites were in Boston, of which nine were within a radius of 2.5 km. Siting was representative of neighborhood scale (i.e., not hotspot/microscale) exposure. Table 3-2 shows the distances from the State House (Joy Street) for each site. Figure 3-4 shows the locations of the sites; those marked with a "+" are year-long, and "-" indicates summer spatial intensive sites.

Table 3-2. Description of 2003 Summer Intensive Sites.

Site Locations	Km	Site Description
Joy Street	0.0	Urban Residential/Commercial. (Beacon Hill, near State House)
Pinckney Street	0.3	Urban Residential (Beacon Hill)
North End	1.1	Urban Residential/Commercial (near the I-93 Expressway)
South Street	1.0	Urban Commercial (near South Station bus and train terminals)

Hereford Street	1.9	Urban Residential (Back Bay)
Albany Street	2.4	Urban Commercial (BU School of Public Health)
South Boston	2.9	Urban Residential
Roxbury	3.5	Urban Residential/Commercial
HSPH	4.0	Urban Residential/Commercial (urban scale)
Brighton	7.0	Semi-Urban Residential

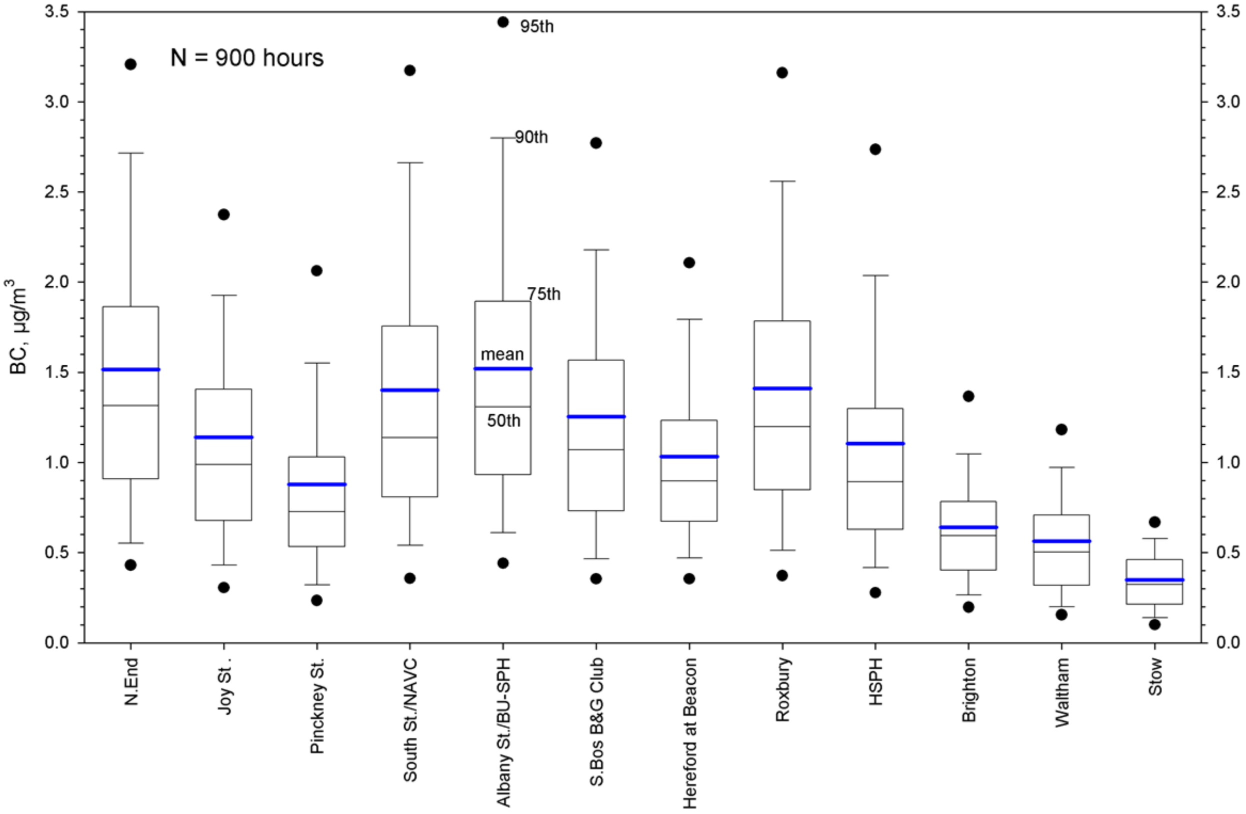
Figure 3-4. Map of 9 of the Boston Summer Intensive Sites.



Sites marked with a square "+" are year-long monitoring sites; those with a circle "-" symbol are sites that ran only during the summer intensive period. The Brighton (Boston) semi-urban site is not shown on this map.

Figure 3-5 shows the distributions for all 12 BC monitoring sites, limited to days where all sites had data. Approximately 20 days were excluded, because two sites had a 10-day period of missing data.

Figure 3-5. BC Distributions of all 12 Sites for 2003 Summer Intensive.



There were substantial gradients for mean BC at neighborhood scale-oriented sites in Boston. The observed variation across sites could be influenced by variability in monitor siting, mobile source strength gradients, and microscale meteorology. The North End and Albany Street sites had the highest gradients, with Roxbury and South Street (near South Station) just slightly lower. The highest and lowest sites, North End and Pinckney Street, respectively, are 1.3 km (0.8 miles) apart, with a ratio of 1.7. The Hereford Street site was relatively low, as it is near both Storrow Drive, where truck traffic is prohibited, and the Charles River.

3.2.1. Population Density and BC

The association between population density and mean BC was explored for the year-long study and the summer intensive study of core Boston sites. Population estimates were generated using LandView5 software, a database application created by the U.S. EPA, Census Bureau, Geological Survey, and NOAA. LandView's population estimator function uses block data from the 2000 U.S. Census, and can generate demographic information for circular areas using block centroids whose coordinates fall within a prescribed radius. Geographic coordinates for the nine Aethalometer monitoring sites were used as center points to estimate population density.

Figures 3-6 and 3-7 show regressions of BC versus population density (1-mile radius) for these two cases. The year-long study showed that BC decreased with population density (Figure 3-6), but the regression was not significant (p = 0.07). Removing the Brighton site increased the adjusted R^2 to 0.68 (p = 0.03). Brighton may have a high amount of student and multifamily housing relative to the other sites.

The summer 10 urban-site regression shown in Figure 3-7 had the opposite slope from the year-long sites, with $R^2 = 0.68$ ($p = 0.003$). This could be explained by core commercial and transit corridor areas such as the South St. site near South Station having lower population density but high traffic activity.

Figure 3-6. Regression of BC on Population Density for Year-Long.

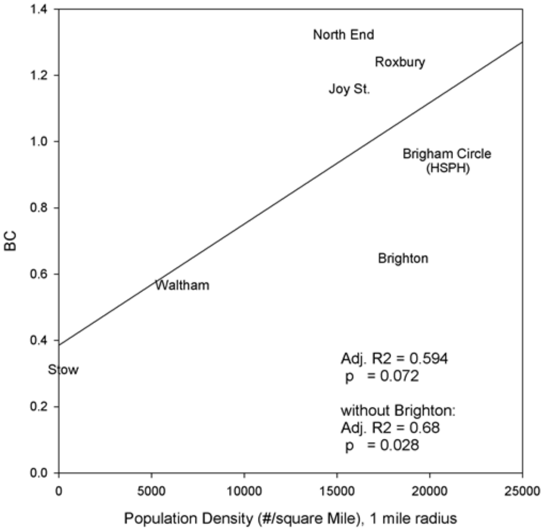
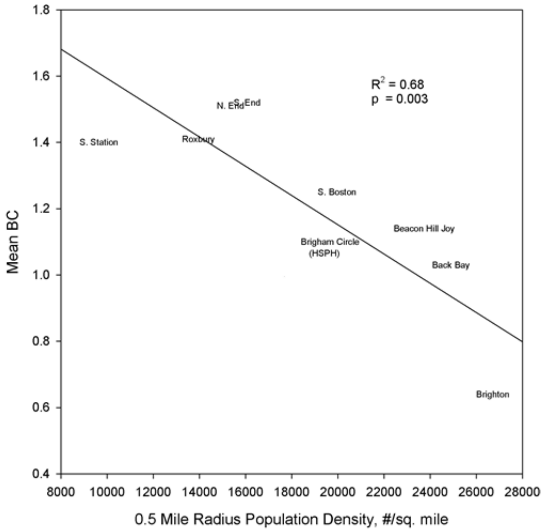


Figure 3-7. Regression of BC on Population Density for Summer Intensive.



3.2.2. Two Time-Series Case Study Examples.

Two time series plots, Figures 3-8 and 3-9, show examples of short term patterns and gradients of hourly BC across the Boston area. Both showed a distinct "clean Sunday and dirty work-day" effect. Figure 3-8 presents data for the nine core Boston sites and the Stow background site during July 13-15, 2003. Tuesday, July 15, 2003 was one of the dirtier days of the summer, with several sites exceeding 4 $\mu g/m^3$ BC for several morning hours. The ratio of the Boston to the background sites for this peak period was approximately 10, which is similar to that observed during events from the 2003 winter pilot project.

Figure 3-9 presents data for all 12 sites during the period August 6 through 11, 2003. Thursday, August 7 showed a distinct evening rush-hour peak, which is not a common feature. The very high peak in South Boston on Friday, August 8 at 7 a.m. EST was substantially higher than the other sites, although the other urban sites peak at the same hour. The South Boston site may have been influenced by local marine diesel sources, as major Boston Harbor piers are about one mile away to the north-northeast. Winds at Logan Airport were north-northeast to northeast at a few miles per hour during this time. The peak hour was influenced by two contiguous very high 5-minute BC values (22 and 13 $\mu g/m^3$, not shown). Without those values, the mean for this hour would have been 6 $\mu g/m^3$, which is more consistent with the other sites.

Figure 3-8. July 13-15, 2003 Time-Series.

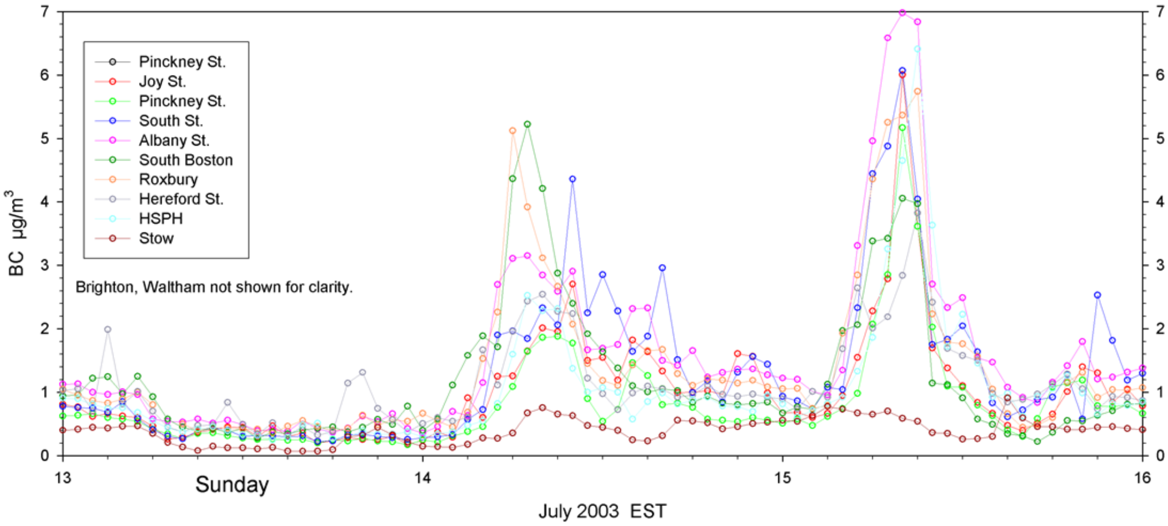
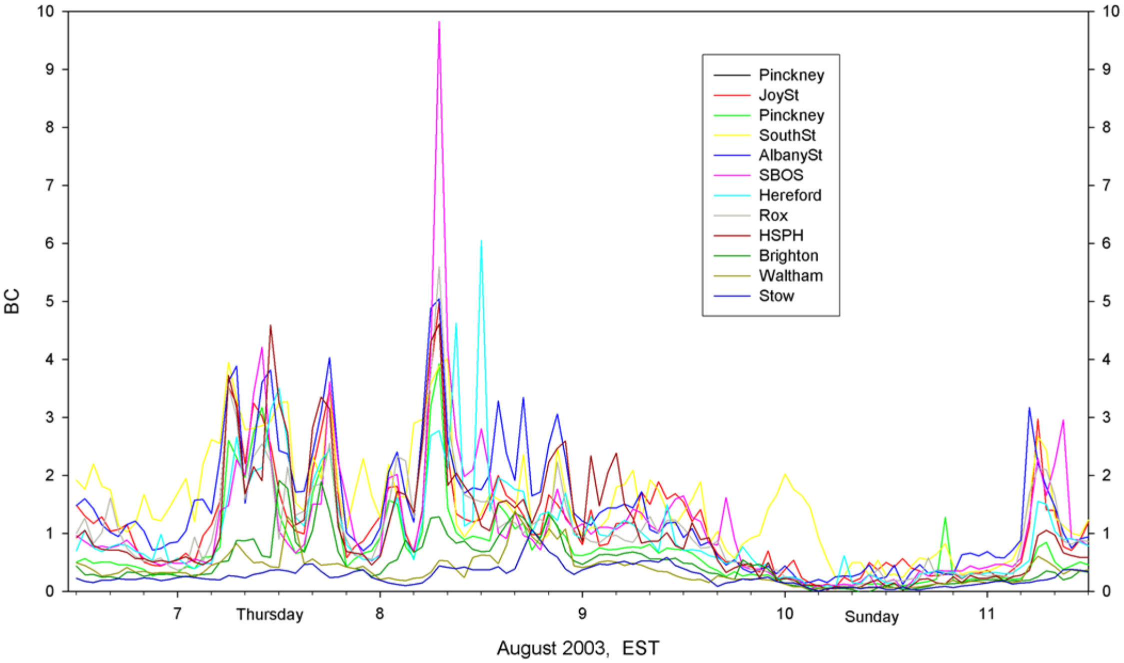


Figure 3-9. August 6-11, 2003 Times-Series.



August 6-11 case study: hourly scatter plots and correlation matrix

Scatter plots for hourly BC for six site-pairs presented in Figure 3-10, and R^2 values for all site pairs during the August 6-day period shown in Table 3-3, are examples of the short-term (hourly) relationships across different spatial scales. There was a wide range of correlation from high ($R^2 = 0.85$ for the two Beacon Hill sites) to very low (0.07 for Stow and South Street). All regressions are significant at $p = 0.05$.

Distance between sites was not always a good predictor of how well they were correlated. Joy Street and Roxbury, 3.5 km apart, had an R^2 of 0.79. The R^2 for Hereford and South Streets, 2.4 km apart, was 0.29 for the same time period. Some sites, such as South and Hereford Streets, were not well correlated with other urban sites. Others, such as Roxbury, Joy Street, and Albany Street, seemed to be reasonably well correlated with most urban sites.

The scatter plots show interesting patterns for some of the site-pairs. The two downtown Boston sites with the lowest mean BC, Hereford and Pinckney Streets, were well correlated when levels were below about 1 µg/m^3 BC. When levels were high at either site, however, they tended to be temporally decoupled. The South Boston and South Street sites were clearly influenced by different sources. North End and Stow, the highest and lowest sites in the study, were largely decoupled at this time scale. Note that the scatter plot axes are not scaled the same, and the bottom line is the 1:1 line. As would be expected, essentially all hours at North End were at or above the Stow BC levels.

Figure 3-10. Scatterplot for Hourly BC for Six Site-pairs During August 2003 Event Period.

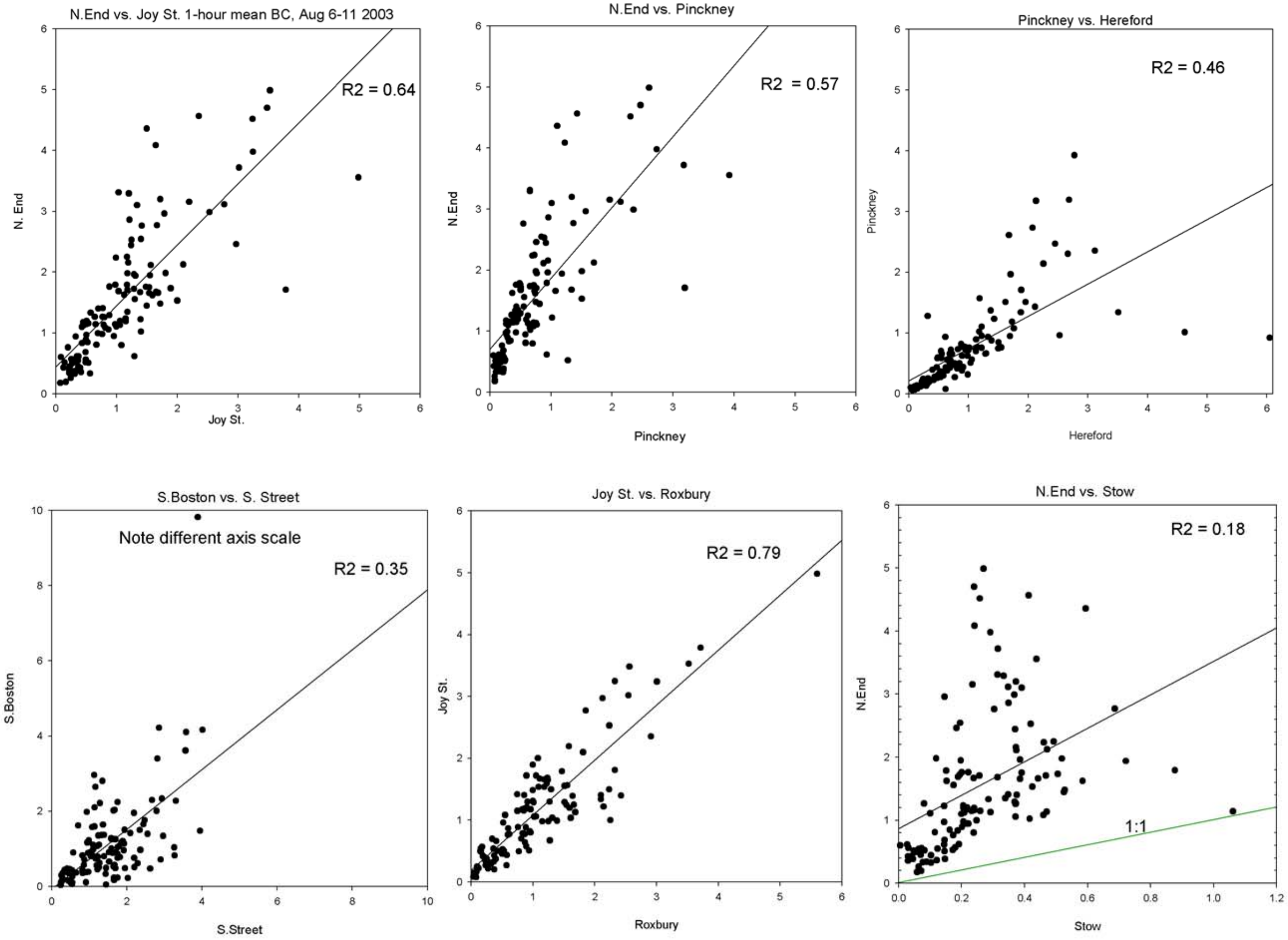


Table 3-3. One-Hour R^2 Matrix, August 6-11, 2003

(R^2 0.70 or higher R^2 0.50 to 0.69)

	North End	Joy St.	Pinckney St.	South St.	Albany St.	South Boston	Hereford St.	Roxbury	HSPH-Brigham Circle	Brighton	Waltham	Stow
North End	X	0.64	0.57	0.53	0.58	0.43	0.46	0.59	0.54	0.44	0.33	0.18
Joy	0.64	x	0.85	0.59	0.77	0.66	0.43	0.79	0.67	0.41	0.21	0.14
Pinckney	0.57	0.85	X	0.54	0.77	0.63	0.46	0.73	0.73	0.46	0.19	0.13
South St.	0.53	0.59	0.54	x	0.57	0.35	0.29	0.57	0.52	0.34	0.20	0.07
Albany	0.58	0.77	0.77	0.57	x	0.53	0.49	0.77	0.76	0.55	0.36	0.19
S. Boston	0.43	0.66	0.63	0.35	0.53	x	0.30	0.57	0.44	0.24	0.09	0.10
Hereford	0.46	0.43	0.46	0.29	0.49	0.30	x	0.45	0.52	0.48	0.33	0.18
Roxbury	0.59	0.79	0.73	0.57	0.77	0.57	0.45	x	0.69	0.40	0.23	0.12
Brig. Cir.	0.54	0.67	0.73	0.52	0.76	0.44	0.52	0.69	x	0.62	0.29	0.21
Brighton	0.44	0.41	0.46	0.34	0.55	0.24	0.48	0.40	0.62	x	0.51	0.39
Waltham	0.33	0.21	0.19	0.20	0.36	0.09	0.33	0.23	0.29	0.51	x	0.45
Stow	0.18	0.14	0.13	0.07	0.19	0.10	0.18	0.12	0.21	0.39	0.45	x

4. UPDATED BC SPATIAL ANALYSIS, 2009-2012

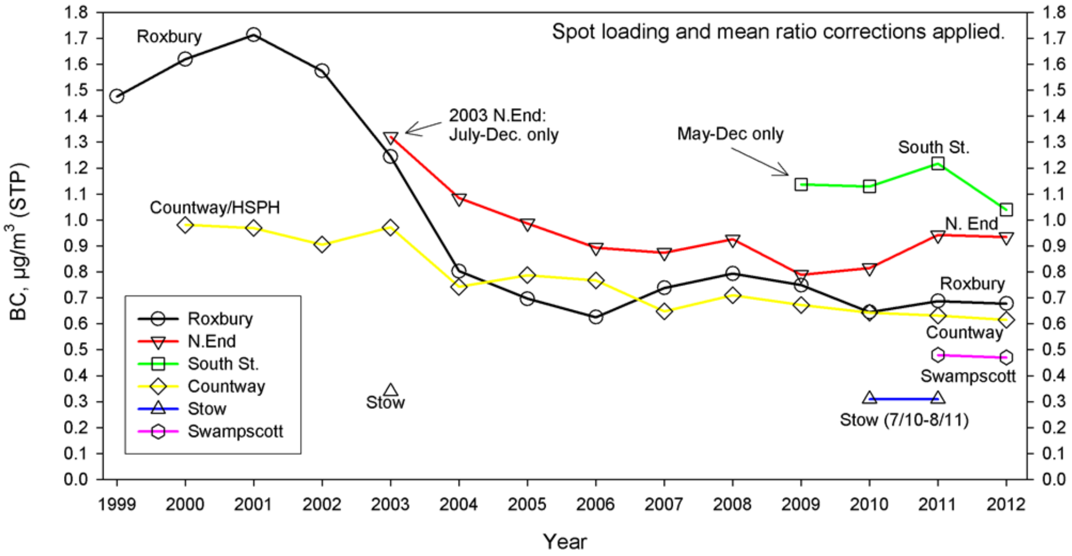
In retrospect, the 2003 spatial study was conducted during a year when substantial reductions in heavy-duty diesel PM emissions were occurring from changes to both the Boston public transit system (MBTA) and the Boston school bus fleets. The changes in BC concentrations and details on the bus fleet cleanups that continued through spring 2005 are discussed in Section 5, Temporal Trends.

Because these changes may have affected spatial patterns of BC in Boston, additional BC monitoring sites were set up and run for this project by NESCAUM between 2009 and 2012. This was done in order to provide a limited assessment of the more recent spatial scale of Boston BC. The Stow regional background site was run for two years (July 2009 through August 2011), a permanent site at NESCAUM's South Street offices started in May 2009, and a BC monitor ran in Swampscott (21 km northeast of Boston) from 2011 through 2012. The existing long-term Boston BC sites at North End, Roxbury, and HSPH were also included in this analysis.

4.1. Trends.

Figure 4-1 shows the trend for the four Boston BC sites, along with means for the Stow and Swampscott sites. BC at the Stow regional background site dropped from 0.34 to 0.31 μg/m^3 over seven to eight years. This is consistent with reduced heavy-duty diesel PM emissions on a regional basis. The Swampscott site's BC concentrations were lower than the Boston and higher than the Stow sites. That Swampscott is downwind of Boston and Stow is upwind may explain the relative BC concentrations at these two non-urban sites.

Figure 4-1. Trend for four Boston BC Sites, Stow, and Swampscott.



In 2010, the ratio of North End to Stow mean BC was 2.6. When comparing Stow with the 2011 North End BC data, the ratio increases to 3.0. This is similar to the ratio observed in 2003.

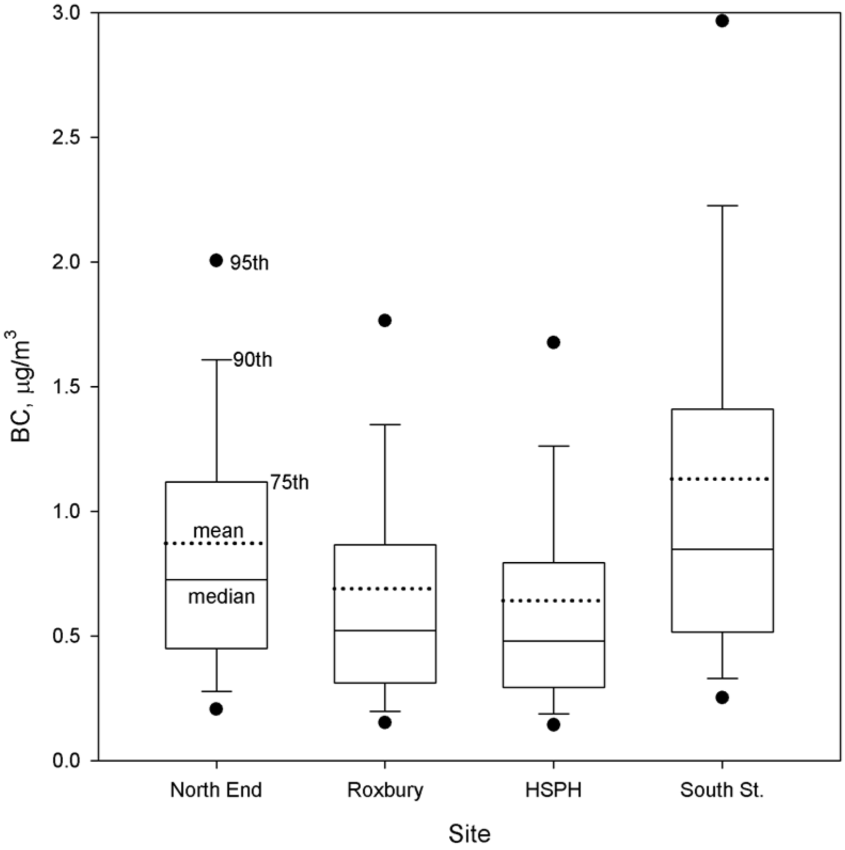
The ratio of the 2010 mean BC between the South St. and Stow sites was 3.6, compared to 3.9 using 2011 data. These comparisons suggest that the gradient from urban to upwind has not changed much over the last seven to eight years.

4.2. Sources of BC at the South St. Site.

The South Street site measured the highest levels of all Boston BC sites between 2009 – 2012, at 1.13 µg/m^3 (Figure 4-1). Means for other Boston BC sites ranged from 0.64 at HSPH to 0.87 µg/m^3 at North End), while the Springfield site's mean was also 0.87 µg/m^3. South Station, a major transportation hub for rail and inter-city buses, is located 300 meters to the southeast of the South St. monitoring location. Pollutant wind rose analysis suggests that the station's bus and train activity is not a major factor in the elevated BC levels, as the wind was not usually from that direction.

Distributions of hourly BC for the four Boston sites from 2009-2012 are shown in Figure 4-2. Roxbury and HSPH distributions are similar, with the North End site somewhat higher. South Street is distinctly higher, with the 95th percentile at 3.0 µg/m^3. This is not driven by the Saturday diesel genset test events, because the one-hour per week was only 0.6% of hours.

Figure 4-2. Distribution of 1-hour BC at Four Boston Sites, 2009-2012.



Additional information on sources of BC in downtown Boston is available from source apportionment analysis done for the North End site (Turner, 2008; *see* Appendix G). Although the BC was primarily from mobile sources, a significant amount was from biomass combustion, e.g., woodsmoke from space heating or recreational use.

Figures 4-3 and 4-4 show South Street pollutant roses using wind data from the MassDEP Roxbury site 3.3 km to the southwest. Figure 4-3 shows BC up to 4 µg/m^3, which is more than 95% of hours during this period. Note that hours with wind from south to southeast were not common nor associated with these levels of BC relative to other directions.

Figure 4-4 shows BC data for hours greater than 3 µg/m^3, including one-hour values up to 19 µg/m^3. Winds for hours with BC between 3 and 5 µg/m^3 were predominately from the southwest to east. These plots suggest that the elevated BC at this site was from many local sources, indicative of an active area of downtown Boston with respect to heavy-duty diesel vehicles.

Figure 4-3. NESCAUM South St. BC Pollutant Rose, less than 4 µg/m^3.

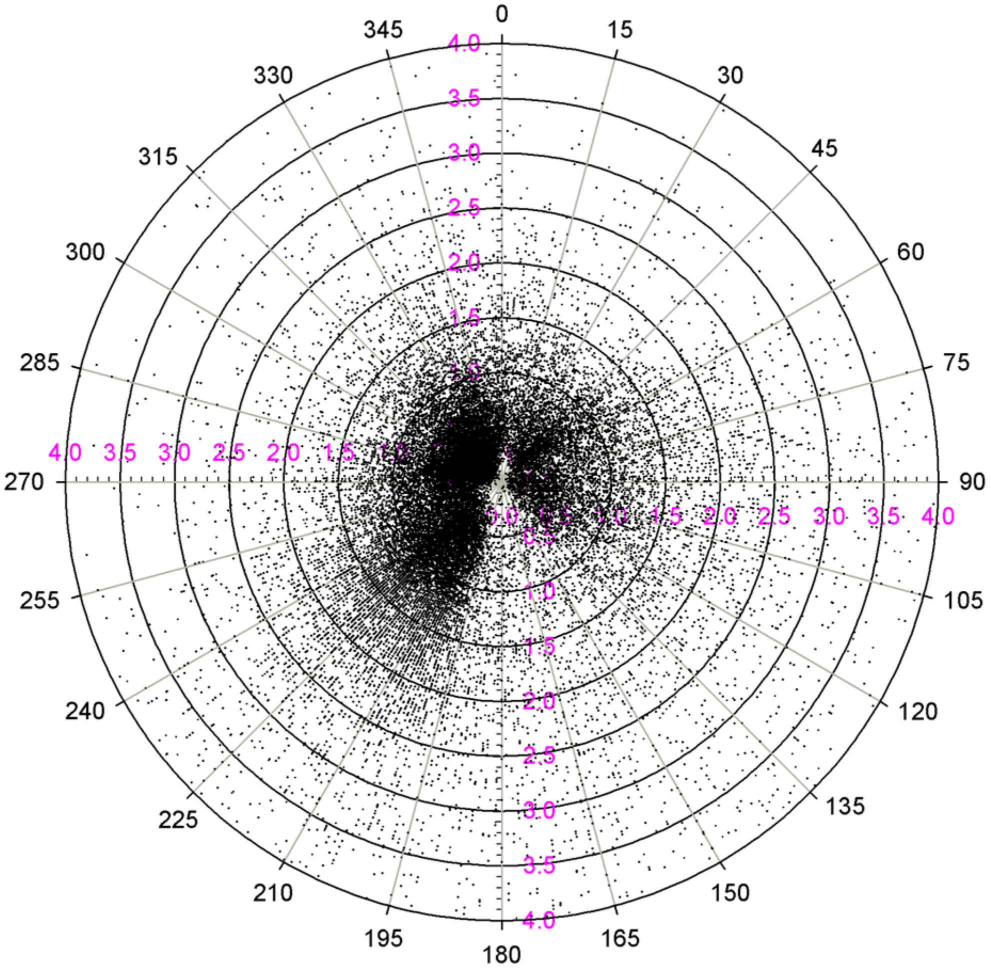


Figure 4-4. NESCAUM South St. BC Pollutant Rose, greater than 3 µg/m^3.

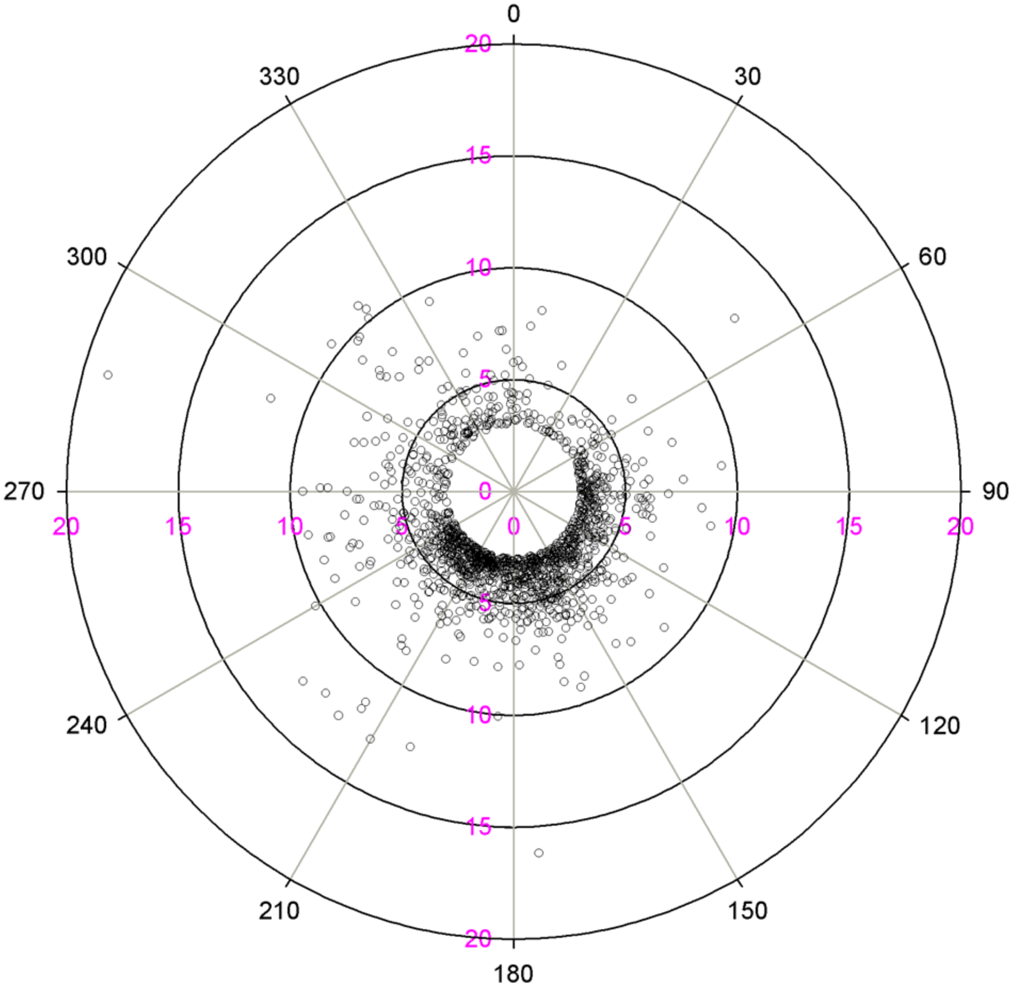
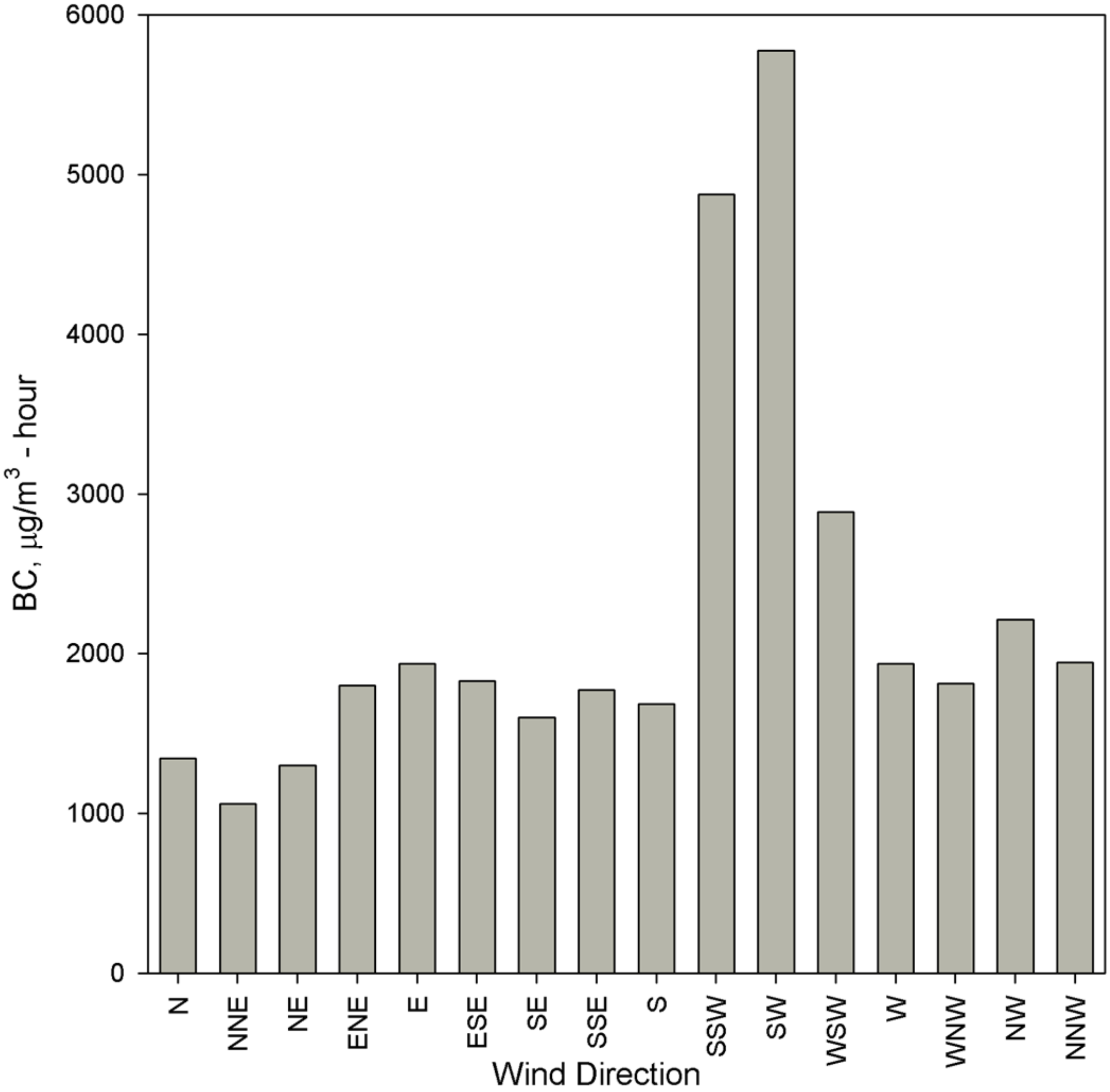


Figure 4-6 shows BC concentration times the number of hours, binned by wind direction using Roxbury wind data. This approach is an exposure metric, taking into account both the average concentration from each direction and the number of hours in each wind direction bin. It is very clear that winds from the south-southwest and southwest account for more BC than any other direction, and winds from South Station (southeast) contribute a relatively small amount of BC measured at this site. This is in part due to prevailing winds being from the south to south-west. The map in Figure 3-4 shows that the Massachusetts Turnpike (I-90), the Southeast Expressway (I-93), and the large interchange between the two are all to the south-southwest and southwest of the South Street site within approximately 650 meters. The large amount of traffic activity from this area and the first km of the I-93 Expressway above ground to the south-southwest are likely reasons for the high mobile source-related BC observed at this site. Figure 4-5 more clearly shows this section of the Expressway, the prevailing wind direction (black line), and the NESCAUM South St. site location.

Figure 4-5. Prevailing wind direction alignment with Expressway and the NESCAUM

South St. BC monitoring site (red dot).

Figure 4-6. South St. BC times Hour by Roxbury Wind Direction.



The 2003 study's South Street site, located at the rear of 112 South Street, is 65 meters from the current South Street Site (at 89 South Street). These two sites are close enough to be compared over time. Figure 4-7 shows the summer spatial intensive BC distribution for the 2003 site along with the 2009-2012 BC data from the NESCAUM South Street site matched for the same days of the year. Except for 2011, BC data distributions were very similar to the 2003 data. The contemporary South St. data include the influence from a local source (a diesel genset weekly test) that produced very high BC once a week for approximately 15-20 minutes. Figure 4-8 shows one-minute data from such an event on October 22, 2011 when the peak 1-min BC concentration measured 100 μg/m^3. The rapid fluctuations in concentration at this time-scale are indicative of a source that is very close (within ~ 50 meters or less).

Figure 4-7. Summer BC Distribution for South Street.

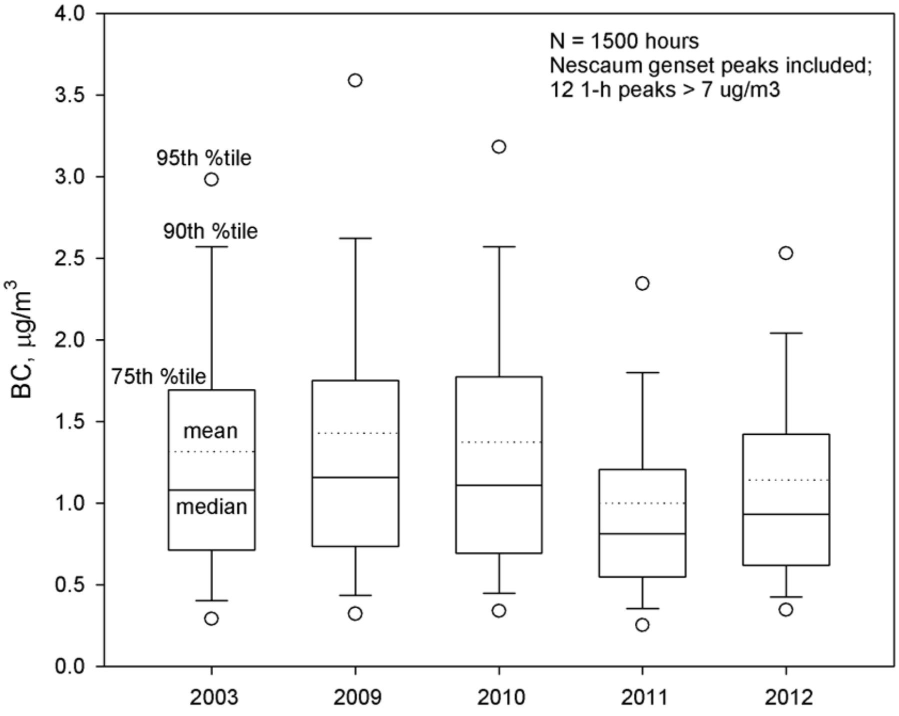
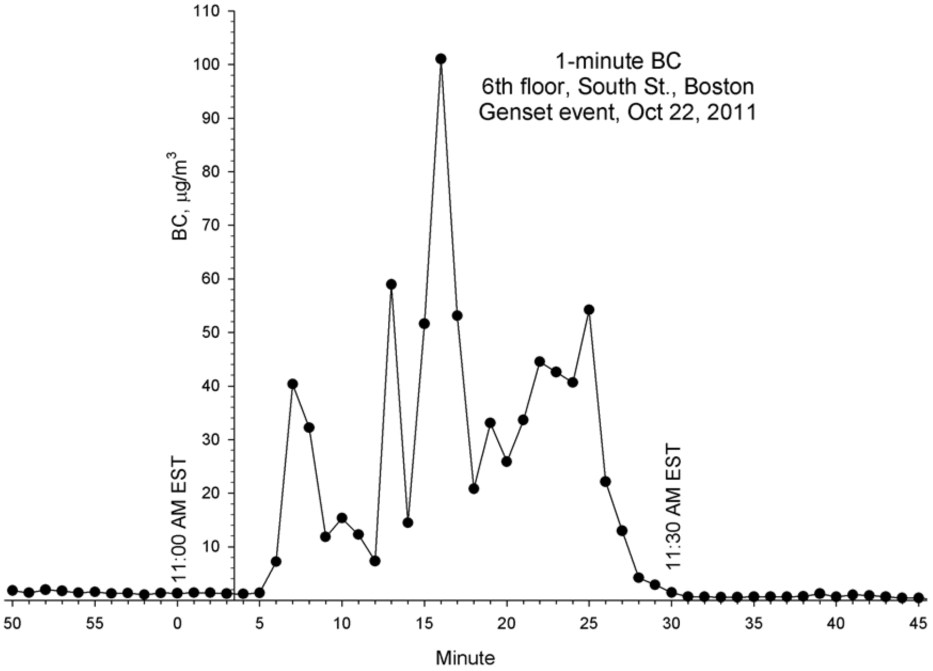


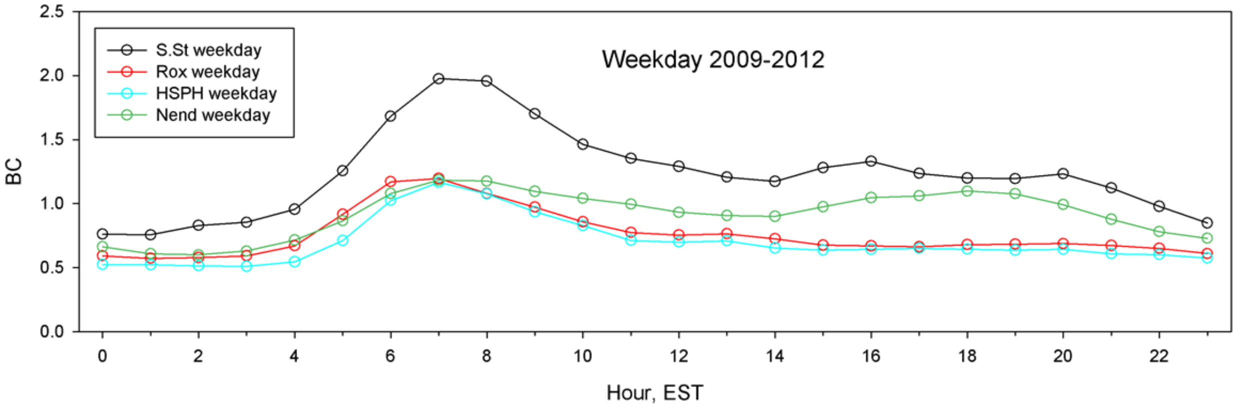
Figure 4-8. October 22, 2011 Diesel Genset Event.

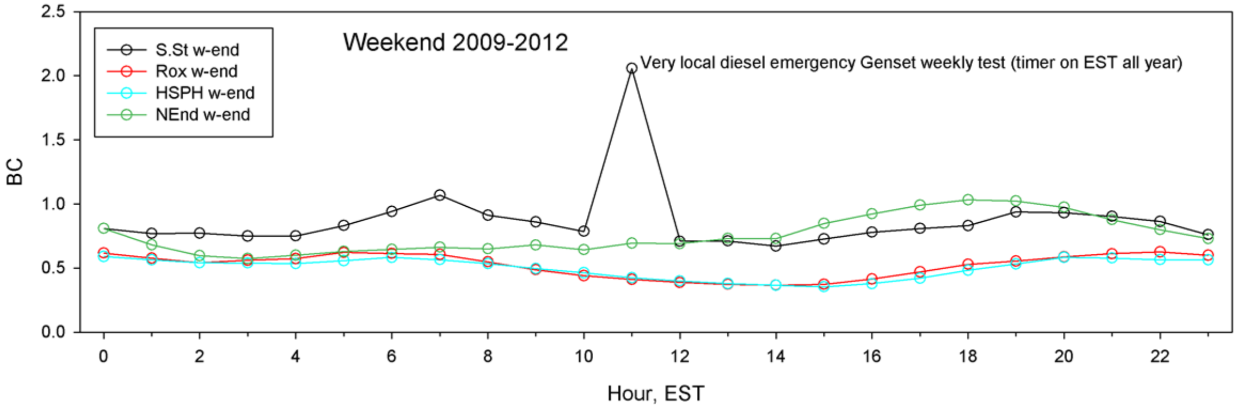


4.3. Diurnal plots for 2009-2012, four Boston sites.

The weekday and weekend diurnal BC plots were updated for data from 2009 through 2012 for three of the Boston sites used in 2003. The South Street site data were also added. These are presented in Figure 4-9. While the general patterns were unchanged relative to 2003, the Roxbury site behaved more like the HSPH site, with a smoother and less pronounced morning rush-hour peak characteristic of an urban-scale site. The South Street site measured highest concentrations for all hours, during weekdays and weekends. The North End site was measuring higher BC concentrations than the Roxbury or HSPH sites for most hours of the day. As with the 2003 diurnal plots, there was a clear morning rush hour peak on weekdays and no peak on weekends, with the exception of the South Street site. That site also showed the effect of a weekly test of the emergency diesel genset on Saturday at 11 a.m. EST.[6]

Figure 4-9. Four-Site 2009-2012 Updated Diurnal Plots.





4.4. Additional HSPH Monitoring Near Street Level.

Limited additional monitoring was performed near the HSPH Countway Library roof site to assess the effect of elevation on BC concentrations from that site (approximately 26 meters above ground level). From January 6 to May 30, 2010, BC was measured at 635 Huntington Avenue, from the second floor of an office building. This monitor was located on the same block as the HSPH Huntington Avenue site, but closer to Longwood Avenue. Figure 4-10 shows the sample location, which was outside of the second floor window on the left.

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[6] The genset timer is on EST year round, resulting in only hour 11 EST being elevated instead of hours 11 and 12.

Figure 4-10. Location of Street Level HSPH Sampler.

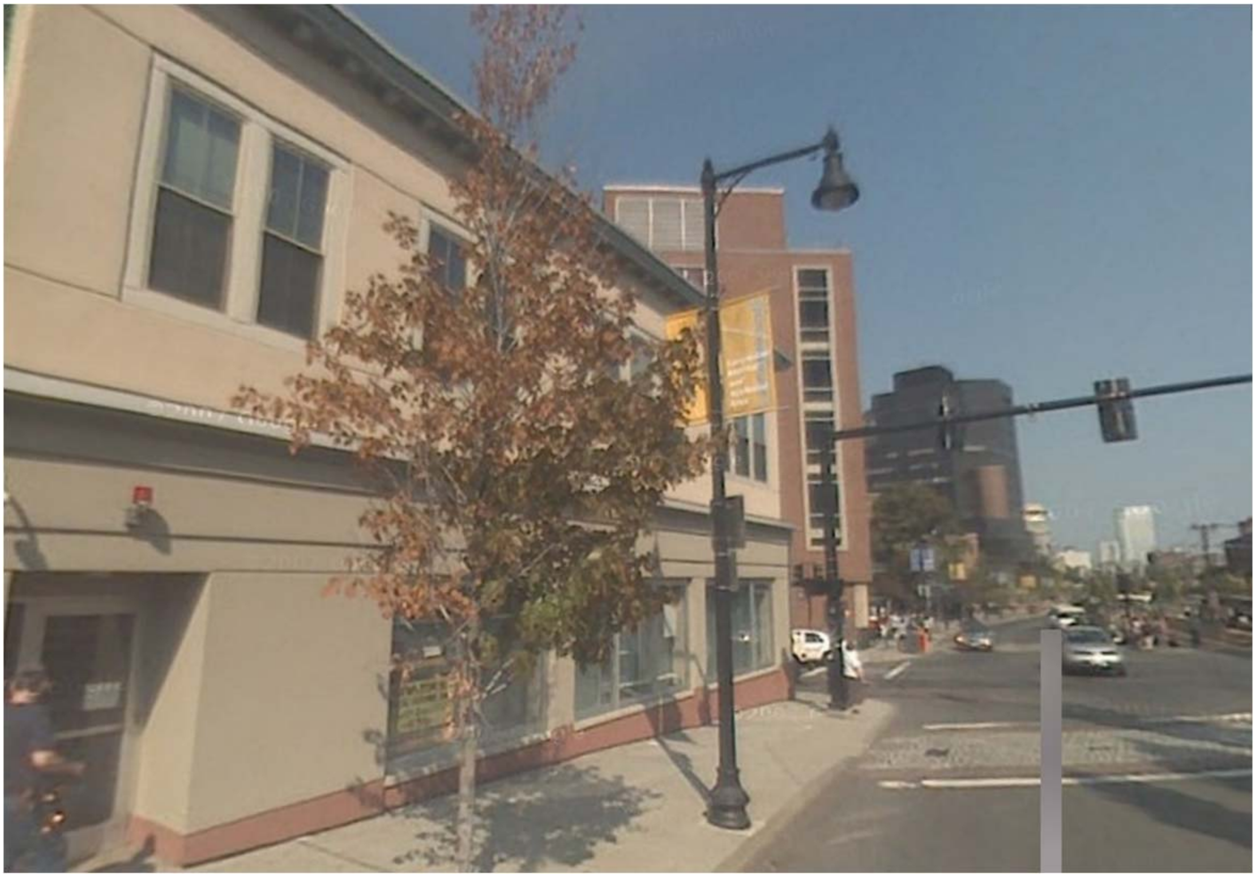
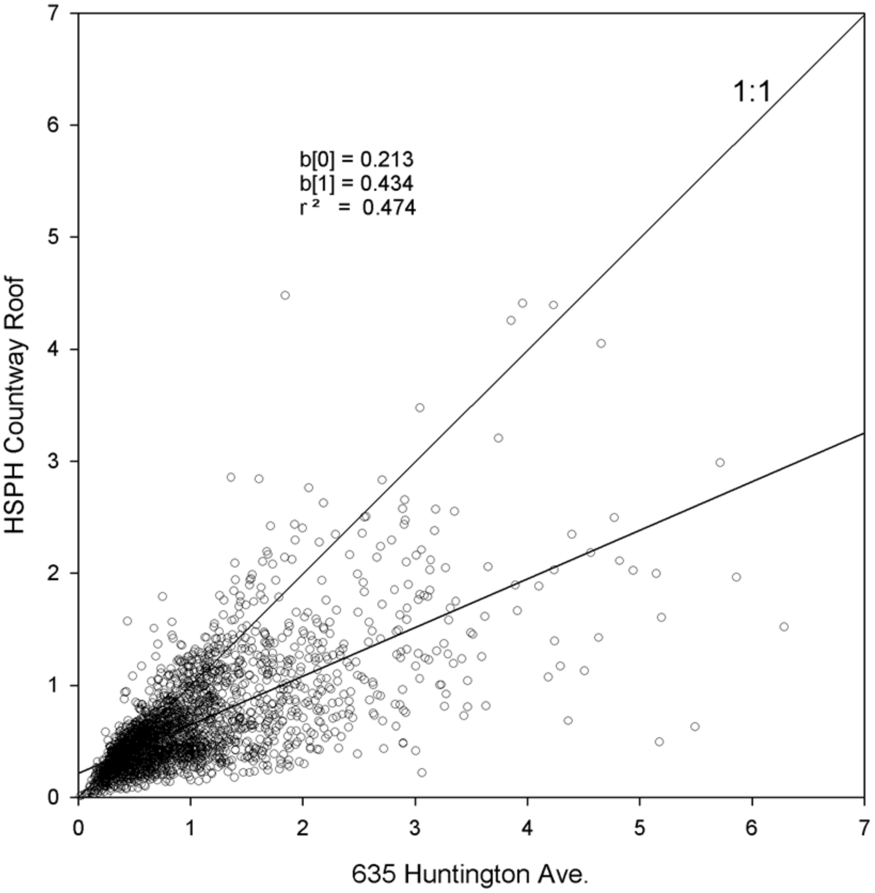


Figure 4-11 shows the relationship of hourly BC between the HSPH and the 635 Huntington Avenue sites. Mean BC was 0.85 µg/m^3 for the street-level site and 0.69 µg/m^3 for the HSPH site, a ratio of 1.23. The hourly R^2 was 0.47. As expected, BC at the street-level site was generally but not always higher than the HSPH site.

Figure 4-11. HSPH Roof vs. Street Hourly BC.



5. TEMPORAL TRENDS OF BOSTON BC

There are four Boston sites with multiple years of BC data. BC trends have both a strong seasonal pattern but a weak long-term trend at most sites.

5.1. Seasonal Patterns of BC.

There was a strong seasonal pattern for monthly mean BC for the urban sites. BC was distinctly lowest in the late winter or early spring, and highest in the summer for all long-term sites except Springfield. This pattern is consistent with monthly wind speeds being lowest in summer and highest in the winter, as dispersion of local ground level pollutants is expected to be driven by wind speed. Figure 5-1 shows monthly mean BC for the four Boston sites (using all available years of data) with the inverse of monthly average wind speed. The patterns for wind speed and BC were stronger for some sites than others. Seasonal patterns for the South Street and the North End sites were strongest and very similar ($R^2 = 0.74$, $p < 0.001$), with a distinct summer peak. These sites have a substantial influence from local traffic and the highest mean BC. Figure 5-2 shows good correlation between the Roxbury and HSPH sites ($R^2 = 0.85$, $p < 0.001$). These sites have a weaker summer peak, consistent with their more urban scale siting. Nine months of the year have a similar pattern, but May, June, and October were different, for unknown reasons. South Street and HSPH are poorly correlated due to the different scales of influence for these sites ($R^2 = 0.21$, $p = 0.14$). For the same reason, Roxbury and South Street are also poorly correlated ($R^2 = 0.14$, $p = 0.12$)

Springfield showed a very different seasonal pattern than the Boston sites, perhaps due to the valley topography. Figure 5-3 shows a late winter minimum and then an increase in BC through November with no clear summer peak. All sites had a peak in November that is not readily explained.

Figure 5-1. Monthly Mean BC for Four Sites with Inverse Wind Speed.

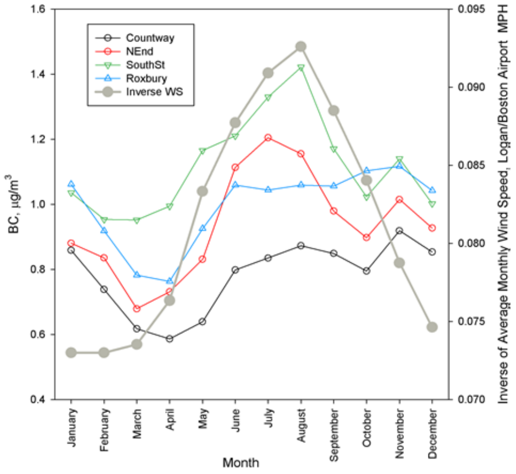


Figure 5-2. Correlation of Monthly Mean BC for HSPH and Roxbury.

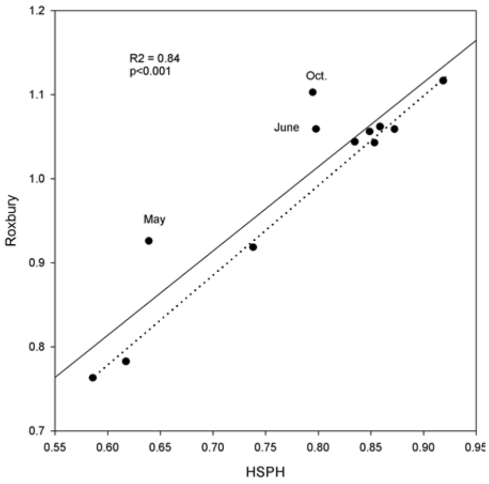
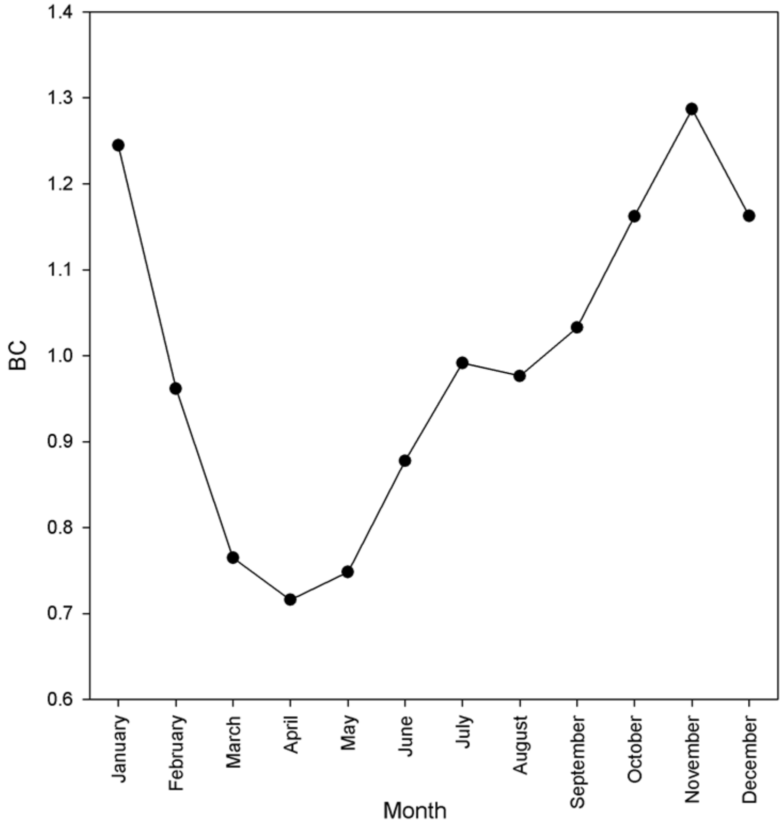


Figure 5-3. Monthly Mean BC for Springfield, 2006-2012.



5.2. Trends of Annual Mean BC.

Figure 5-4 shows the annual mean BC trend data from 1999 to 2012 for the four Boston sites. The dates of MassDEP's heavy-duty diesel control programs and the timing of the MBTA and Boston school bus fleet clean-up are noted. There was a striking drop in Roxbury BC over a three-year period (2002-2004). This directly matched the progress of the MBTA bus fleet clean-up effort, which controlled PM emissions, for the first time, on 100% of the buses between late 2002 and the end of 2004 (Seidman, 2002). The percentage of buses without PM controls is shown on the right axis of Figure 5-4.[7] Note that because of strong seasonal BC patterns that differ across sites, BC trend analysis must be done on annual means.

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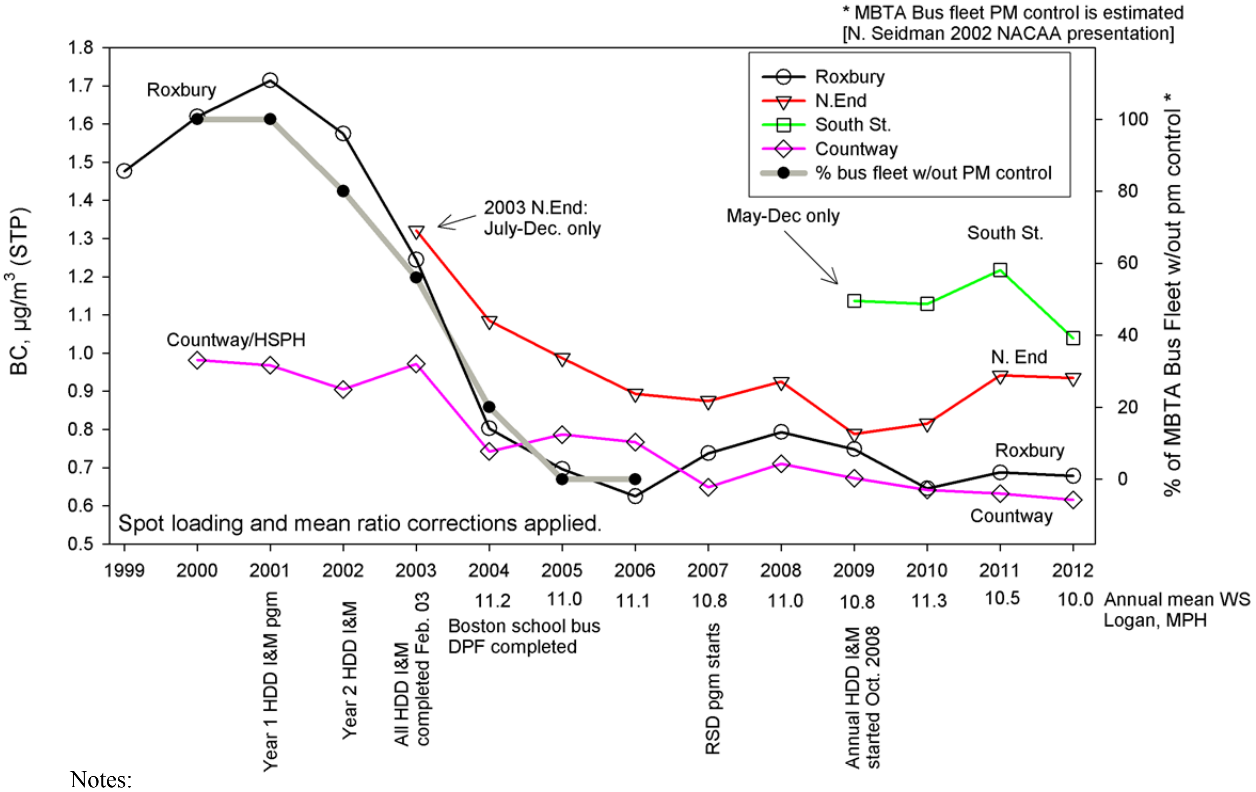
[7] Annual average wind speed from Logan Airport is shown in Figure 5-4 for 2004 and later, as higher wind speed tends to result in lower BC concentrations (due to improved dispersion) and may explain some of the year-to-year variation in mean BC at some sites. Appendix H shows the seasonal and year-to-year variation in wind roses from Logan Airport for 2000-2012.

Figure 5-4. Four Site Boston Trend.



Notes:
"HDD I&M" is the MassDEP heavy duty diesel inspection and maintenance program.
"DPF" is diesel particulate filter
"RSD program" is the MBTA's bus garage Remote Sensing Device program for bus emissions.
"Spot loading and mean ratio corrections" are measurement method artifacts that varied over time and could affect trend analysis if not controlled for.

The MBTA bus fleet clean-up effort is best explained in the following summary, by Nancy Seidman of MassDEP. This is from the National Association of Clean Air Agency's (NACAA) summary of its fall 2002 meeting.[8]

> The Clean Bus Program sprung from 3 events: Governor William Weld's pledge in the mid-1990s that MBTA would not purchase any new diesel buses, Central Artery air quality mitigation commitments to purchase 200 additional and 200 replacement clean buses and a consent decree requiring that 200 additional buses use compressed natural gas (CNG) or, if diesel, be retrofitted. MBTA will have 358 CNG buses by early 2003; as of May 2002, all of its diesel buses use ultra-low-sulfur diesel fuel, and 400 of its buses are scheduled to be retrofitted with diesel particulate filters (DPFs) between now and 2004. All of the oldest (1989) buses will be retired as of December 31, 2004. As a result of these efforts, by 2004, PM emissions are expected to decrease almost 90 percent from 2000 levels.

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[8] NACAA, formerly the State and Territorial Air Pollution Program Administrators/Association of Local Air Pollution Control Officers (STAPPA/ALAPCO). Accessed May 21, 2013. http://www.4cleanair.org/Oldmembers/members/FallMembership02.pdf .

Another factor that likely contributed to this rapid drop in Boston BC was the retrofit of the entire Boston school bus fleet with DPFs between 2003 and 2005. This work was funded by two EPA Supplemental Environmental Projects,[9] and retrofitted the entire fleet of 600 Boston school buses with DPFs starting in 2003 and ending in the spring of 2005. The MBTA closed the Bartlett Street bus garage near Dudley Square at the end of 2003. This may also have been a factor in the reduction of Roxbury BC during this time period.

The "Big Dig" Central Artery downtown tunnel opening occurred during 2003 and thus is another factor to consider when evaluating BC trends. The Northbound lanes of the I-93 O'Neill tunnel (replacing the elevated downtown section of the Expressway) opened in March 2003, and southbound lanes opened in December 2003. Although overall downtown Boston mobile source emissions would not have been expected to change due to the new tunnels, the spatial patterns did, with tunnel exhaust vents at several points along the route. These changes could have affected BC at the North End site, but this is difficult to assess since that site did not start monitoring BC until July 1, 2003. Even after the December 2003 tunnel opening, substantial construction continued on the surface, including demolition of the elevated highway and construction of additional surface access roads in the North End. The opening of the Big Dig tunnels would not be expected to have any influence at the other two Boston BC sites (Roxbury and HSPH/Brigham Circle).

5.3. BC Trends after 2005.

The next step in the trend analysis was to evaluate changes after the large bus fleets were controlled for PM emissions. Starting in 2005 after heavy-duty diesel PM from the MBTA and Boston school bus fleets was controlled and the Bartlett Street Bus garage in Roxbury was closed, there was no clear trend in BC at the North End and Roxbury sites. The annual mean BC for 2005 and 2012 for these two sites was essentially identical: 0.70 and 0.68 $\mu g/m^3$ for Roxbury, and 0.99 and 0.94 $\mu g/m^3$ at the North End. Figures 5-5 and 5-6 show the regression of annual mean BC versus year at these two sites from 2005 through 2012. Although there was an indication of a very small downward trend over these years, the slopes of the regressions were not significant ($p = 0.65$ and 0.8 for North End and Roxbury respectively). The Roxbury BC trend from 2007 through 2012 (Figure 5-7) did have a downward trend, but the regression was still not significant ($p = 0.11$). When all Roxbury BC years are included (Figure 5-8), there was a very significant trend ($R^2 = 0.71$, $p < 0.001$) driven by the large difference in pre- and post-retrofit year BC concentrations.

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[9] United States Department of Justice. "U.S. Enforcement Case Brings Clean Air Benefits to Boston: $6 Million Settlement Includes Largest School Bus Pollution Control Project In Country." Last modified January 30, 2004. http://www.justice.gov/opa/pr/2004/January/04_enrd_058.htm.

Figure 5-5. Regression of Annual Mean BC vs. Year 2005-2012 for North End.

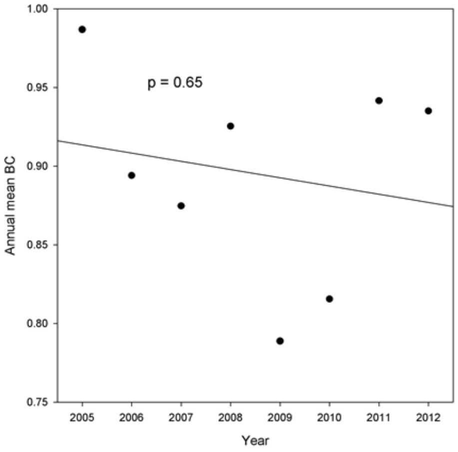


Figure 5-6. Regression of Annual Mean BC vs. Year 2005-2012 for Roxbury.

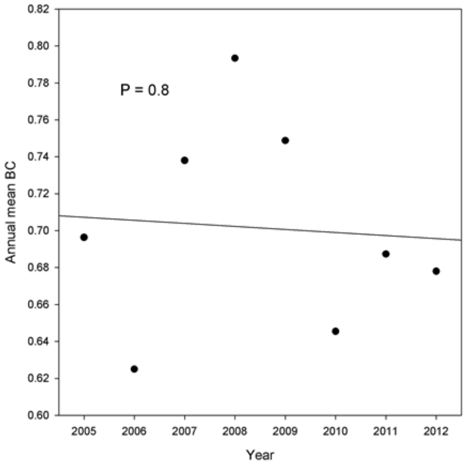


Figure 5-8. Roxbury BC Trend from 2007-2012.

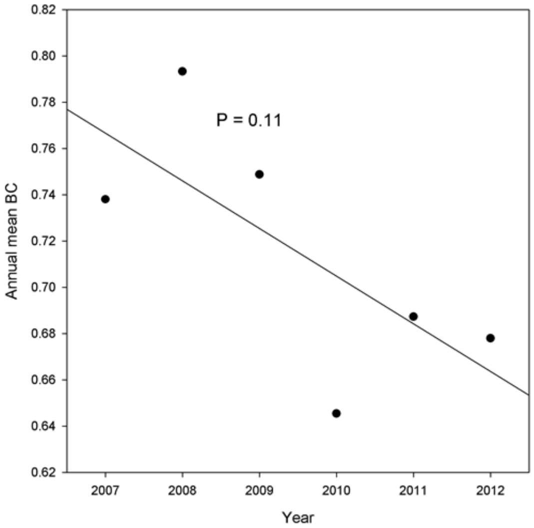
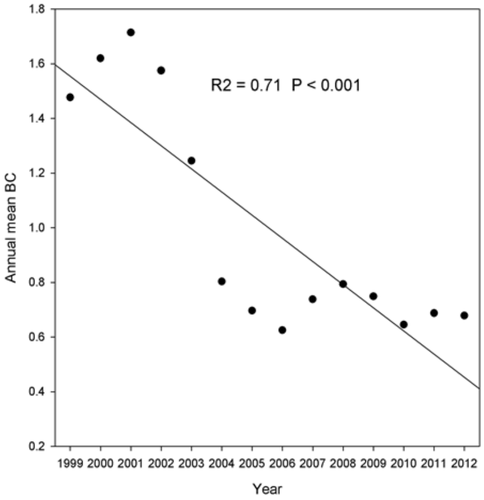


Figure 5-7. Roxbury BC Trend from all years.



The same trend analysis for the HSPH Brigham Circle BC data showed a robust downward trend over time for both all years and limited to 2005 to 2012. Figures 5-9 and 5-10 show the regression of BC versus year for 2000 to 2012 and restricted to 2005 to 2012. It is not clear why the HSPH site showed a trend for 2005 to 2012 and the Roxbury site did not. Both sites are urban scale over the 2005 to 2012 period and had similar mean BC, 0.70 μg/m^3 for Roxbury and 0.68 μg/m^3 for HSPH.

Figure 5-9. HSPH Trend 2000-2012.

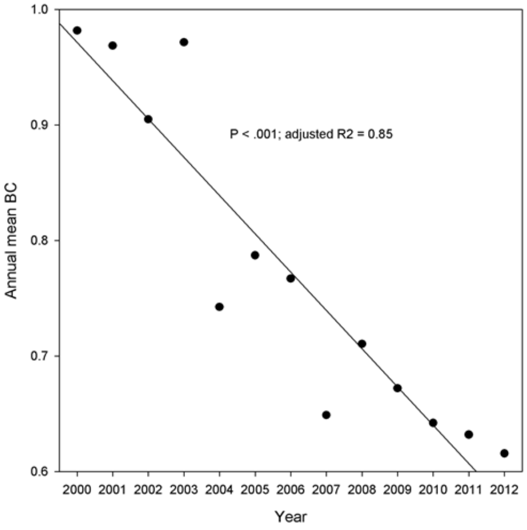
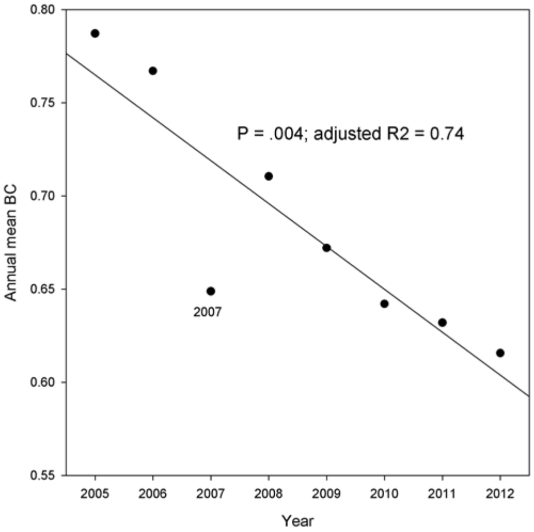
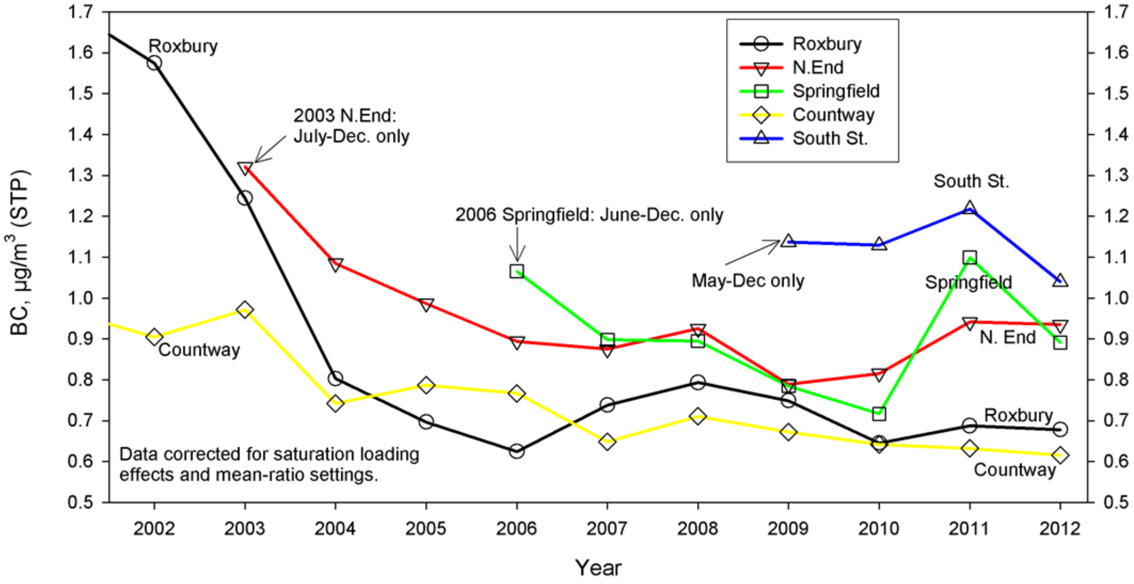


Figure 5-10. HSPH Trend 2005-2012.



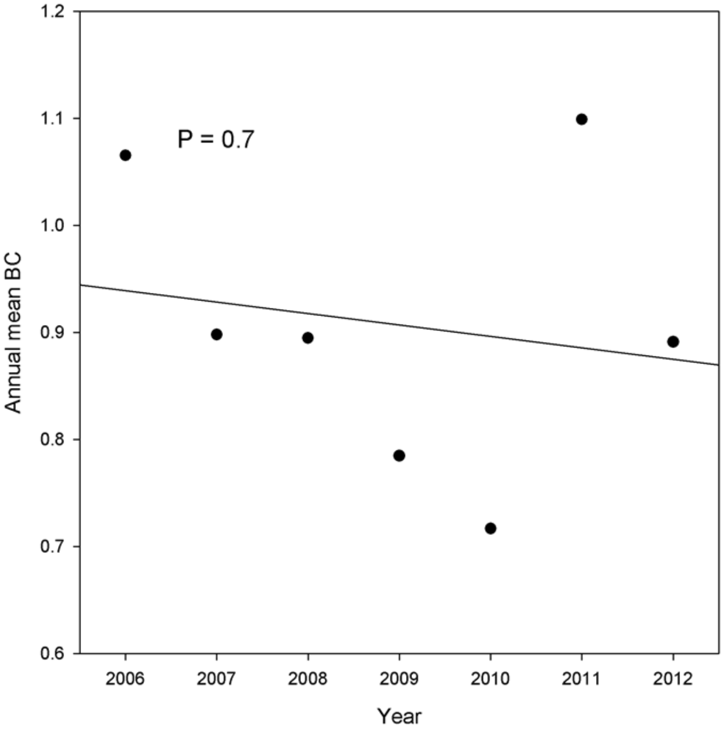
MassDEP started monitoring BC in Springfield in the middle of 2006. Figure 5-11 shows BC for the Springfield and the four Boston sites. While there was a slight downward BC trend in Springfield from 2006 to 2010, 2011 was slightly higher than the seven-month mean in 2006 (1.10 μg/m^3 for 2011, and 1.07 μg/m^3 for 2006). All BC sites, except the HSPH site, increased from 2010 to 2011, implying a weather-related factor. In 2012, BC levels at the South Street and Springfield sites dropped slightly, while levels in the North End did not change.

Figure 5-11. BC Trend for Four Boston BC Sites with Springfield.



The seven years of BC data for the Springfield site presented no trend. Figure 5-12 shows BC versus year from 2006 through 2012. The cause of the large increase at Springfield from 2010-2011 is unknown, although all sites except Countway did increase at the same time, implying a regional process at least in part. Weather patterns would be one possible factor, but not sufficient alone to explain the observed increase in Springfield BC.

Figure 5-12. BC vs. Year for Springfield.



5.4. Wildfire Event of May 31, 2010

On the morning of May 31, 2010, smoke from a large wildfire in Quebec arrived in Boston, causing fine particulate ($PM_{2.5}$) to exceed 120 μg/m^3 for several hours. BC concentration levels between 6 to 8 μg/m^3 were recorded, consistent with woodsmoke BC being between 5% and 10% of the total woodsmoke PM (Naher et al., 2007). Figure 5-13 shows hourly data for $PM_{2.5}$, BC, and Delta-C, a woodsmoke indicator[10] from South Street, and particle number concentration (PNC, or ultra-fine particles) from the HSPH site. PNC peaked early in the morning, before photochemistry could accelerate the particle aging process. BC, DC, and PM2.5 tracked well from this common source, as expected.

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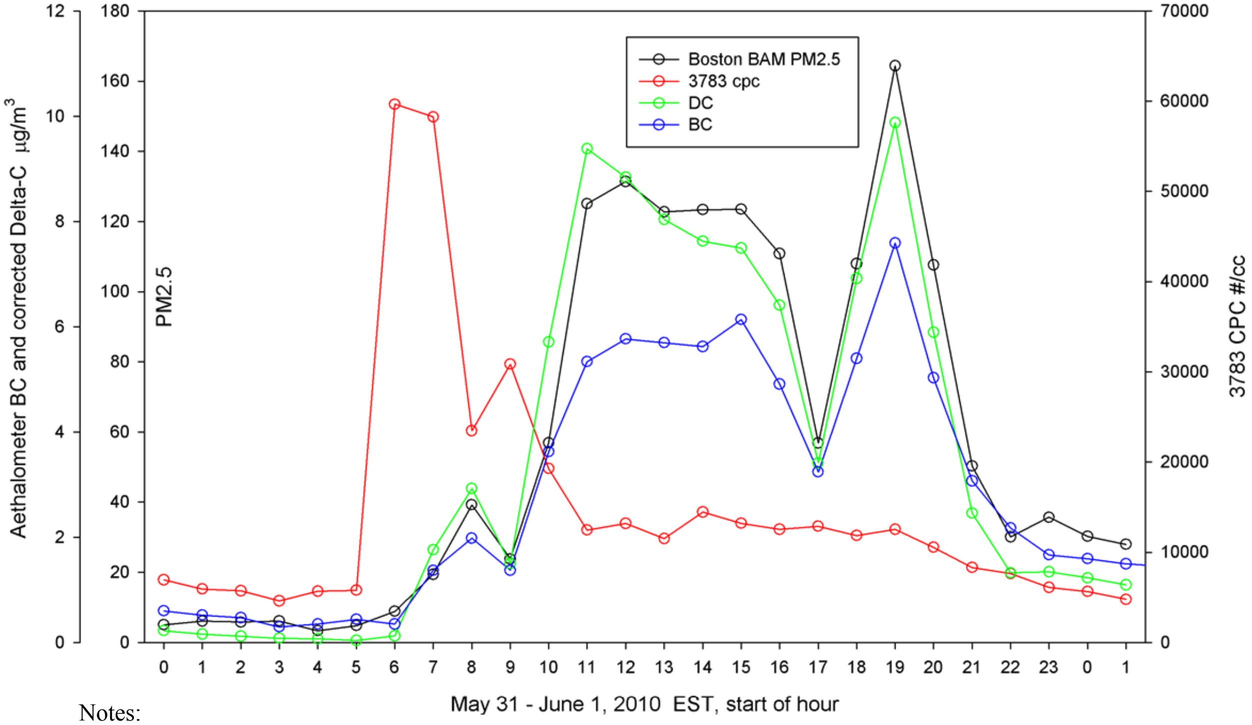
[10] Delta-C is UVC minus BC. UVC is the same measurement as BC but at a shorter wavelength of light. The shorter wavelength of UVC responds to organic compounds in fresh woodsmoke that the BC channel does not measure. BC is measured at 880 nm (near-IR), and UVC at 370 nm (near-UV).

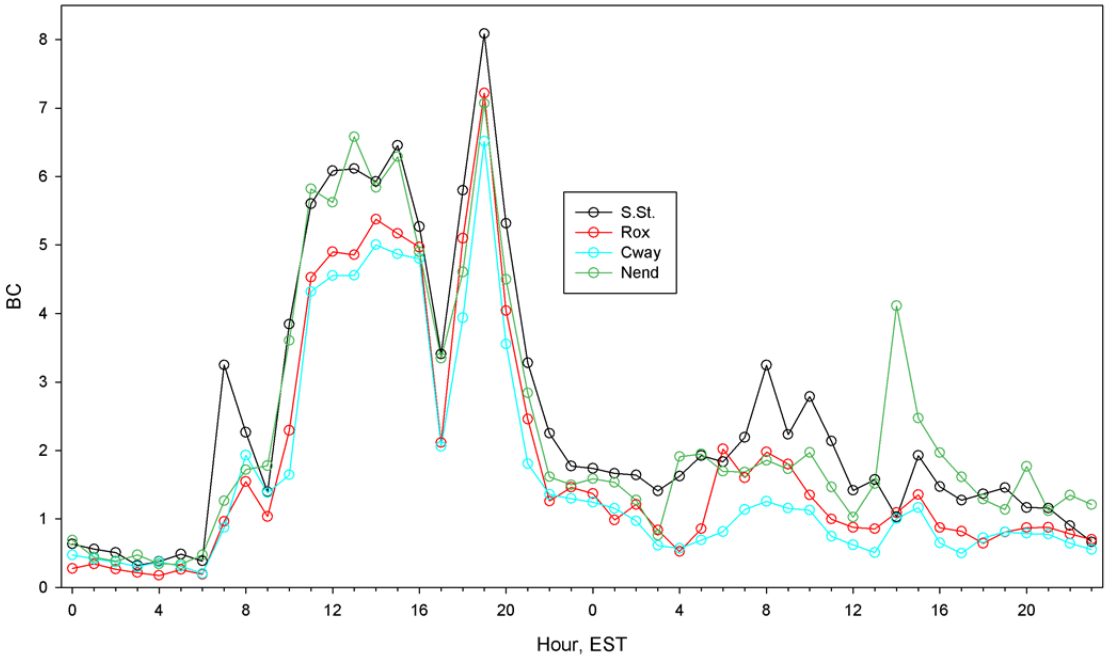
Figure 5-13. Hourly Event Data.



Notes:
BAM is the beta-attenuation continuous PM monitor
3783 CPC is the method for particle number concentration measurement.
DC is “Delta-C”, the 2-channel Aethalometer woodsmoke surrogate measurement.

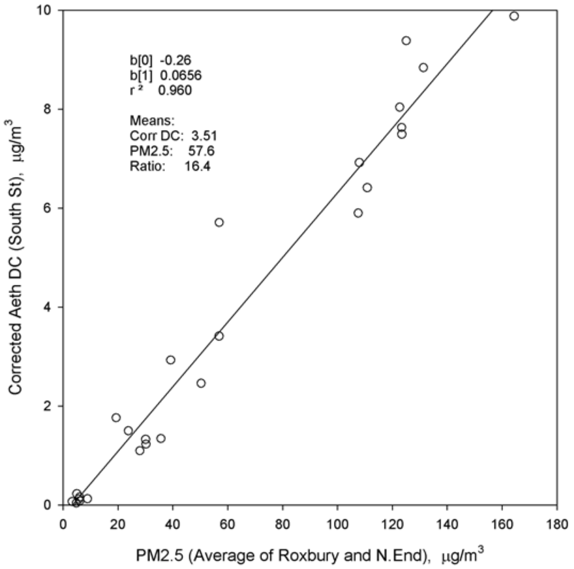
Figure 5-14 shows BC from the four Boston sites within the two-day time period of May 31 to June 1, 2010. Despite the source of the fire being several hundred kilometers away, there was some spatial difference across the sites. The only consistent pattern was that the HSPH Countway site was often the lowest. Roxbury generally tracked HSPH well. South Street or the North End site usually measured the highest BC levels.

Figure 5-14. Hourly BC for Four Boston Sites During the Woodsmoke Event.



Moreover, the wildfire event clearly shows the value of the Delta-C Aethalometer woodsmoke indicator. Figure 5-15 presents the regression of hourly Delta-C from South Street for $PM_{2.5}$ (the average of the North End and Roxbury MassDEP continuous PM monitors). The R^2 value was 0.96. The ratio of $PM_{2.5}$ to Delta-C was 16, which was in the expected range for woodsmoke that had undergone some photochemical aging.

Figure 5-15. Regression of Hourly Delta-C from South St. on PM2.5.



6. CONCLUSIONS.

6.1. Spatial Analysis.

Substantial gradients in BC existed over a 35 km scale, both in 2003 and for 2010 through 2012. Mean BC in 2003 varied by a factor of 3.5 from downtown Boston to the regional background site, and was much larger for sub-daily event periods (10 times or more). The data indicate that the neighborhood spatial scale of urban-excess $PM_{2.5}$ for Boston was limited to approximately 10 miles from the downtown area. This is important from both an air toxics exposure and a control strategy perspective. In 2010, the ratio of North End to Stow mean BC was 2.8; when 2011 North End BC is used, the ratio increased to 3.2, which was similar to the ratio of 3.5 observed in 2003. The ratio between 2010 mean BC at South Street and Stow was 3.9. These data suggest that the relative gradient has decreased slightly since 2003. This is consistent with the majority of diesel PM controls implemented between 2002 and early 2005 being in place by the end of 2003.

For the core urban area, BC levels at all neighborhood-scale sites were elevated relative to the background site, but urban gradients were not distinct for most of these sites. Short-term (one-hour) correlations across these sites ranged from very good to poor. Some urban sites were much better indicators of BC in the general downtown area than others.

BC appeared to be a reasonable indicator of local mobile source aerosol. Winter oil space heating and woodsmoke did not appear to be significant BC interferences in the urban area.

A limited assessment of spatial trends from 2009 to 2012 at four sites showed results similar to the 2003 data. BC at the South Street site at the NESCAUM office was distinctly higher than other Boston sites, and was similar to BC measured at another South Street site in the summer of 2003. Based on pollutant-wind analysis, the proximity of the South Street site to the I-90 and I-93 interchange to the southwest as well as I-93 above ground to the south is the likely reason for the elevated BC at that site. The transportation complex at South Station did not appear to be a contributor.

Diurnal patterns for these four sites were similar in shape to 2003, with a distinct week-day morning peak and diurnal patterns only during weekend days. A notable exception to the weekend pattern was a large peak at 11 a.m. EST for South Street; this was due to a very local emergency diesel genset test every Saturday morning. One-minute BC has peaked to over 100 $\mu g/m^3$ during those tests.

6.2. Temporal Trends.

A substantial decrease in BC was observed between 2002 and 2005. At least two major factors likely drove this decrease: the drastic clean-up of PM emissions for the MBTA bus and the Boston school bus fleets, which occurred during this period. MassDEP’s heavy-duty diesel Inspection and Maintenance program began in 2001, and was fully implemented by early 2003. This program likely contributed to the observed decrease in BC levels in 2003 and subsequent years. Thus the large decrease in BC between 2002 and 2004 is the result of specific intervention programs, and demonstrates the effectiveness of such efforts in reducing diesel PM. There are limited data from other urban areas that show a general downward trend in BC or elemental carbon (EC) over the last decade, including data from the EPA chemical speciation network, but Boston is the only urban area where a rapid and substantial drop in BC can be attributed to intervention programs.

Trends after 2005 were present but not consistent across the three long-term Boston BC sites. Roxbury had a downward trend from 2007 to 2012, but it was not significant, with a p value of 0.11. When data from 2005 and 2006 data were included, there was no observed trend (p = 0.8). At the HSPH site, there was a significant downward trend from 2005 to 2012 (p = 0.004). The North End site showed no trend for any period after 2004. The Springfield BC data from July 2006 to 2012 also showed no trend for that period.

At all sites, there was a strong seasonal pattern for BC. In Boston, at all sites except for Roxbury, BC was substantially higher in the summer than in winter. This is consistent with seasonal wind speeds. The pattern was strongest at the North End and South Street sites. Roxbury BC was lower from February to May and constant during the remainder of the year. Springfield had a strong but different seasonal pattern; BC was lowest in April and highest in November.

6.3. Future Work.

BC will continue to be monitored at the four existing Boston sites, thus allowing assessment of future trends. The new MassDEP near-road monitoring site, located on the Southeast Expressway inbound, 2 km east of the Roxbury site, includes BC measurements starting November 1, 2013. This makes a total of five Boston BC monitoring sites.

A new version of the Aethalometer has been recently introduced (Model AE33 or TAPI-633). While its basic operating principles are unchanged, it is a radically different design. The new instrument attempts to correct for spot loading errors in real-time, but may produce data that are different from the older AE21 / AE22 Aethalometer. To ensure the integrity of ongoing trend analyses, it will be important to characterize any differences in BC data produced by the older and newer versions of the Aethalometer.

NESCAUM has been evaluating the performance of prototype and production versions of the AE33/633 compared with the AE21/AE22 (older models) Aethalometer performance over the last two years at the South Street site. The production version of the AE33 was evaluated from December 2012 to September 2013 using two Model 633 Aethalometers that MassDEP purchased. From August through October 2013, a comparison of the old and new Aethalometer instruments was performed at the Roxbury MassDEP site. Results show good correlation, but BC data from the new model 633 Aethalometer is substantially higher (~25 to 30%) than the existing AE22 Aethalometer at that site.

As mobile source BC continues to be reduced in a manner similar to the dramatic reduction of carbon monoxide over the last two decades, the utility of BC as an indicator is also likely to decrease. While this is desirable from a health and exposure perspective, there are other mobile source pollutants of concern that may not be reduced, and it may be difficult to find another easily measured marker of mobile sources.

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