NIWA
Taihoro Nukurangi

SpaRTANZ Auckland Pilot Study

Spatially Resolved Technique for Source Apportionment in New Zealand

December 2016

Prepared by:
Ian Longley (NIWA), Jane Clougherty & Brett Tunno (University of Pittsburgh)

For any information regarding this report please contact:

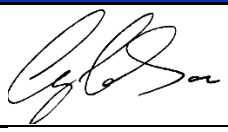
Ian Longley
Programme Leader - Air Quality

+64-9-375 2096
i.longley@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
Private Bag 99940
Viaduct Harbour
Auckland 1010

Phone +64 9 375 2050

NIWA CLIENT REPORT No: 2016157AK
Report date: December 2016
NIWA Project: CAAP1701

Quality Assurance Statement		
	Reviewed by:	
	Formatting checked by:	
Ken Becker Regional Manager	Approved for release by:	

Contents

Tables

Figures

Executive summary

"Spatially Resolved Techniques for Source Apportionment in New Zealand" (SpaRTANZ) is an observationally-based approach to understanding spatial patterns in urban air pollution. By using a dense network of samplers, and analysing specific chemical markers associated with key emission sources, the technique aims to describe the magnitude and spatial extent of the impacts of those sources.

The techniques were originally developed in the US and have been adapted in this project for New Zealand. Two **pilot studies** were conducted in 2014 – in the Auckland CBD in April and in Christchurch in May. This report presents the observational results from the Auckland pilot study.

METHODS

This pilot study was intended to demonstrate the capability to measure multiple pollutants, including source tracers, at many locations throughout a city – with particular attention to the new information that such an approach can provide towards air quality management.

International studies of this type have previously included at least 40 sites for every pollutant, and have monitored during at least two seasons. For this pilot-scale study, the sample size for the monitoring campaign was limited to 12 spatially-distributed locations, plus two reference sites sampled every week over four weeks. For nitrogen dioxide (NO_2), using passive samplers which are simpler and cheaper to install and analyse, we were able to examine an additional 30 sites.

Work-week (Monday-Friday 7am-7pm) air sampling for fine particles ($PM_{2.5}$) and particle components was conducted in April 2014. $PM_{2.5}$ refers to particles less than 2.5 microns aerodynamic diameter, capable of reaching the furthest extents of the lungs and directly impacting health. These particles are comprised of many elemental and organic compounds, some of which have been closely associated with specific pollution sources, such as vehicular emissions, diesel, or oil burning.

The samplers were previously used in major campaigns in New York City and Pittsburgh, and demonstrated very high data quality. The samplers were contained in a purpose-built box mounted on street light poles at a consistent height of 3 m.

Due to the small scale of this pilot study, the pollutant concentrations reported and spatial patterns reported here are not definitive, but rather indicate key sources which may require further study, and demonstrate an approach, using spatial-distributed sampling and source tracers, to more specifically characterize air pollution across an urban area, and to identify potential sources which may influence these patterns.

Likewise, due to the small scale of this current pilot study, it does not yet enable assessment of associated health outcomes. Such epidemiological studies – examining air pollution impacts on childhood asthma, birth outcomes, and other conditions – has been possible from the larger datasets collected in New York and Pittsburgh.

RESULTS

The study was successful in revealing strong spatial patterns in air quality in Auckland's CBD, patterns which changed in response to wind direction, consistent with the source impacts identified.

Meteorological conditions (especially wind direction) varied substantially during the study, strongly influencing observed pollutant concentrations and source effects. However, large spatial variation was observed under all meteorological conditions.

During three of the four sampling weeks, winds were predominantly from the southwest (as is the norm for Auckland). Across the 11 sites sampled during these weeks, $PM_{2.5}$ concentrations averaged 7.2 $\mu g\ m^{-3}$, and ranged from 4.4 to 12.4 $\mu g\ m^{-3}$, a nearly 3-fold variation, with higher concentrations in locations with high traffic volumes. We found very similar patterns for several markers of diesel exhaust (black carbon, nitrogen dioxide, and several organic compounds) or road dust.

In winds from the north-east, captured during one sampling week, our observations suggested an additional emission source to the north-east of the CBD. This source had an impact which diminished with distance from the waterfront, and was characterised by a different chemical composition with strongly elevated levels of vanadium, nickel and sulphur - all markers of heavy oil combustion. Our data strongly suggests that this source is from shipping emissions at near the port. We estimated that this source raised $PM_{2.5}$ concentrations by approximately 50 % at Albert Park.

DISCUSSION/ IMPLICATIONS

Two common approaches for assessing impacts of observed air quality on health are to compare observed concentrations with health-based standards and guidelines, to conduct a health impact assessment by combining established dose-response relationships with data characterising the exposed population. Our current pilot study design does not directly permit either approach due to its limited scale and sample size, though such analyses would be possible with a larger dataset.

Regulatory air quality monitoring in New Zealand is focussed on monitoring at a small number of fixed sites. As a result, there is little existing data on air pollution variation within urban areas, and thus the range of concentrations (and the causes of spatial variability) within cities and towns remains unknown. This pilot study is the first to document wide variability in particulate air pollution within the CBD, thus showing how the impact of pollution sources are highly localised. This indicates that central Auckland's air quality is sensitive to the way road traffic, and especially heavy diesel traffic, moves through the street network – both the nature of the permitted vehicle fleet and the way it is routed.

Our data indicated greater variability in air pollution within the CBD than within the rest of the Auckland region. This implies that the CBD area is under-monitored. Our data also indicates that while Auckland Council's Queen Street air monitor may be representative of the CBD in general, it substantially under-represents the more polluted locations within the CBD.

The pilot and short duration nature of this study means that these results should not be interpreted as definitive. Nevertheless they do demonstrate that the technique is capable of revealing and quantifying significant spatial variation in air quality over short distances. A full-scale study will deliver a much more comprehensive and robust assessment of the extent of the impact that road traffic, shipping and other activities have on air quality, as well as providing the foundation for health risk assessment and health outcomes research.

1 Background

1.1 Purpose and scope of this report

"Spatially Resolved Techniques for Source Apportionment in New Zealand" (SpaRTANZ) is an observationally-based approach to examining spatial patterns in air pollution within urban areas. The techniques were originally developed in the US and have been adapted for New Zealand. Two pilot studies were conducted in 2014 – in Auckland in April and in Christchurch in May. This report presents the observational results from the Auckland pilot study.

This is not a health outcomes study. Two common approaches for assessing the impacts of air quality on health are to compare observed concentrations with health-based standards and guidelines, or to conduct a health impact assessment by combining established dose-response relationships with data characterising the exposed population. Our current pilot study design does not directly permit either, due to its limited scale and sample size. However, the method demonstrated here, if implemented at scale, could be used to support health risk assessment in the future.

1.2 Project background

The Auckland Plan sets an ambitious vision for Auckland to be the world's most liveable city. The plan aims to dramatically increase the prospects of Auckland's young people, strongly commit to environmental sustainability and action, and radically improve the quality of urban living.

A vibrant and successful city centre is an important part of this vision, as it provides a strong sense of place, heritage, and character. Is also where an increasing number of people live, work and play.

A high volume of cars, vans, trucks and diesel buses converge in the Central Business District (CBD), and larger trucks service the Port, which is seeing a growth in shipping traffic. These are all responsible for emissions of air pollutants, which can have huge effects on public health, amenity and subjective wellbeing.

These impacts, however, are difficult to quantify, and to track, without air pollution monitoring. These impacts can also be highly localised – that is, greatly varying from street-to-street or block-to-block. For this reason, they cannot be fully described by relying on one or two monitors. Previously, monitoring in Auckland has been designed primarily to inform regional-scale air quality management. However, the challenges facing the CBD – to improve the environmental quality and vitality - address a different scale and range of outcomes, and require a different approach to monitoring.

Spatial saturation monitoring - wherein a large number of semi-portable air samplers are distributed across an urban area for a period of weeks to months - has previously been shown to reveal a wealth of useful information, to augment existing regulatory networks. For example, it can offer more precision in identifying high-concentration locations, and the ability to link higher concentrations to sources distributed across the urban area. Combined with the use of chemical tracers (elemental and organic components of fine particles, associated with specific sources), it can more precisely identify and separate the impacts of different emission sources (e.g. diesel traffic versus shipping).

The SpaRTANZ project was developed as a collaboration between Dr Jane Clougherty of the University of Pittsburgh and Dr Ian Longley of NIWA. Dr Clougherty previously demonstrated the efficacy of spatial monitoring combined with compositional analysis in New York City and Pittsburgh

(Matte et al., 2013, Clougherty et al., 2013; Tunno et al., 2015). The approach was brought to New Zealand for the first time for this pilot study.

1.3 Project Objectives

1. Observe and quantify spatial variation in fine particulates ($PM_{2.5}$) and nitrogen dioxide (NO_2) concentrations across the Auckland CBD.

2. Observe spatial variation in concentrations of a range of $PM_{2.5}$ components (i.e., black carbon, elements, selected organic compounds) across the Auckland CBD, with attention to those components previously associated with diesel traffic and shipping.

3. Explore any particular challenges or opportunities presented by Auckland's unique geography and climate that can inform and improve the technique.

1.4 Project funding and participants

The project was entirely self-funded by NIWA and the University of Pittsburgh.

Sampling was conducted by Dr Clougherty's team from the University of Pittsburgh, supported by the Air Quality team of NIWA. Laboratory analyses were conducted by the University of Pittsburgh, Desert Research Institute (organic compounds), and Wisconsin State Laboratory of Hygiene (elemental analyses).

Planning, site selection, data analysis and reporting was jointly conducted by the Pittsburgh and NIWA teams.

2 Study Methods

2.1 Background

Auckland Regional Council (ARC) has conducted air quality monitoring in Queen Street in central Auckland since 1975. The current Auckland Council station has operated continually since 1982, producing hourly data since 1998. However, it has not previously been known how well this dataset actually represents air quality across the whole CBD.

Previous screening monitoring by ARC has indicated that Auckland's regional background air (beyond the city's periphery) is very clean but indicated the potential for specific locations of poor air quality in the CBD (ARC, 2007, Watercare, 2011). The 'PENAP' (Personal Exposure to Noise and Air Pollution) study in 2013 investigated levels of three traffic-related pollutants (nitrogen dioxide, carbon monoxide and ultrafine particles) in the Queen Street valley, finding large differences in air quality between high- and low-traffic streets (Longley et al., 2014a).

The SpaRTANZ pilot study (reported here) sought to investigate a much wider suite of pollutants over the full CBD area, by monitoring a number of sites simultaneously, and examining chemical components of airborne particles which provide tracers for pollutant sources.

It is important to note that the work described here was a pilot-scale study – designed to demonstrate a method and to explore the likelihood of novel and useful results if the study were repeated at a larger scale. Because this data includes only one measure per site, over only one month (April 2014), the results should not be interpreted as definitive.

2.2 Study area

To demonstrate and test the SpaRTANZ method, we focused on one area, the Auckland CBD, likely to contain very different concentrations (i.e., some high, and some low-pollution locations), and impacted by many pollution sources (e.g., traffic, diesel, shipping emissions, etc.), the effects of which are difficult to disentangle without spatially-dense monitoring and source-specific tracers.

The Auckland CBD, broadly defined by the Northern and North-Western Motorways and fringe areas of Parnell, Newmarket and Ponsonby, provided such an area. We hypothesised that different parts of this CBD area would be differently impacted by general traffic, trucks, buses, and emissions associated with the port. For example, there are several roads designated for use by trucks and heavy-duty vehicles (i.e. motorways, The Strand, Beach Road and Quay Street), and locations nearer the port may be more impacted by shipping emissions.

2.3 Overview of methods

We collected each sample over 5 workdays (Mon-Fri 7am-7pm). Each site was sampled during one of four consecutive weeks in April 2014. Due to equipment limitations and time constraints, sample size for fine particle ($PM_{2.5}$) and chemical constituents monitoring was limited to twelve (12) spatially-distributed locations, each monitored on one randomly-selected week during the four week study period. To temporally-adjust data collected over different weeks, we monitored at two (2) additional 'reference' sites (chosen to represent high- and low- traffic sites) sampled every session.

Eight (8) of the distributed monitoring sites were selected using a systematic geographic information systems (GIS)-based method to cover high and low anticipated impacts of total traffic density, diesel (truck and bus) density, and distance to the port. To better capture the full range of spatial variation, one additional site was selected from the highest-source-intensity strata (high traffic - high diesel – near port), and one from the lowest-intensity strata (low traffic - low diesel – far from port). Two additional monitoring sites were selected near key points of interest (i.e., Britomart transportation hub, and on The Strand near the main railway line).

The samplers used were previously deployed in major campaigns in New York City and Pittsburgh, and previous work has demonstrated very data high quality (Clougherty et al., 2013, Tunno et al., 2015; Shmool et al., 2014). The samplers were contained in a purpose-built box which can be rapidly mounted on street light poles. Further details are supplied in Appendix A.

Due to the relatively low cost of passive samplers for gases, thirty (30) additional sites were selected for sampling of the gases nitric oxide (NO) and nitrogen dioxide (NO_2). These pollutants are commonly-used indicators of vehicle emissions, and NO_2 was previously sampled in the Queen Street valley for the PENAP project (Longley et al., 2014a).

Figure 2-1: Three SpaRTANZ air samplers installed on Princes Street, Auckland.

2.4 Pollutants analysed

Most of the pollutants in the air are emitted as complex mixtures. Diesel and petrol engine exhausts, and the exhaust from burning heavy fuel oils on ships, are mixtures with a lot of similarities but some key differences. They all contain particles largely consisting of elemental carbon (soot) and a huge

and complex range of organic compounds. They also contain traces of metals. It is the subtle variation in organic compounds and trace metals that allow different combustion sources to be distinguished. Emissions from industry are often more distinct in terms of the trace metals present. Furthermore emissions from domestic heating, dust resuspension, mechanical abrasion and from natural sources also contain distinct elemental signatures that allow them to be distinguished.

For this study we analysed the presence of black carbon, 26 metallic elements and 34 organic compounds. In this report we do not exhaustively cover all of these constituents, but focus on those which tell the strongest story about sources of air pollution in central Auckland.

In advance of the study, based on previous studies and literature, we hypothesised that

- Black carbon and nitrogen dioxide (NO_2) would be indicative of combustion generally, but diesel vehicles in particular
- Sodium would be mainly indicative of sea salt
- Calcium, aluminium and silicon would be indicative of mineral dusts
- Chromium would be indicative of brake wear from road vehicles
- The organic compounds pyrene, phenanthrene and hopanes would be indicative of diesel emissions
- Sulphur, vanadium and nickel would be indicative of heavy fuel oil burning, especially from ships

As well as representing the pollutant mixtures associated with particular sources, some of the pollutants analysed (chromium, nickel, lead, arsenic, cadmium) represent independent risks to health.

3 Results

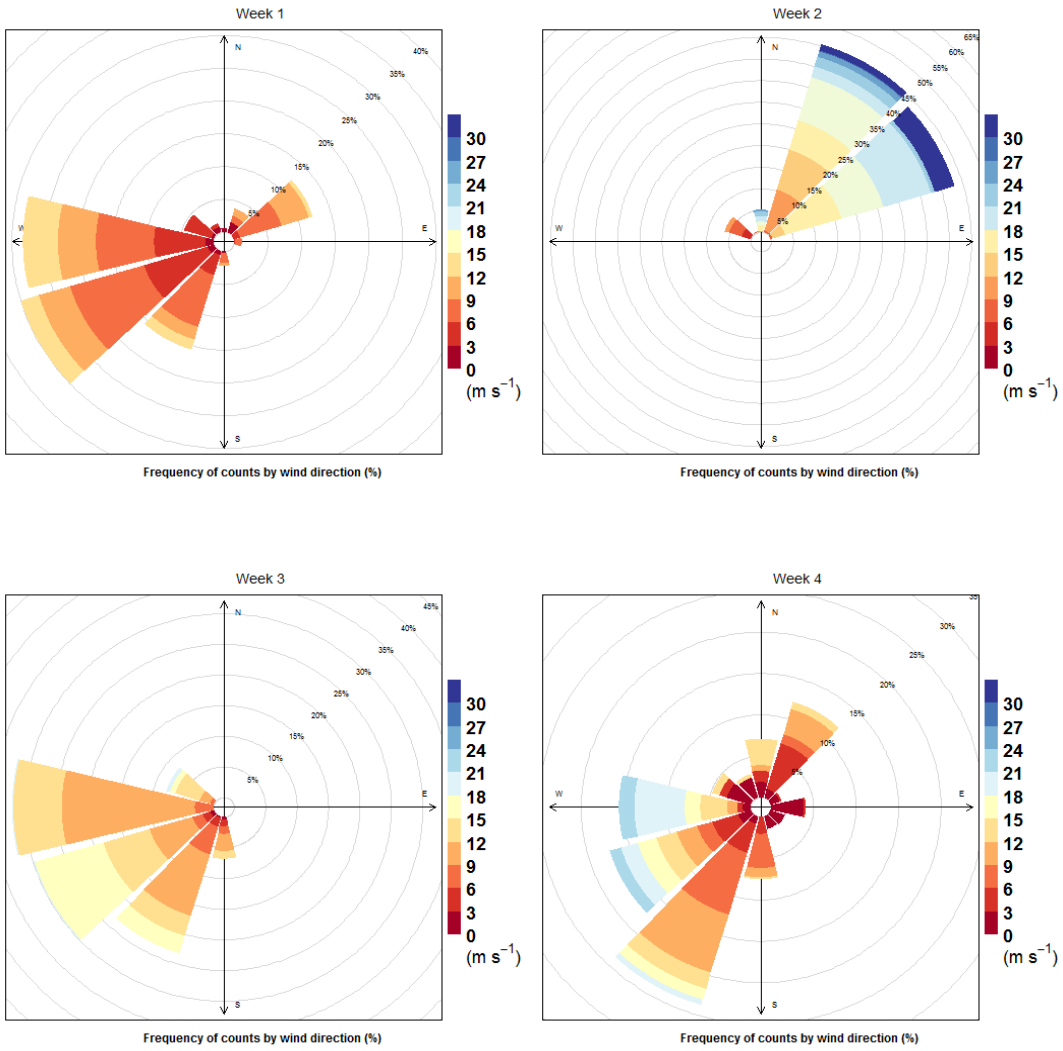
3.1 Meteorological conditions

By chance, two substantially different weather conditions were observed during the campaign.

As shown in the wind roses in figure 3-1 (data collected by NIWA from the Sky Tower), winds in Auckland were predominantly from the south west during sampling sessions 1, 3 and 4. This is in keeping with the predominant wind conditions in Auckland.

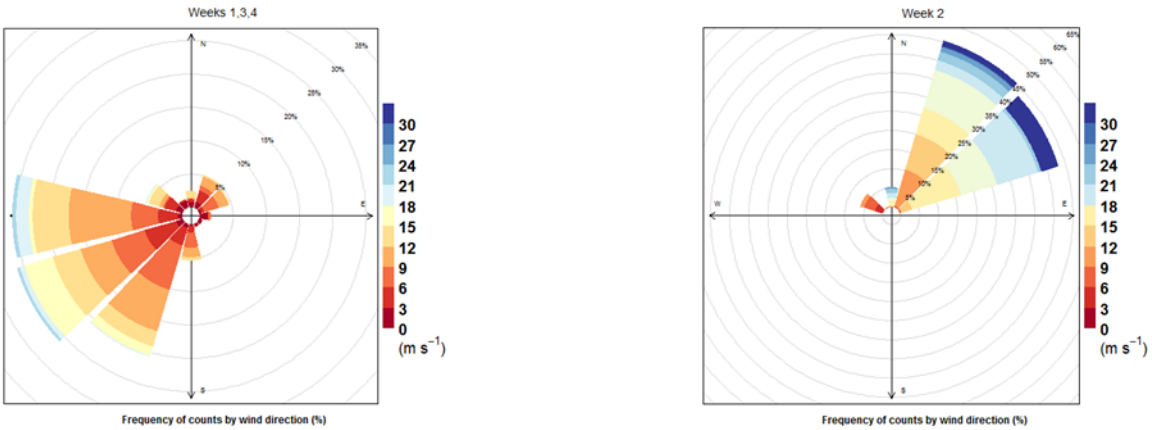
Session 2, however, consisted almost entirely of winds from the north-east, and higher average wind speeds. One 12-hour period during this session had very high winds and a heavy rainstorm.

Figure 3-1: Wind roses for the four sampling weeks of the campaign indicating wind direction and wind speed (colours).



Under these very different scenarios of wind speed and direction, we would expect the impacts of key pollution sources in and around the CBD to look very different. Because our primary goal is to understand the spatial extent of these impacts, we used this opportunity to examine pollution patterns under two very different meteorological scenarios. Thus, for the remainder of this report, we present data separately for those sessions marked by south-westerly winds (sessions 1-3-4) and the session characterized by north-westerly winds (session 2).

Figure 3-2: Wind roses for sessions 1, 3 and 4 (left) and session 2 (right). Data from Sky Tower.



3.2 Spatial summary of results: Sessions 1-3-4 vs. session 2

In this section, we present observed concentrations of various pollutants are presented in two maps: sessions 1, 3 and 4 (S or W winds) on the left, and session 2 (NE winds) on the right. In all cases, figures to the left and right depict concentrations on the same colour scale. The scale is linear except where otherwise stated.

Figure 3-3 depicts $PM_{2.5}$, black carbon (BC) and nitrogen dioxide (NO_2) respectively. BC is a commonly-used tracer from diesel emissions, and NO_2 a commonly-used tracer for local combustion/ vehicle emissions.

Figure 3-3: Concentrations of PM2.5 (top), black carbon (middle) and nitrogen dioxide (bottom). BC and NO2 are commonly-used tracers for diesel emissions. .

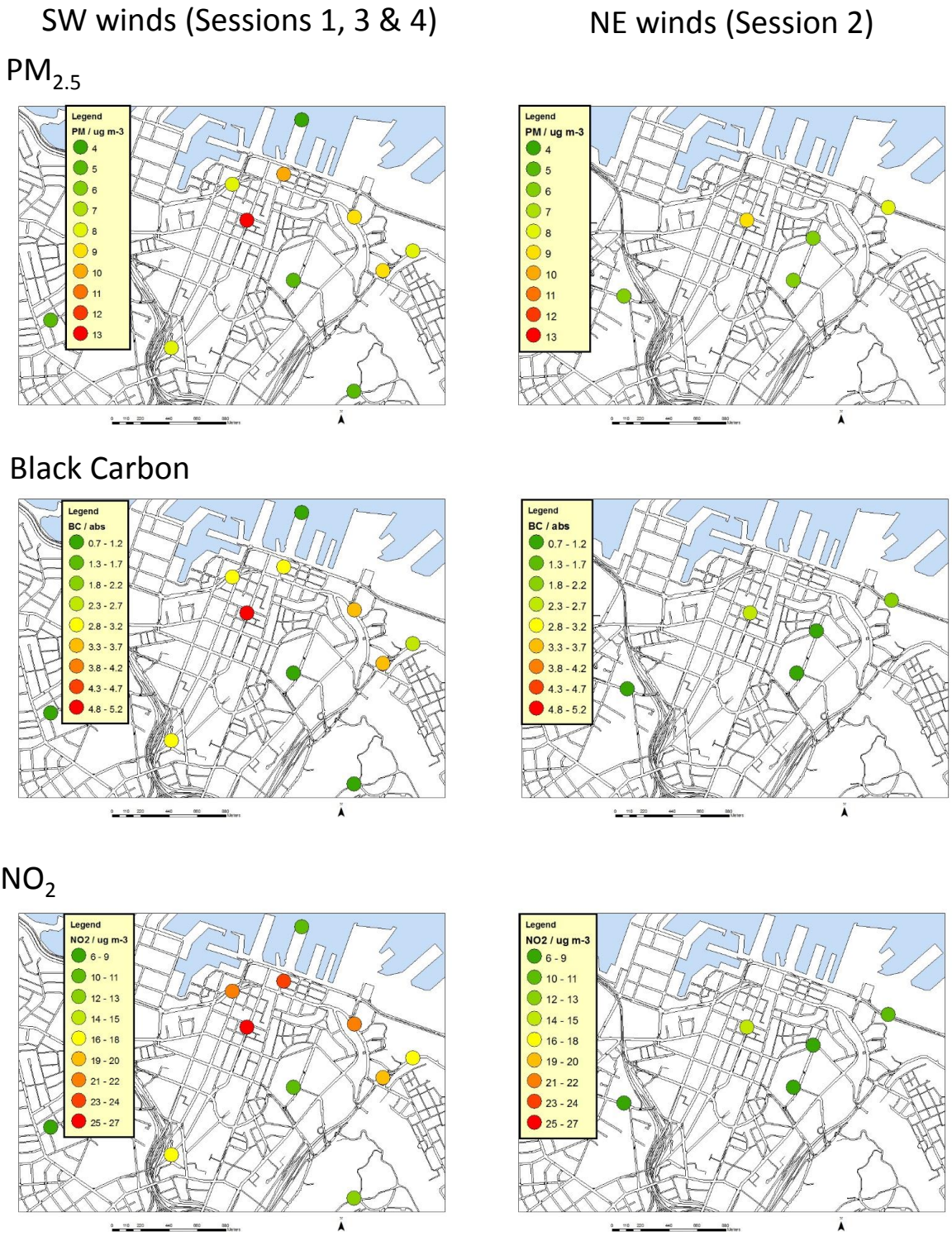


Figure 3-4 depicts chromium (a commonly-used indicator of vehicle brake wear), calcium (a marker of mineral dust and soil resuspension) and sodium (a marker of airborne sea salt). In Auckland's case, sea salt is the largest upwind source of airborne particles, and thus serves as indicates the upwind contribution to $PM_{2.5}$ concentrations.

Figure 3-4: Concentrations of chromium (top), calcium (middle) and sodium (bottom). Left: sessions 1, 3 and 4, right: session 2.

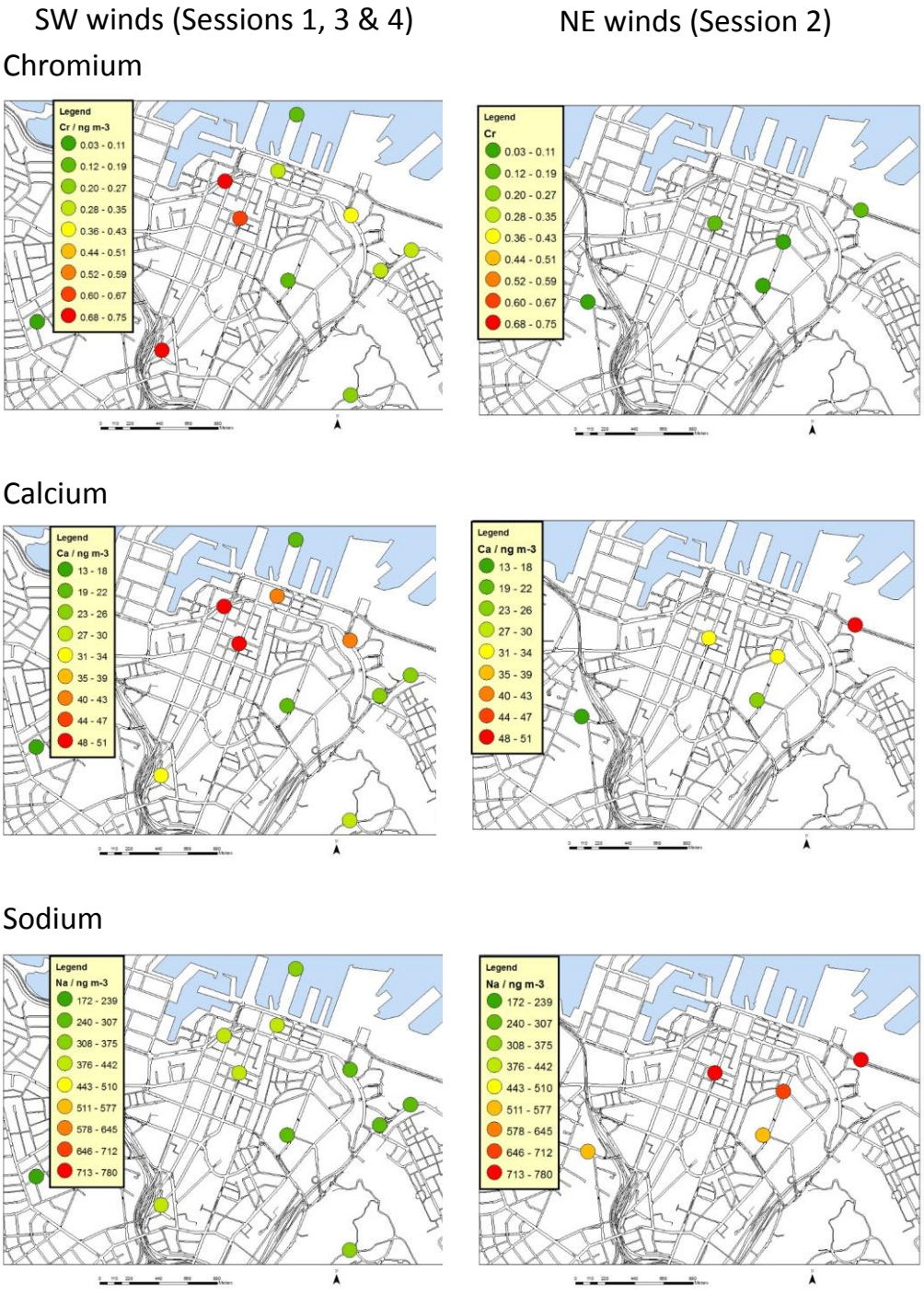


Figure 3-5 shows four groups of organic compounds: total PAHs, hopanes, phenanthrene and pyrene. Each of these have been associated with diesel-related emissions.

Figure 3-5: Concentrations of total PAHs (top), hopanes (upper middle), phenanthrene (lower middle), pyrene (bottom). Left: sessions 1, 3 and 4; right: session 2.

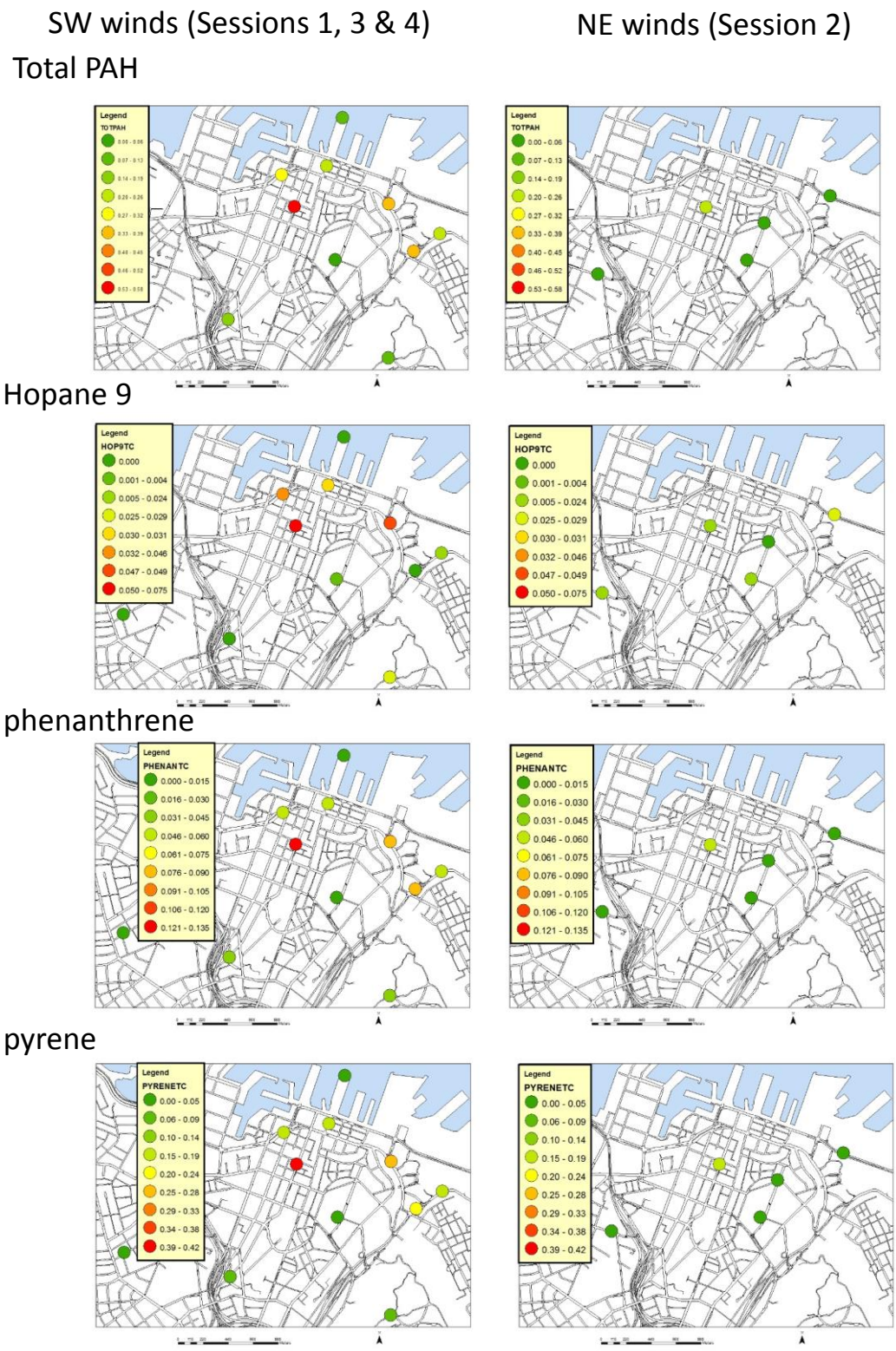
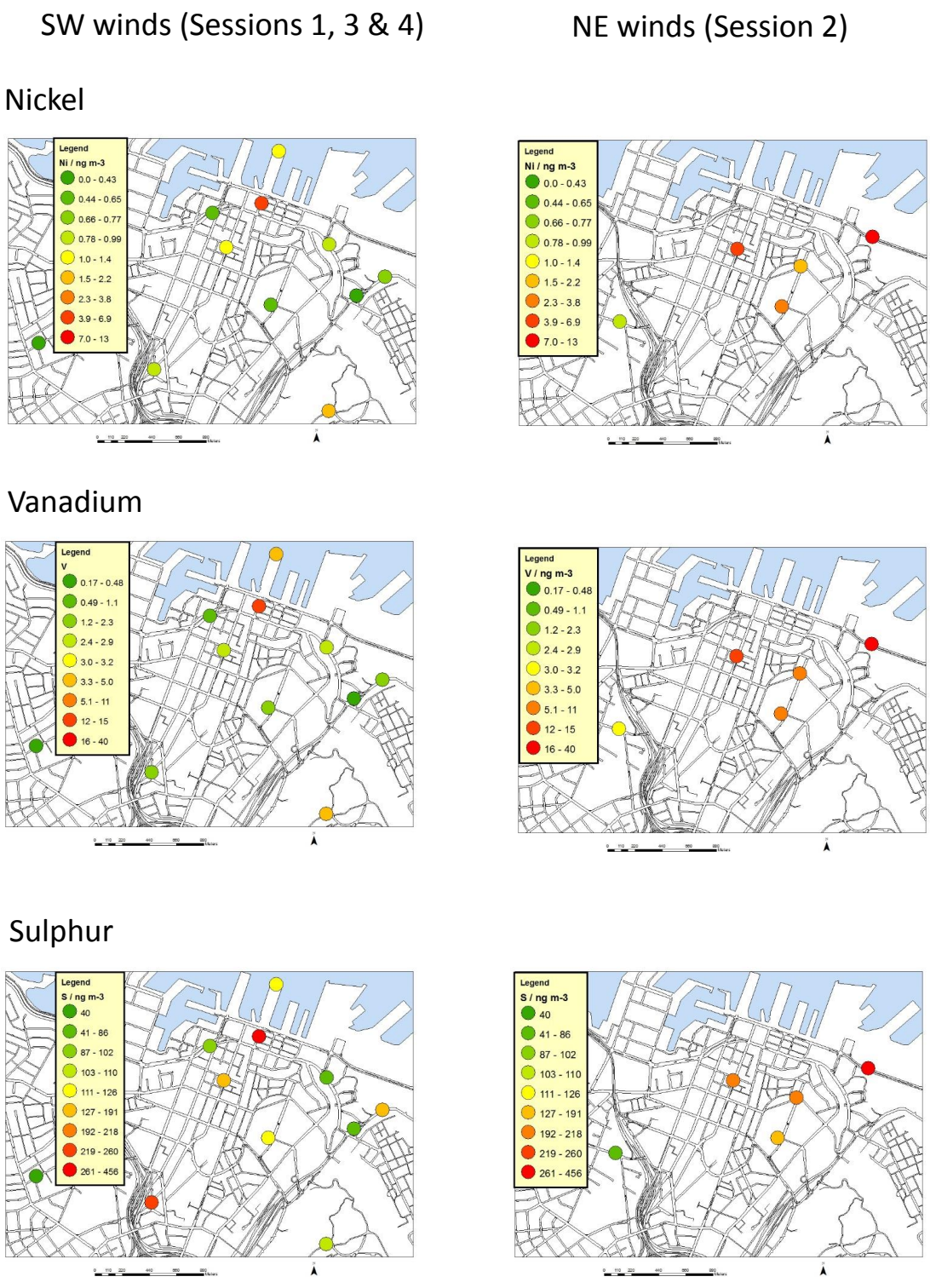


Figure 3-6 depicts nickel (Ni), vanadium (V), and sulphur (S), respectively. Each of these have been previously associated with, and used as tracers for, emissions from shipping (heavy oil burning) sources.

Figure 3-6: Concentrations of nickel (top), vanadium (middle) and sulphur (bottom). Left: sessions 1, 3 and 4; Right: session 2. Note logarithmic scales.



4 Interpretation of results

Results from sessions 1, 3 and 4 (SW winds, left hand panels of figures 3-3 to 3-6) will be discussed separately from results from session 2 (NE winds, right hand panels of figures 3-3 to 3-6).

4.1 Scenario 1: Winds predominantly from the west-southwest

4.1.1 $PM_{2.5}$ concentrations and variation across sites

For sampling weeks 1, 3, and 4, characterized by winds from the south-southwest (Auckland's predominant wind direction) $PM_{2.5}$ across all sites averaged 7.2 μg/m^3. Concentrations measured at individual sites ranged from 3.5 to 12.4 μg/m^3, a nearly 4-fold variation, or a range of 8.9 μg/m^3.

During the four weeks of the campaign, $PM_{2.5}$ measured across five Auckland Council monitoring sites ranged from 3.7 to 7.0 μg m^{-3}, a range of only 3.3 μg m^{-3}. Importantly, we observed more variability using a larger numbers of sites in this small 2 km x 2 km CBD area than was simultaneously observed at regulatory monitors across the whole Auckland region.

In general, we found higher concentrations at locations near heavy traffic (Figure 3-3, top). The highest concentrations were recorded in a street canyon (which may reduce air dispersal, and thus trap pollution) with a high volume of diesel buses, and near a signalled intersection, where vehicles idle and accelerate (associated with higher emissions). The lowest concentrations were recorded in low-traffic locations and in parks.

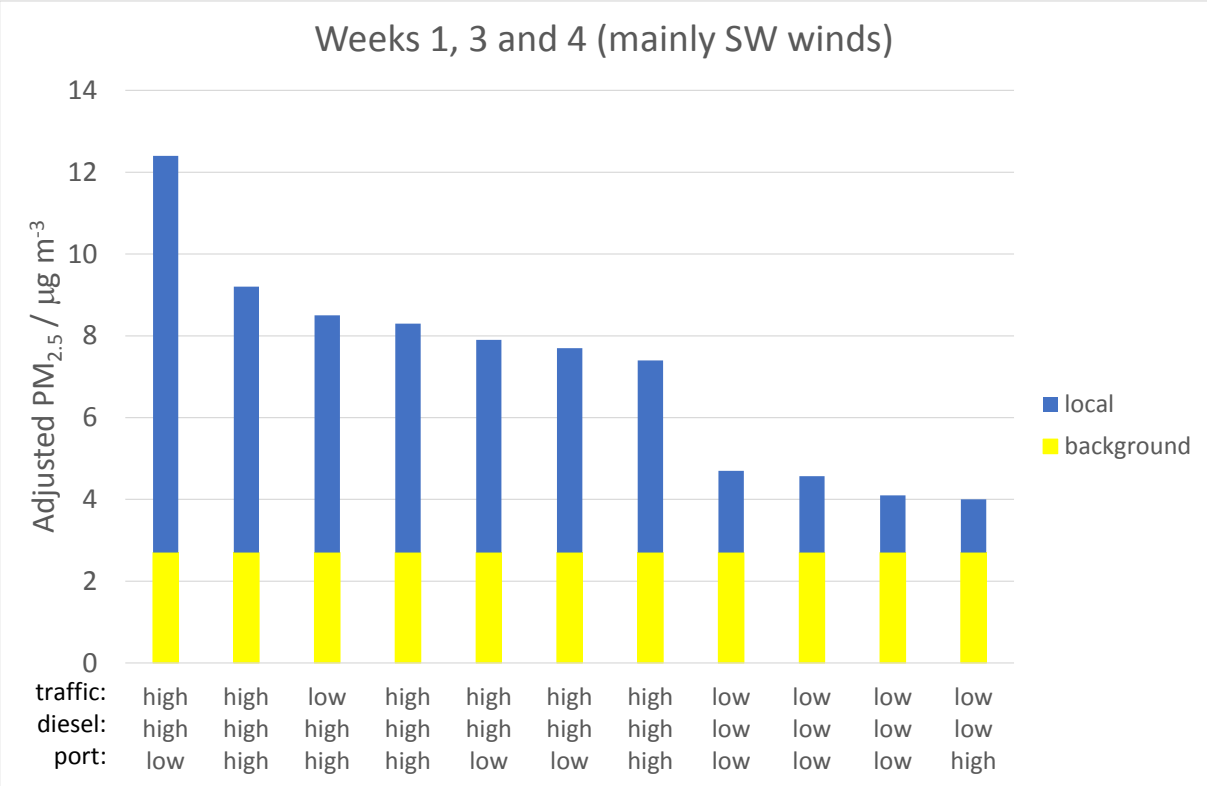
4.1.2 Diesel markers

The importance of diesel emissions in contributing to spatial variation in $PM_{2.5}$ levels was corroborated through analysis of the chemical constituents of the sampled particles. Black carbon ("BC", or "soot") is strongly related to diesel emissions and we found a very strong linear correlation between BC and $PM_{2.5}$ levels in our study in both wind directions (Figure 3-3, middle). $PM_{2.5}$ levels were also strongly correlated with NO_2 in SW winds (Figure 3-3, bottom). Our results indicated that local (mainly diesel) emissions were contributing an additional 0 - 9 μg m^{-3} across our measurement sites.

$PM_{2.5}$ and BC were also correlated with several other metallic elements and organic compounds found on the samples, previously used as markers for road traffic emissions. In particular, concentrations of chromium (associated with brake wear) were higher on major traffic routes (Figure 3-4, top). Furthermore, concentrations of fluoranthene, pyrene, hopanes (Figure 3-5), all markers of diesel exhaust, were higher on major traffic routes.

Diesel engine exhaust contributes substantially to ambient PM, and is considered to be likely carcinogenic to humans. Black carbon also has a strong climate-warming effect and poses a soiling risk for buildings. Whereas this data does not provide adequate coverage for health risk assessment, it indicates that diesel emissions are significant and detectable in central Auckland, and that the SpaRTANZ approach could be used to characterise the risk if implemented at full-scale.

Figure 4-1: $PM_{2.5}$ concentrations disaggregated into local and background contributions.



4.1.3 Mineral/ road dusts

Aluminium, potassium, calcium were all correlated with $PM_{2.5}$, BC, and NO_2, presenting the same general spatial pattern (Figure 3-4, middle). These elements are associated with mineral dusts. However, their correlation with markers of diesel traffic suggests that resuspension of mineral dusts by road traffic was a significant pollution source at some of our measurement sites.

4.1.4 Background contributions

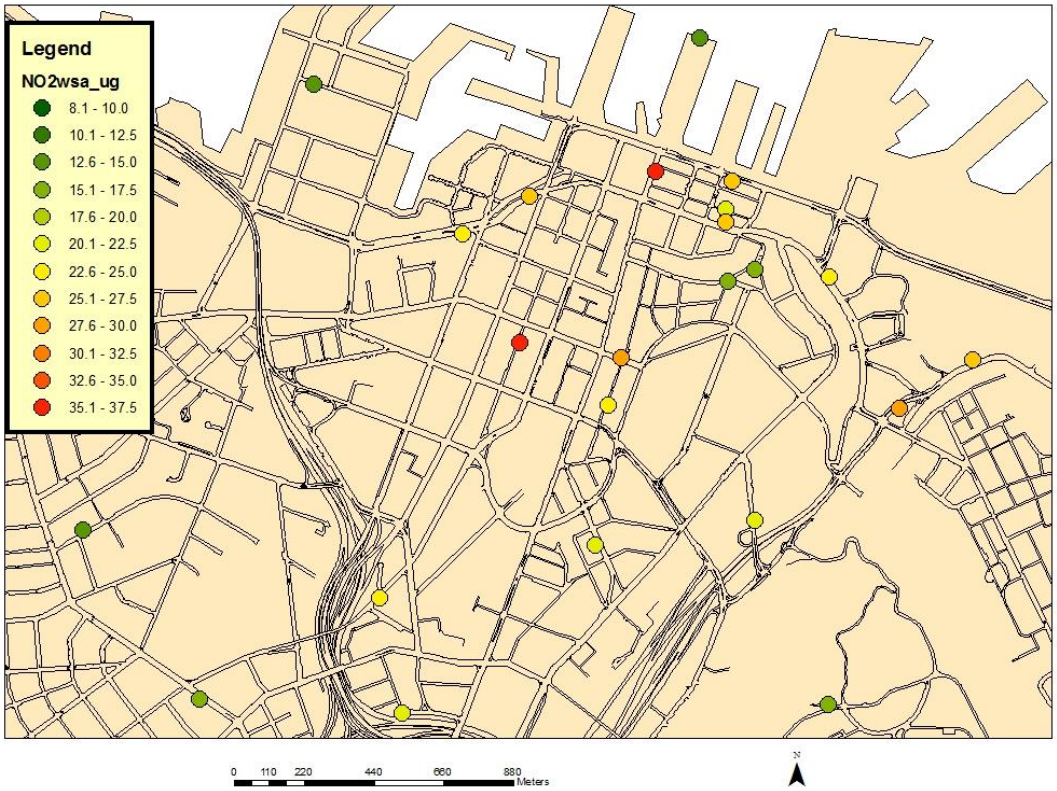
Among the elements, sodium contributed by far the largest amount to $PM_{2.5}$ in SW winds, with relatively little variation across sites (Figure 3-4, bottom), suggesting sea salt was a major contributor to background concentrations. Potassium (wood smoke and biomass burning) and calcium (soils) were lesser contributors to background air pollution concentrations.

4.1.5 Levels of Nitrogen Dioxide (NO_2)

A larger dataset was collected for NO_2, which has then been further adjusted for seasonality based on previous analysis of NO_2 data from Auckland (Longley et al., 2014b). In brief, previous analysis has shown that NO_2 measurements made in April are typically 18 – 38 % above the annual mean.

The adjusted NO_2 data indicates a wide range of NO_2 concentrations across the CBD (Figure 4-2). Higher concentrations were observed at locations near heavy-duty diesel traffic (i.e., trucks or buses), but not necessarily high traffic volumes overall. Locations with higher concentrations were also largely characterised by tall buildings or relatively narrow street canyons, with lesser air dispersal. We observed lower concentrations in outlying areas, or more open sites, surrounding the CBD.

Figure 4-2: Estimated annual mean NO_2 during winds from the southwest.



4.2 Scenario 2: Winds predominantly from the north-northeast

4.2.1 $PM_{2.5}$ concentrations and spatial variation

Session 2 (unlike sessions 1, 3 and 4) was characterised by predominantly **north-easterly winds**, including one 12-hour period of very high winds during a rainstorm. Five sites (two reference sites and from three distributed sites) were sampled during this session. The results are presented in the right hand panels of Figures 3-3 to 3-6.

During session 2, we observed lower $PM_{2.5}$ concentrations, on average (Fig 3-3). These concentrations, however, revealed a very different spatial pattern, and a much higher prevalence of certain chemical tracers.

Concentrations of chemical tracers associated with traffic were generally lower during session 2, as shown for BC and NO_2 (Figure 3-3), chromium (Figure 3-4, top) and diesel-related organics (Figure 3-5).

During session 2, had wind direction and speed been consistent, we estimate that $PM_{2.5}$ at Albert Park would have been ~3.4 $\mu g/m^3$. However, concentrations were actually 5.3 $\mu g/m^3$ during session 2 at this site, suggesting a substantial impact of an additional non-traffic source during that week.

We hypothesized that the port, or shipping-related emissions, may be a substantial contributor. If so, we would expect that source to impact the CBD in north-easterly winds, given the relative location of the port and shipping lanes.

To explore this further, we analysed results for vanadium, nickel and sulphur (V, Ni and S), associated with heavy oil burning, including shipboard oil-burning, in other studies (Davy et al., 2010, Clougherty et al, 2009a, b). In weeks 1, 3, and 4 of our study, V concentrations ranged from 0 – 6 ng/m^3 (Figure 3-6, middle) across all sites except at the Britomart, where the V concentration was 15 ng m^{-3}.

During week 2, however, V concentrations ranged from 3 ng/m^3 at locations far from the Port, and increased with proximity to the Port, reaching 40 ng/m^3 at the Port boundary. Ni and S concentrations (Figure 3-6) followed a similar pattern, decreasing with distance from the port. This result is consistent with an observational screening study of SO_2 conducted in 2011 by Auckland Council (Watercare, 2011) which sampled for three months at 33 sites across the CBD.

These data strongly suggest a localized heavy oil burning source to the north/ north-east of the CBD, which has much less impact on the CBD in southerly or westerly winds. Although these conclusions are far from definitive they are suggestive of the port or shipping being that source.

However, at least two other components were also elevated in NE winds, and towards the harbour. Calcium (mineral dust) showed an increasing trend towards the port (Figure 3-4, middle). Moreover sodium concentrations were not only higher towards the harbour, but were also substantially higher at all sites in NE winds than in SW winds (double on average), suggesting a much stronger influence of sea salt. Our limited study is unable to determine how much of this was due to the high storm winds for 12 hours within session 2 or not.

4.2.2 Background contributions to air pollution

Because air pollution is carried on the wind, in most cities across the globe, some portion of the air pollution experienced locally was actually generated in locations upwind, beyond the city boundaries. This is often referred to as 'background' or 'long-range transport' air pollution. In New Zealand, geographically far removed from other industrialized countries and large cities, the largest contributor to background air pollution is generally sea salt, suspended into the air by the action of the wind and surf breaking.

Our results suggested a 'background' $PM_{2.5}$ concentration of 4.1 μg/m^3 with winds from the northeast, versus only 2.6 μg/m^3 under winds from the SW. Although this study is not designed to show this, we hypothesise that this difference is due to the CBD being closer to the east coast.

The composition of background air pollution is suggested by its composition. Sodium (Na), a component of sea salt, contributed on average 5% to $PM_{2.5}$ in SW winds and 10 % in NE winds.

Potassium (K) is a commonly-used tracer components of biomass and wood smoke burning. Potassium concentrations were elevated under winds from the SW, and reduced from most locations under NE winds. These observation suggest an influence of pollution from other parts of urban Auckland which impacts the CBD, only under winds from the south or west.

5 Implications of the study

5.1 Limitations of the current study

The study reported here should be considered as a pilot study, designed to demonstrate a capability. Though limited in space and time, our results point to substantial spatial variation in overall $PM_{2.5}$ concentrations, and key sources impacting pollution concentrations and composition, across the CBD.

The concentrations and spatial patterns reported here are indicative, rather than definitive, and point to the need for more spatially-dense data on concentrations of key source tracers across the CBD and city more broadly.

Each of our 12 distributed sites was sampled only once. To determine whether these patterns are consistent over time, and to quantify the long-term impacts, would require a larger and longer-term campaign. Our current study is also unable to provide quantitative data on the likelihood and causes of short-term (24-hours or less) episodes of poor air quality.

The actual scope and extent of a larger study will depend on the objectives but, depending on design, one could answer questions about the real-life relationships among diesel and general vehicle emissions, the influence of wood smoke and other sources outside of central Auckland on pollution concentrations in highly-populated areas, and the influence of shipping on pollution exposures across Auckland.

5.2 Impacts on health

5.2.1 Comparison of our results with health-based standards and guidelines

Our data was collected during daytime hours over a week, whereas the available standards and guidelines apply to exposures to 24-hour averages of PM_{10}, 1-hour averages of NO_2, and 8-hour averages of CO, none of which were measured in this study.

We measured $PM_{2.5}$ (particulate matter smaller than 2.5 μm), which is a subset of PM_{10}, but more closely approximates that portion of airborne PM which can pass by the respiratory system's natural defences and reach the alveoli (furthest extent of the lungs' bronchioles, where gas-blood exchange occurs).

Currently, New Zealand does not have a standard for $PM_{2.5}$. $PM_{2.5}$ standards (as an annual average or a 24-hour average) are in force in many other countries across the world. The WHO recommends an annual mean limit of 10 $\mu g\ m^{-3}$, although some countries have adopted alternative values (e.g. the standard is 12 $\mu g/m^3$ in the USA and 8 $\mu g/m^3$ in Australia). Standards for PM are not believed to provide complete protection from health effects, as research has not identified a minimum threshold concentration below which adverse health effects do not occur.

Although we did not measure for a year, the concentrations measured may not differ substantially from the annual average. Measurements by Auckland Council showed that weekly $PM_{2.5}$ averages during our campaign deviated from the 2014 annual mean by no more than 3.5%. **As such, most of the sites we sampled are likely to meet an annual $PM_{2.5}$ standard of 10 $\mu g/m^3$, but those with the highest concentrations may not.**

The Ministry for the Environment have adopted a guideline value of 40 μg/m^3 of nitrogen dioxide (NO_2) as an annual mean, based on the World Health Organisation guidelines. An annual mean value cannot be accurately measured during a campaign of only a few weeks, such as ours. The concentrations we observed, however, suggest that **annual mean NO_2 concentrations at some CBD locations may exceed the WHO 40 μg/m^3 guideline**, as is consistent with the 2013 PENAP study implemented by NIWA.

Guideline values for key elemental tracers measured in this study are shown in table 5-1, below. Most guidelines are expressed as annual means.

Table 5-1: Guidelines and observed concentrations for selected metals. All values in μg m^{-3}.

Element	NZ Guideline	Other guidelines	Values observed in this study
Lead	0.2 (3-month moving average)	0.5 (EU)	0 – 2.3
Chromium	0.11 (annual mean)	No guideline	0.03 – 0.75
Arsenic	0.0055 (annual mean)	0.006 (EU)	0.4 – 1.2
Nickel	No guideline	0.02 (EU)	0 – 12.7
Cadmium	No guideline	0.005 (EU)	0 – 0.065

5.2.2 Health risk assessment

Our pilot study is under-powered to support a health risk assessment. This is because 1) the study is under-powered to develop models which estimate air quality in locations we did not sample, and 2) sampling was of insufficient duration to establish the representativeness and long-term persistence of the spatial patterns observed, preventing us from robustly describing patterns in chronic exposure. These limitations could be address in a larger-scale study (see below).

5.3 Implications for long-term monitoring of air quality in central Auckland

$PM_{2.5}$ has been monitored routinely for over a decade on Queen Street by Auckland Council. Queen Street was historically Auckland's major central thoroughfare. This site is situated in the centre of our study area, in a street canyon. The average daytime $PM_{2.5}$ concentration at Queen Street during the campaign was ~7 μg/m^3, but varied from 3.5 – 12.4 μg/m^3 across our sampling locations. Thus, the **Queen Street site is over-estimating concentrations in some parts of the CBD, and under-estimating it in others.**

A larger study of this type could better elucidate how well the Queen Street site captures air pollution trends at other CBD locations, estimate the degree to which it under-estimates peak concentrations, and inform on the potential siting of new monitoring stations.

Regulatory air quality monitoring in New Zealand tends to be biased towards monitoring at sites expected to represent "peak" concentrations. This means there has not previously been much data available on the less-polluted locations within urban areas, and thus the range of concentrations (and causes of spatial variability) have remained unknown. This pilot study is the first to document wide variability in particulate air pollution within the CBD, revealing that the impact of key pollution sources can be highly localised. As a result, air quality in Auckland's CBD is sensitive to roadway

configurations, traffic density, and heavy diesel traffic – both the nature and size of the permitted vehicle fleet, and the way it is routed.

Our data indicate greater variability in air pollution within the CBD than is generally observed across all of the regulatory monitors in the Auckland region, suggesting that the CBD area is under-monitored. Our data also indicates that the Queen Street monitor may under-estimate concentrations in some parts of the CBD, and over-estimate concentrations in others.

5.4 What a larger study could provide

This pilot study was based on previous studies in Pittsburgh and New York City. Due to resource constraints, it included a smaller number of monitoring sites, and short duration (only four weeks), hence the small sample size.

A more appropriately-resourced study would increase the study duration and sample size, enabling a wider range of study outputs and outcomes. Such a study could:

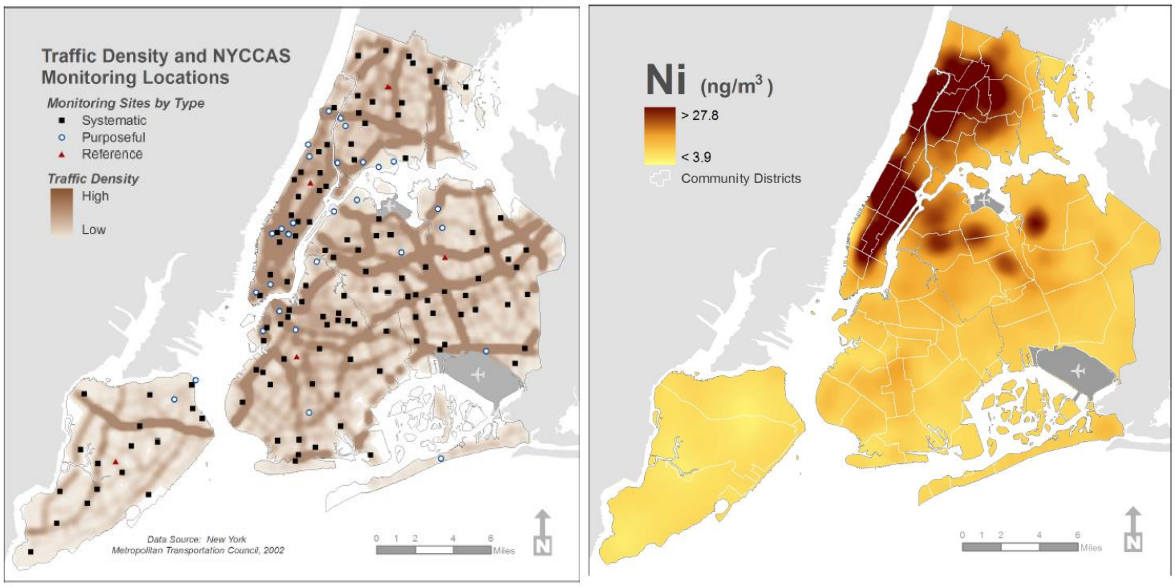
- More definitively establish long-term patterns, enabling comparison with long-term guidelines.
- Capture spatial patterns in air pollution concentrations and composition under a wider range of meteorological conditions, and across seasons.
- Expand the spatial scope of the study, to include locations outside of the CBD and across the harbour.
- To delineate the spatial impact of key emission sources, using a larger number of sampling sites and source-specific chemical tracers (e.g. to examine pollution impacts from shipping lanes).
- Increase the number of emissions sources that can be studied, by examining tracers for g, biomass burning).
- Distinguishing more specific source types (i.e. different types of on-road and off-road diesel sources, different types of shipping-related sources).
- Identify factors which may affect pollution emissions (e.g., different vehicle emissions rates by roadway gradient).
- Investigate the role of local topography and buildings/ street canyons in shaping pollution movement or build-up within the CBD or greater Auckland area.
- Explore variation in pollution concentrations and composition between day and night, or weekdays and weekends.
- Enable health risk assessments, to estimate health effects associated with local pollution or specific sources.

More generally, a larger study would support air pollution modelling approach and creation of maps describing pollutant concentrations across the whole study area. Such a modelling approach would quantify associations between air pollution concentrations and geographical data describing key

sources (e.g. traffic volumes, built topography, distance to port, etc.). This approach provides a clearer, more quantitative identification of the most important sources that contribute to pollution exposures, and to estimate the potential impact of reducing emissions from these sources.

An example of this modelling approach, from the New York City Community Air Survey (NYCCAS), is shown in Figure 5-1 (Clougherty et al., 2010). In that study, data from 150 monitoring sites and a technique called "land-use regression" were used to estimate (model) pollution exposures across the city. Exposure maps were created for specific pollutants (in this case, nickel), and the models supported identification of key sources and cost-effective interventions.

Figure 5-1: Example from New York City Community Air Survey (NYCCAS): Data from many monitoring sites (left) was used to create a map of pollution concentrations (right) (Clougherty et al., 2010).



The example shown here is airborne nickel (Ni), a metal linked with neurocognitive impairment. The "land use regression" model strongly linked high Ni concentrations to locations of heavy residual oil burning (commonly used for heat and hot water in large NYC buildings). This evidence provided a strong basis for cost-effective policy development to reduce airborne Ni exposures.

Once created, such pollutant-specific maps can be used for detailed health impact assessments and research studies. For example, data and maps from the NYCCAS have been used to investigate patterns in cardiovascular hospital admissions and mortality and birth weights (Savitz et al., 2013) in New York.

6 Conclusions

Although "spatial saturation" studies including many monitoring sites have been conducted in other cities worldwide, few have been conducted in New Zealand, and very few have been implemented at this very dense spatial scale, or across complex topography. Our pilot study demonstrates that even a small spatial sampling campaign, focused on meaningful source tracer chemicals, can provide valuable insights into key pollution sources, and help to better understand variation in air quality across urban areas.

Under winds from the southwest, the prevailing wind direction in Auckland, $PM_{2.5}$ concentrations varied nearly 3-fold (4.4 to 12.4 µg/m^3), across the 11 sites in this small two km^2 area. We found higher $PM_{2.5}$ concentrations in locations with higher traffic volumes. We found very similar patterns for black carbon, nitrogen dioxide and several chemical markers of diesel exhaust or road dust.

Under winds from the northeast, we detected higher concentrations of pollutants and markers associated with heavy oil burning (e.g., vanadium (V)) and mineral dusts, especially closer to the Port or harbour front. Concentrations of sodium (Na), a tracer for sea salt, decreased with distance from the harbour front in NE winds, corroborating previous work by GNS Science.

Because this was a short-duration pilot-scale study, its results are not definitive. Nevertheless, they do demonstrate a technique capable of revealing and quantifying the substantial variation in air quality over short distances. A full-scale study will deliver a much more comprehensive and robust assessment of the impacts of various emission sources, can guide selection of cost-effective interventions, and can provide a basis for health impact assessment and health outcomes research.

7 Acknowledgements

This study would not have been possible without the following contributors.

Permission to mount sampling equipment on lampposts was provided by Auckland Transport. Road traffic data for site selection was provided by Auckland Council. Laboratory analysis was conducted by University of Pittsburgh, Desert Research Institute (organic compounds), and Wisconsin State Laboratory of Hygiene (elemental analyses).

The field team comprised Sally Gray, Elizabeth Somervell and Sam Edwards for NIWA, and Leah Cambal, Cortney Roper, and Lauren Chubb for University of Pittsburgh.

Further analytical and managerial assistance was provided by Sally Gray, Elizabeth Somervell, Gustavo Olivares and Guy Coulson for NIWA.

8 References

Auckland Regional Council, 2007. Nitrogen dioxide in the air in the Auckland Region: Passive sampling results. Auckland Regional Council Technical Publication TP346.

Clougherty, JE, Kheirbek, I, Eisl, HM, et al. (2013). Intra-urban spatial variability in wintertime street-level concentrations of multiple combustion-related air pollutants: The New York City Community Air Survey (NYCCAS). *J Exposure Science and Environmental Epidemiology*. doi:10.1038/jes.2012.125.

Clougherty, JE, Johnson, S, et al. (2010). The New York City Community Air Survey Supplemental Report. Nickel concentrations in ambient fine particles: winter monitoring 2008-2009. NYC Health.

Clougherty JE, H. E., Levy JI, (2009a) Examining intra-urban variation in fine particle mass constituents using GIS and constrained factor analysis. *Atmospheric Environment* 2009**,** *43*, (34), 5545–5555.

Clougherty JE, I. K., S Johnson, G Pezeshki, J. Bryan Jacobson, HM Eisl, JE Gorczynski, Z Ross, H Kitson, A Benson, A Camacho, J Werbe-Fuentes, J Haviland-Markowitz, R Munoz, A Tilles, CH Strickland K Charles-Guttman, S Markowitz, D Kass, T Matte (2009b) *The New York City Community Air Survey: Results from Winter Monitoring 2008-2009*; New York City Department of Health and Mental Hygiene, and NYC Mayor's Office for Long-Term Planning and Sustainability: 2009.

Davy P, T. B., Markwitz A, Source apportionment of airborne particles in the Auckland region : 2010 Analysis. In GNS Science Consultancy Report 2010, 2011; Vol. 262.

Longley, ID, Salmond, J, Dirks, K, Welch, D, Shepherd, D, Grange, S, Olivares, G, Miskell, G, 2014a. Personal exposure to noise and air pollution (PENAP) in the Queen Street Valley, Auckland. Technical Report 2014/036. Prepared for Auckland Council.

Longley, I.D., Gadd, J., 2014b. A regression approach to assessing urban NO_2 from passive monitoring – Application to the Waterview Connection. NIWA Report AKL-2014-023.

Matte, TD, Ros, Z, Kheirbek, I, Eisl, H, Johnson, S, Gorczynski, JE, Kass, D, Markowitz, S, Pezeshki, G, Clougherty, JE, 2013. Monitoring intraurban spatial patterns of multiple combustion air pollutants in New York City: Design and implementation. *Journal of Exposure Science and Environmental Epidemiology* 23, 223–231

Savitz, DA, Bobb, JF, Carr, JL, Clougherty, JE, Dominici, F, Elston, B, Ito, K, Ross, Z, Yee, M, Matte, TD, (2013). Ambient fine particulate matter, nitrogen dioxide and term birth weight in New York, New York. *American Journal of Epidemiology* doi: 10.1093/aje/kwt268

Shmool, JLC, Michanowicz, DR, Cambal, L, Tunno, B, Howell, J, Gillooly, S, Roper, C, Tripathy, S, Chubb, L, Eisl, HM, Saturation sampling for spatial variation in multiple air pollutants across an inversion-prone metropolitan area of complex terrain. *Environmental Health* 13, 28, doi: 10.1186/1476-069X-13-28

Tunno, BJ, Michanowicz, AR, Shmool, JLC, Kinnee, E, Cambal, L, Tripathy, S, Gillooly, SE, Roper, C, Chubb, L, Clougherty, JE (2015). Spatial variation in inversion-focused measures of fine particulate matter and elemental carbon in Pittsburgh, PA. *J Expos Sci Environ Epidem.* doi: 10.1038/jes.2015.14

VanDonkelaar, A, Martin, RV, Brauer, M, Boys, BL, 2015. Use of Satellite Observations for Long-Term Exposure Assessment of Global Concentrations of Fine Particulate Matter Sampling methods. *Environmental Health Perspectives* 123, 135-143.

Watercare, 2011. Auckland Council ambient passive nitrogen dioxide and sulphur dioxide monitoring winter 2011. Prepared for Auckland Council by Watercare Services Ltd. October 2011

Appendix A Sampling Methods and Filter Analysis

Analytical procedures:

Teflon™ filters were pre- and post-weighed using an ultramicrobalance (Mettler Toledo Model XP2U, Columbus, OH USA), inside a temperature and relative-humidity controlled glove box (PlasLabs Model 890 THC, Lansing, MI USA), to determine total mass of $PM_{2.5}$. An EEL43M Smokestain Reflectometer (Diffusion Systems, Ltd., London, UK) was used to determine BC absorbance. For elemental composition of $PM_{2.5}$, inductively-coupled plasma mass spectrometry (ICP-MS) analyses were conducted on Teflon™ filters, following documented protocols (ESS INO Method 400.4; EPA Method 1638),[26] by the Wisconsin State Laboratory of Hygiene. Concentrations of organic constituents were determined using thermal desorption gas-chromatography mass-spectrometry (TD-GCMS) on quartz fibre filters, by Desert Research Institute (DRI) (Reno, NV USA). For NO_2 concentrations, Ogawa passive badges were analyzed using water-based extraction and spectrophotometry (Thermo Scientific Evolution 60S UV-Visible Spectrophotometer, Waltham, MA) (ppb).

Sampling Instrumentation:

Portable ambient air sampling units were used to collect samples of $PM_{2.5}$, black carbon (BC), and elemental constituents using Harvard Impactors (Air Diagnostics and Engineering, Inc.) and 37 mm Teflon™ filters (PTFE membrane, 2 µm pores, Pall Life Sciences). Battery-operated vacuum pumps (SKC, Inc.) were operated at a flow rate of 4 litres/minute (LPM); pre- and post-flow rates were averaged to determine a mean temperature-corrected flow rate. A comparable co-located instrument, adapted to use a cyclone inlet for size selection to avoid potential contamination of quartz filters by impactor grease (Air Diagnostics and Engineering, Inc.) was used to collect samples for organics analysis, on pre-baked 37 mm quartz fibre filters (Pallflex Tissuquartz non-heat treated filters, Pall Life Sciences). A HOBO data logger was used to monitor temperature and relative humidity throughout sampling (Onset Computer Corporation). Instruments were housed in weather-tight Pelican boxes mounted approximately 3 m above ground (near the breathing zone). Nitrogen dioxide (NO_2) samples were collected in weatherized external shelters, using Ogawa badges (Ogawa & Co. USA). Sampling instrumentation and protocols are detailed in Tunno et al. (2016).

Filter Handling Protocols:

Due to the relative instability and volatility of organic compounds, we developed laboratory and field protocols to minimize contamination and improve reproducibility. We used pure quartz filters with no binder or glass fibres, which we placed into porcelain dishes using Teflon-coated tweezers, and baked for four hours at 900°C before deployment (Thermo Scientific Thermolyne oven, Waltham, MA) to remove any trace organics. All cyclone accessories were cleaned using methanol in a fume hood, and methanol-cleaned and foil-covered sampler inlets before deployments, to further reduce passive contamination. During retrieval, the quartz filter was quickly removed from the cyclone, enclosed in a petri dish, and placed inside an insulated box with ice packs. Once in the lab, quartz filters were kept in the petri dishes, wrapped in aluminium foil, and placed into a freezer for storage at -20°C until shipped overnight on ice for analysis.

Sampling Intervals:

Sampling was performed over four weeks from April 6th to May 2nd, 2014. To focus on work-hour exposures in the central business district, samplers were programmed using a chrontroller (ChronTrol Corporation, San Diego, CA) to run over five days (7 am – 7 pm, Monday through Friday). NO_2 passive badges collected samples continuously throughout the five days.

Quality Assurance/ Quality Control:

We collected four laboratory blanks, four field blanks, and four co-located samples for all pollutants every session, to identify any potential sources of contamination. For each sampling session, two co-located monitor pairs (one pair each for Teflon™ and quartz filters) were paired at distributed sites, to examine reproducibility.

All Teflon™ and quartz samples (100%) reported met acceptable pre- and post-collection flow rates within 5% of 4 LPM. Co-located measures of $PM_{2.5}$, BC, and NO_2 were highly correlated (r = 0.91 to 0.99) across monitoring locations. Field blanks for all pollutants were near zero, comparable across all four sampling sessions, and used to blank-correct session-specific measured concentrations.

Tunno, B, Michanowicz, DR, Shmool, JLC, Kinnee, E, Cambal, L, Tripathy, S, Gillooly, S, Roper, C, Chubb, L, Clougherty, JE, 2016. Spatial variation in inversion-focused vs 24-h integrated samples of PM2.5 and black carbon across Pittsburgh, PA. *Journal of Exposure Science and Environmental Epidemiology* 26, 365-376