Black Carbon in New Zealand

PK Davy WJ Trompetter

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EXECUTIVE SUMMARY

This report presents a stocktake of black carbon (BC) concentrations measured in atmospheric aerosol samples collected at approximately 40 air quality monitoring sites across New Zealand and identifies the primary sources of the black carbon.

Black carbon is a combustion-derived atmospheric aerosol that has important implications for human health and the Earth's climate. Black carbon is a major component of soot and is produced by incomplete combustion of fossil fuels and biomass emitted from various sources including diesel cars and trucks, residential stoves, forest fires, agricultural open burning and some industrial facilities. The Climate and Clean Air Coalition (on the back of the Paris Agreement) has urged countries to aggressively decrease their emissions of black carbon because significant climate gains are possible over the short-term, given the short atmospheric lifetime of black carbon. As well, the Intergovernmental Panel on Climate Change (IPCC) indicated that they will begin work on a black carbon inventory and associated methodologies for quantifying black carbon. It is important for New Zealand to contribute to this inventory due to its international climate agreements.

The BC monitoring data for New Zealand shows that BC concentrations vary both temporally and spatially. Receptor modelling results indicate that diesel vehicle emissions and biomass combustion are the primary sources of BC in New Zealand urban settings and that high concentrations are associated with areas of greatest combustion emissions density such as adjacent to busy roads or residential locations with a high prevalence of solid fuel fires for domestic space heating. There was also a general north-south increase in biomass combustion contributions to ambient BC concentrations due to a combination of increasing use of solid fuel fires for residential space heating and environmental confinement factors limiting the dispersion of emissions.

It was found that peak BC concentrations were highest (10-15 µg m^{-3} as a 24-hour average) at NZ urban monitoring sites during winter due to BC emissions associated with the use of solid fuel fires for residential space heating, while the influence of motor vehicle related BC emissions resulted in higher annual average (2- 5 µg m^{-3}) BC concentrations in urban centres with high traffic densities relative to the local air quality monitoring site location. At monitoring sites with sufficient data (Whangarei, Auckland and Nelson) the long-term trends showed that BC concentrations were generally decreasing and this was largely due to reductions in motor (diesel fuelled) vehicle emissions of BC, except at Nelson where local policy initiatives to remove open-fire places and replacement of old wood burners with newer, more efficient models also appears to have had a significant effect on reducing local BC concentrations during winter.

Black carbon concentrations at New Zealand urban locations were generally higher than those found in Western European and United States cities. This is most likely due to the time lag for motor vehicle engine emissions technology improvements to enter the New Zealand vehicle fleet and the prevalence biomass combustion for residential heating during winter.

1.0 INTRODUCTION

Black carbon (BC) is a combustion-derived atmospheric aerosol that has important implications for human health and the Earth's climate. Exposure to ambient concentrations of BC has been associated with significant negative impacts on human health, including increased hospital admissions and mortality due to cardiovascular diseases (Dockery et al. 2005; Zanobetti and Schwartz 2006; Geng et al. 2013). Black carbon also plays a unique role in the Earth's climate system. While most aerosols in the atmosphere scatter incoming solar radiation, resulting in a net cooling effect on the atmosphere, BC absorbs significantly more light than it reflects, resulting in a net warming effect. Light absorbing particles radiate long-wave energy that heats the surrounding air. This results in a positive (warming) forcing (Jacobson 2001). The magnitude of BC's warming has recently been estimated to be the 2nd highest warming species, trailing only the effects of carbon dioxide (Bond et al. 2013). Research regarding the concentrations and effects of BC is ongoing, and as more research is undertaken, it is likely that these and other effects will be further quantified.

The primary global sources of BC are combustion engines (especially diesel), residential burning of wood and coal, shipping emissions, power stations using heavy oil or coal, field burning of agricultural wastes, as well as forest and vegetation fires (Bond and Bergstrom 2006; Koch et al. 2009; Chow et al. 2010; Jacobson 2014).

GNS Science has used a particulate matter composition analysis and receptor modelling approach to identify sources of particulate matter in New Zealand airsheds. A direct result of using this technique is that the sources of BC were also derived and the mass contribution of each BC emission source to atmospheric BC concentrations was determined. Therefore, this report not only presents the concentrations of BC measured in New Zealand urban environments but also the primary sources of that BC.

1.1 Report Structure

This report is comprised of 5 main chapters. The remaining chapters have been broken down as follows:

1. Chapter 2 describes BC measurement, sources and physico-chemical properties including composition, size range and consequent human health and global warming effects
2. Chapter 3 presents the BC concentration data currently available from New Zealand air quality monitoring sites, including seasonal variations, observed inter-annual trends and comparisons with international BC data.
3. Chapter 4 assesses methodologies for accounting for BC emissions and identifies the major emission sources in New Zealand.
4. Chapter 5 presents a summary and synthesis of the New Zealand BC data.

The appendices provide more detailed information on BC measurement techniques and monitoring site metadata.

2.0 BLACK CARBON

2.1 Measurement of Black Carbon Concentrations

The absorption and reflection of visible light by particles in the atmosphere or collected on filters is dependent on the particle emission source, concentration, density, refractive index and size. For atmospheric particles, BC is the most highly absorbing component in the visible light spectrum with very much smaller absorption coming from soils, sea salt, sulphates and nitrate (Horvath 1997b). Hence, to the first order it is assumed for the purposes of this study that all of the light absorption by particles on filters is due to BC (sometimes called light absorbing carbon or LAC). Light absorption measurements are an internationally recognised and accepted method of BC determination (Bond and Bergstrom 2006).

Black carbon concentrations in PM samples collected on filters have been determined by the same methodology across all sample sets held by GNS Science. This consistency provides confidence in any inter-comparison between sites and the analysis of temporal trends in BC concentrations. Black carbon has been measured by light absorption using a M43D Digital Smoke Stain Reflectometer (Trompetter et al. 2005; Ancelet et al. 2011b) since PM speciation studies were initiated at GNS Science in 1996. Full descriptions of the light absorbance measurement methodology and derivation of BC concentrations are provided in Appendix 1. A remarkable feature of BC is the stability of measured concentrations even after years of storage. Figure 2.1 presents a plot of BC concentrations on filters from several Auckland sites that were measured in 2007 and then again in 2016 after being stored in the meantime (individual petri dishes in cardboard boxes at room temperature).

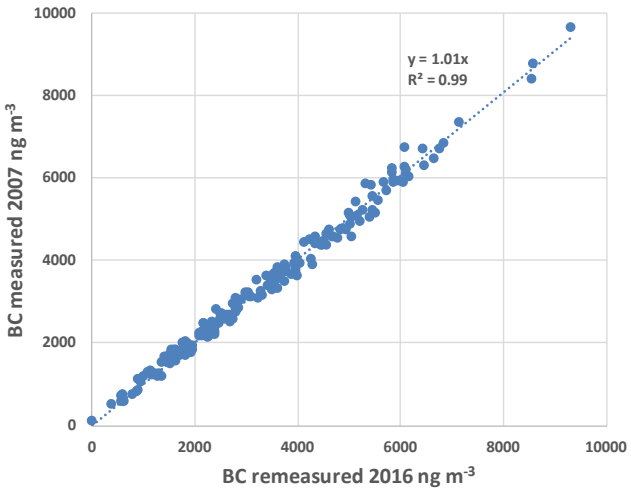

Figure 2.1 Comparison of BC measurements on the same filters after 10 years in storage.

The New Zealand BC measurements have formed part of PM speciation programmes to better understand the composition and sources of PM in New Zealand urban airsheds for exposure assessment, human health protection and air quality management.

2.2 Physico-Chemical Properties of Black Carbon

2.2.1 Black Carbon Formation and Particle Size

Black carbon particle size ranges have been well characterised over a variety of emission sources, both in New Zealand (Davy, Markwitz, et al. 2007; Ancelet et al. 2011a; Ancelet et al. 2011b; Davy et al. 2012; Salako et al. 2012; Ancelet, Davy, Trompetter, et al. 2013; Trompetter et al. 2013) and internationally (Ke et al. 2007; Schneider et al. 2008; Lack et al. 2009; Hays et al. 2011; Lopez-Reyes et al. 2016) and are invariably found to be in the sub-micrometre size range. Black carbon particles can consist of individual spherules 10-30 nm in diameter to larger agglomerations (300 – 500 nm diameter) of individual particles as shown in Figure 2.2. Black carbon (often called "soot" by the combustion community) is usually formed under conditions in which insufficient oxygen is present for complete oxidation of carbonaceous fuel to CO_2 (fuel-rich) (Bond et al. 2004). The characteristics of the combustion source therefore have an important bearing on particle size and carbonaceous composition with high temperature combustion conditions (diesel engines, power stations) producing smaller, graphitic carbon particle entities (Allen et al. 2001; Huang et al. 2006; Ancelet et al. 2011b; Hung et al. 2014) whereas lower temperature biomass combustion (wood fires for home heating, wild fire, forest fires) produce a mixture of carbon agglomerations and larger particles (500 – 900 nm) composed of a soot core and coated in organic 'tar' from incomplete combustion (Posfai et al. 2003; Posfai et al. 2004; Davy, Markwitz, et al. 2007).

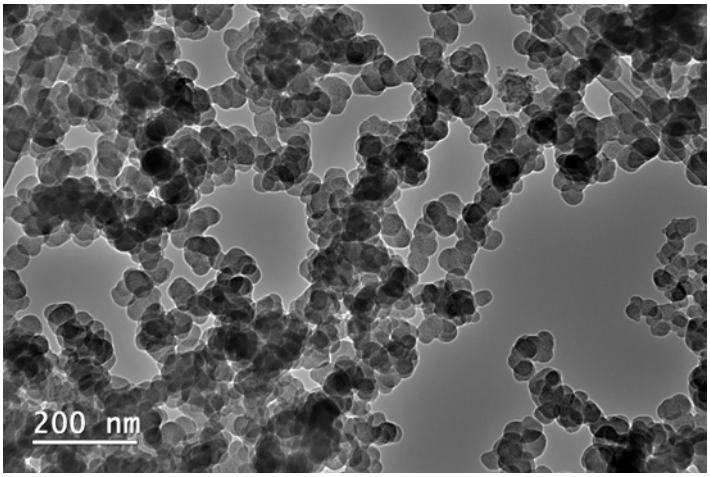

Figure 2.2 Transmission electron microscopy image of carbonaceous particle agglomerations from biomass combustion (the white bar at bottom left spans 200 nanometres) (Source: (Davy and Ancelet 2015).

2.2.2 Health Effects

There is a growing body of evidence for significant health effects associated with exposure to airborne particulate matter pollution less than 10 µm in aerodynamic cross section (denoted as PM_{10}) with an estimated 3.7 million deaths worldwide each year (World Health Organisation 2014) with many more affected by air pollution related illnesses. Since BC is emitted primarily in the sub-micron range and intimately associated with combustion sources, exposure to ambient concentrations of black carbon (BC) have been associated with significant negative impacts on human health (Jansen et al. 2005; Janssen et al. 2011), including increased hospital admissions and mortality due to cardiovascular diseases (Dockery et al. 2005; Zanobetti and Schwartz 2006; Geng et al. 2013). The knowledge base for the health effects of BC has changed over the years in the US, Canada, and Western Europe with regard to all cause, cardiovascular, and cardiopulmonary mortality and morbidity, as well as birth outcomes, cognition, and lung cancer (Grahame et al. 2014). The national burden of BC related health

effects in the United States has been estimated at approximately 14,000 deaths per year (2010 BC levels), and hundreds of thousands of illness cases, ranging from hospitalizations and emergency department visits to minor respiratory symptoms (Li, Henze, et al. 2016).

2.2.3 Atmospheric Lifetime and Global Warming Potential of Black Carbon

Black carbon plays a unique role in the Earth's climate system. While most aerosols in the atmosphere scatter incoming solar radiation, resulting in a net cooling effect on the atmosphere, BC absorbs significantly more light than it reflects, resulting in a net warming effect. Light absorbing particles radiate long-wave energy that heats the surrounding air which results in a positive (warming) forcing effect (Jacobson 2001). Additionally, when BC is deposited on, or precipitated with snow, it lowers the albedo (reflective properties) and the absorbed light heats the snow causing it to melt which has important implications for permanent snowpack such as the Himalayan, Arctic and Antarctic regions (Kim et al. 2005; Flanner et al. 2007; McConnell et al. 2007; Qian et al. 2011; Santos et al. 2014).

The magnitude of BC's warming has recently been estimated to be the 2nd highest warming species, trailing only the effects of carbon dioxide (Bond et al. 2013). The atmospheric lifetime of BC, particularly due to the small particle size which can be transported over long distances, is therefore an important factor in determining the range of such effects. A number of parameters influence the atmospheric lifetime of BC including the emission source (which also dictates composition and internal chemical mixing), the emission height, local meteorology and atmospheric circulation patterns. The most important removal mechanism of BC from the atmosphere is wet deposition (Park et al. 2005; Cape et al. 2012). The results from various studies indicate that the atmospheric lifetime of BC is in the order of days to several weeks which means it is relatively short lived and this is one of the reasons that reductions in BC emissions have been identified as a prime candidate for near-term mitigation of climate forcing (Park et al. 2005; Jacobson 2010; Sasser and Chappell 2011; Cape et al. 2012; Smith and Mizrahi 2013) and associated health effects (Anenberg et al. 2012; Weinhold 2012).

3.0 BLACK CARBON IN NEW ZEALAND

This chapter presents the BC data currently available for the New Zealand monitoring locations identified in Section 3.1 and Appendix 2.

3.1 Black Carbon Sampling Sites in New Zealand

Black carbon samples have been collected and analysed at approximately 40 sites across New Zealand, with some urban areas including multiple sites. For example, Auckland BC data includes sites at Takapuna, Henderson, Kingsland, Newmarket, Auckland CBD, Penrose and Patumahoe (40 km southwest of the CBD). All sites where BC has been collected also included PM elemental speciation with the accompanying receptor modelling and reporting. Figure 3.1 presents the BC sampling locations in New Zealand to date. Appendix 2 identifies the specific locations, sampling period and reporting details.

Figure 3.1 Black carbon sampling locations in New Zealand.

In addition to the urban monitoring locations, several studies have targeted source specific black carbon, these include motor vehicle tunnels (Ancelet et al. 2011b; Davy et al. 2011a) and wood burner emissions (Davy et al. 2009b; Ancelet et al. 2010; Ancelet et al. 2011a) in order to better understand emission source characteristics including BC emissions. The majority of black carbon sampling and analysis campaigns have been targeted studies collecting 24-hour time integrated samples that ran for 1-2 years in order to better understand the local drivers of air pollution for air quality management purposes. The exception to this is the Auckland multi-site air particulate matter speciation database that has been running since mid-2004 and, using archived filters, the BC measurements have been extended back to 1998 at some sites providing a 20-year BC dataset.

For several locations, high-resolution sampling (hourly) and analysis was undertaken as part of a research programme[1] in order to better understand the observed diurnal variation in particulate matter concentrations in New Zealand urban centres (Trompetter et al. 2010; Ancelet et al. 2012; Ancelet, Davy, et al. 2014b; 2014a).

[1] MBIE Contract C05X0903: Understanding air particulate matter pollution
Sources, patterns and transport of air particulate matter in polluted New Zealand urban environments

3.2 Sources of Black Carbon in New Zealand

As indicated in the introduction to this report, the primary global sources of BC are combustion engines (especially diesel), residential burning of wood and coal, shipping emissions, power stations using heavy oil or coal, field burning of agricultural wastes, as well as forest and vegetation fires (wildfire) (Bond and Bergstrom 2006; Koch et al. 2009; Chow et al. 2010; Jacobson 2014). Most of these sources are also present in New Zealand as discussed in this section, however those such as thermal power stations and agricultural waste burning (stubble or scrub and tree burnoffs) are intermittent and more seasonally based. For example, thermal power stations burning fossil fuels are generally only brought into the network if necessary to cover peak power usage and this is most likely during winter or when hydro-lake storage levels are low. While forest and vegetation wildfires can release significant quantities of BC and other pollutants to atmosphere, such (accidental) fires are relatively rare and are generally aggressively managed and extinguished to prevent loss of life, property damage and to protect the forestry estate. Another category of combustion sources emitting BC are those stationary industrial heat generation plant used for manufacturing or processing and localised emergency power generation (primarily diesel powered) used to support essential facilities and services during interruptions to normal electricity supply networks.

3.2.1 Receptor Modelling of Black Carbon Sources

The multivariate analysis of air particulate matter sample composition (also known as receptor modelling or source apportionment) provides groupings (or factors) of elements that vary together over time. This technique effectively ‘fingerprints’ the sources that are contributing to airborne particulate matter concentrations and the mass of each element (including BC) attributed to that source. Most commonly used receptor models are based on conservation of mass from the point of emission to the point of sampling and measurement (Hopke 1999). Their mathematical formulations express ambient chemical concentrations as the sum of products of species abundances in source emissions and source contributions. In other words, the chemical profile of filter based samples of particulate matter collected at a monitoring station is resolved mathematically to be the sum of a number of different factors or sources.

GNS Science has widely used the receptor modelling approach to identify sources of particulate matter in New Zealand airsheds by applying a technique known as Positive Matrix Factorisation (PMF) analysis to particulate matter composition data (Paatero and Tapper 1994; Hopke et al. 1999). A direct result of using this technique is that the sources of BC (or any other variable) were also derived and the mass contribution of each BC emission source to atmospheric BC concentrations was determined. Therefore, this report not only presents the concentrations of BC measured in New Zealand urban environments but also the primary sources of that BC.

3.3 Ambient Black Carbon Sources

The most well characterised sources of BC in New Zealand are those combustion sources that are ubiquitous in the urban setting, namely motor vehicle emissions, solid fuel fires (primarily wood) for home heating and shipping emissions in port towns and cities. Of the New Zealand sampling sites identified in Figure 3.1 and Appendix 2, the most substantive and informative is the multi-site, multi-year speciation network in Auckland where PM samples for BC and elemental analysis have been collected continuously since 2004 (Davy, Trompetter, et al. 2007; Davy et al. 2009a; Davy et al. 2011b; Davy et al. 2014). Using one of these Auckland sites, Takapuna as an example, it was shown that the main sources of particulate matter (PM_{10}) at this location are biomass (wood) combustion, diesel vehicles, petrol vehicles, secondary sulphate aerosol, marine aerosol (sea salt), crustal matter (soil) and an intermittent industrial source (concrete batching plant). The time-series plots for the source contributions to PM_{10} at Takapuna are provided in Figure 3.2. A full description of the site, analytical methodology and derivation of these sources is provided in (Davy et al. 2014). When the analogous plot for BC is examined (Figure 3.3) it shows that the sources of BC are indeed confined to biomass combustion, motor vehicles (primarily diesel fuelled vehicle emissions) and secondary sulphate aerosol. A significant influence on secondary sulphate concentrations is the production of precursor gases such as SO_2 from combustion of sulphur containing fuels in urban areas, hence the association of BC with this source. Shipping emissions from the combustion of high sulphur fuels (fuel oil, bunker oil or residual oil) have been shown to contribute to secondary sulphate aerosol at Auckland sites, particularly since sulphur has been reduced to low levels in automotive diesel and petrol fuels (Davy et al. 2014).

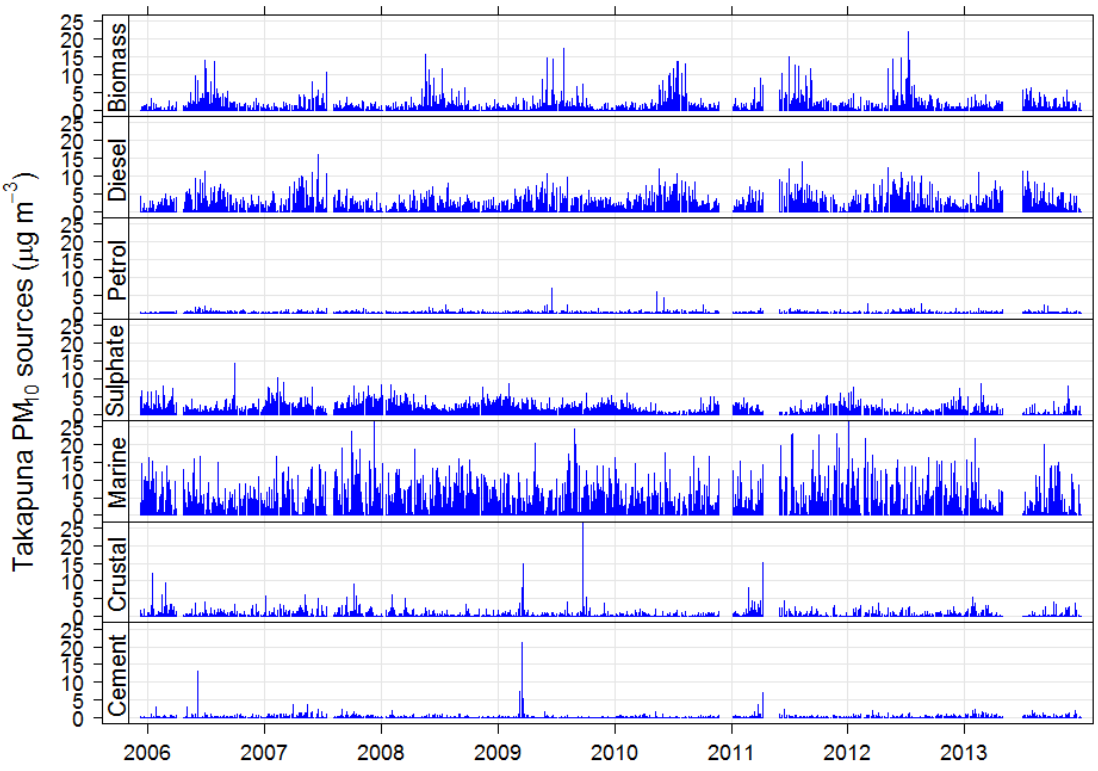

Figure 3.2 Time-series plot of source contributions to PM_{10} at the Takapuna site, Auckland.

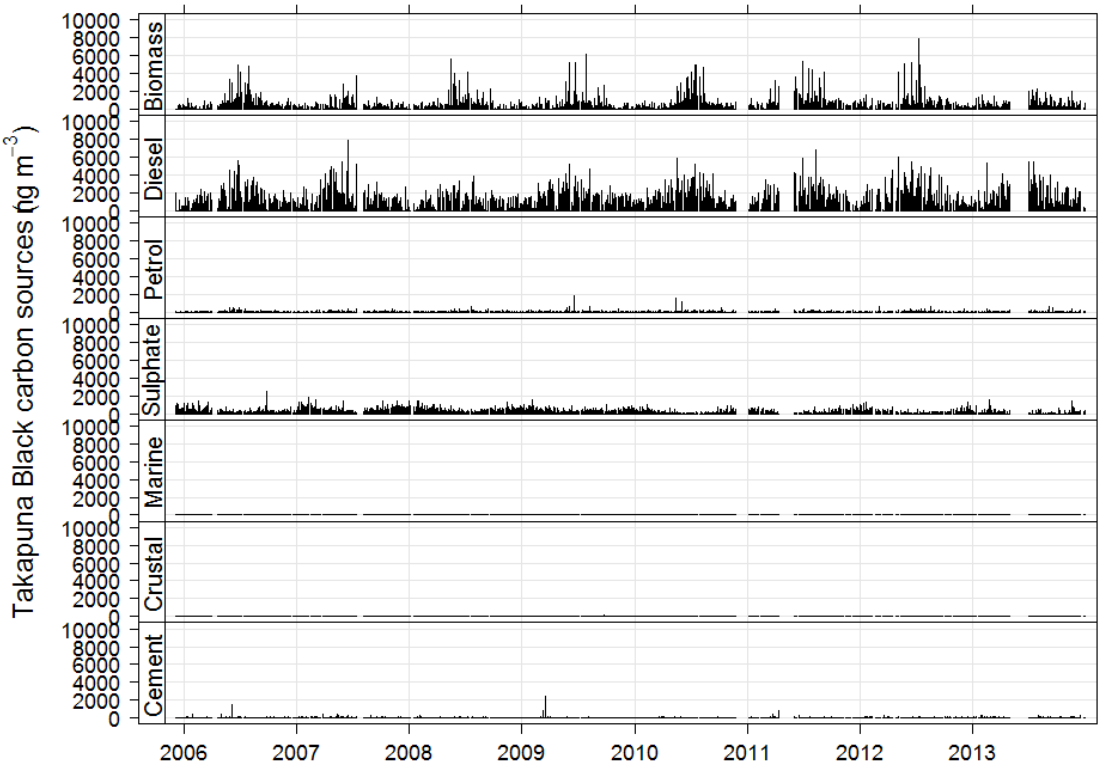

Figure 3.3 Time-series plot of source contributions to BC at the Takapuna site, Auckland.

The average contribution of the Takapuna sources to BC are highlighted in Figure 3.4 where diesel vehicles and biomass combustion dominate BC concentrations. This pattern is repeated across New Zealand with the relative contribution to BC from motor vehicles and biomass combustion dependent on location, proximity of monitoring sites to major roads and whether there is any impact from shipping emissions (in port towns and cities only) or industrial combustion emissions.

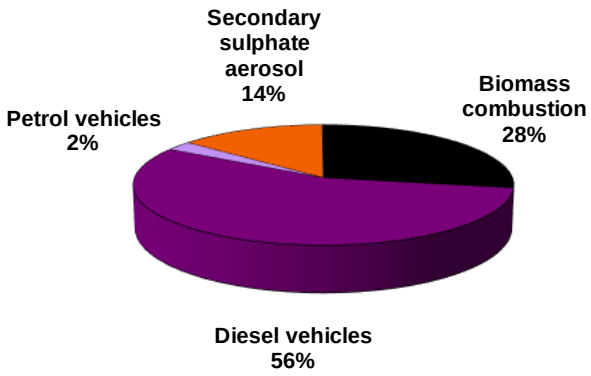

Figure 3.4 Average contribution of sources to ambient BC concentrations at the Takapuna site, Auckland.

3.3.1 Motor Vehicle Emissions of Black Carbon

A PM monitoring and speciation programme was conducted in the north-bound tunnel of the twin Johnstone's Hill road tunnels on State Highway 1 (SH1) north of Auckland over the period from 29 March 2010 until 14 July 2010 on behalf of the New Zealand Transport Agency (NZTA) (Davy et al. 2011a). Amongst the variables included were vehicle type and vehicle counts which enabled the apportionment of BC concentrations in the tunnel to the type of vehicle passing through. As shown in Figure 3.5, the study found that heavy commercial diesel vehicles emissions were responsible for 67 % of motor vehicle related BC concentrations while only making up 10% of the total number of vehicles passing through the tunnel. Diesel powered vehicles in general accounted for 94% of total motor vehicle related black carbon concentrations in the tunnel with only 6% attributed to petrol powered vehicles.

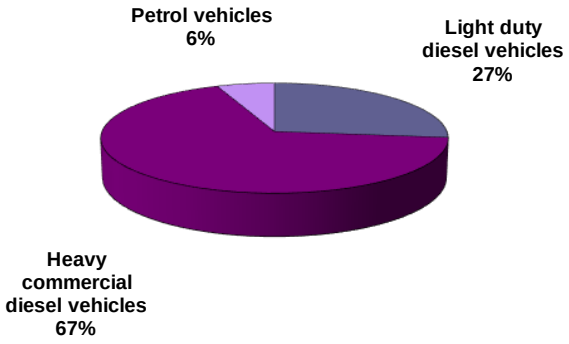

Figure 3.5 Average contribution of motor vehicle related BC emissions to tunnel BC concentrations in the Johnstone's Hill road tunnels, north of Auckland.

This result is not dissimilar to that from the Takapuna monitoring site receptor modelling study, where the motor vehicle BC split was 90% attributed to diesel fuelled vehicles and 10% to petrol vehicle emissions. These results indicate that it can be reasonably assumed that diesel vehicle emissions are primarily responsible for motor vehicle related black carbon concentrations in New Zealand urban airsheds and that this is consistent with international research (Kirchstetter et al. 2008; Kim Oanh et al. 2009; Ancelet et al. 2011b; Wang, Tao, Shen, et al. 2012; Targino et al. 2016). The Auckland ambient BC source apportionment dataset also shows that diesel vehicle $PM_{2.5}$ BC/PM ratios range from 60% to 90% on a mass basis depending on monitoring site location.

3.3.2 Wood Burner Emissions of Black Carbon

In a study of wood burner emissions, samples of wood smoke were taken directly from the flue of a range of different wood burner models (Davy et al. 2009b). The wood burner emission samples were analysed by various techniques, including BC by light reflectance to determine the concentrations of primary elemental species and compound classes associated with emissions from domestic solid fuel fires. It was found that organic carbonaceous (OC) matter from incomplete combustion dominated wood burner mass emissions (91%). Black carbon comprised 5% of total emissions and that inorganic elemental species made up the remaining 4% of wood burner emissions. Furthermore, the OC associated with wood burner emissions contain a range of organic compounds such as polyaromatic hydrocarbons (PAHs) that can have adverse health effects in their own right (Ancelet et al. 2011a; Cavanagh et al. 2012; Ancelet, Davy, Trompetter, et al. 2013). Figure 3.6 presents a plot of the contributions of the different elemental or compound classes to wood burner emissions.

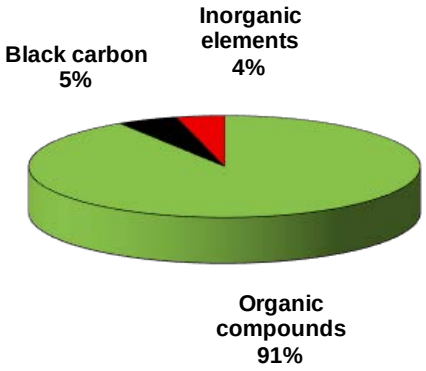

Figure 3.6 Average contribution of black carbon, elemental species and organic compound classes to wood burner total PM mass emissions.

These results help explain why biomass combustion emissions can dominate airborne particulate matter concentrations at times but not necessarily black carbon concentrations, especially at urban locations with denser traffic volumes (higher diesel BC emissions).

3.4 Black Carbon Monitoring Results for New Zealand

As discussed in Section 3.1, most of these BC datasets extend only for 1-2 years except for the Auckland sites where up to 20 years of continuous BC data is available. Table 3.1 presents the BC data from monitoring sites across New Zealand where at least one year of data was available, also included is the ratio of BC to PM concentration. Note that the Auckland datasets have been amalgamated to provide a pan-Auckland average. A number of interesting features in the BC data can be observed from Table 3.1, firstly it shows that winter concentrations are higher than summer due to the influence of biomass combustion emissions of BC combined with calmer more stable wintertime meteorology limiting atmospheric dispersion. Auckland has the highest summer and annual average ambient concentrations of BC due to the influence of motor vehicle emissions of BC and, as a consequence of being the largest urban centre, therefore has the highest population exposure. Smaller centres such as Richmond and Timaru have relatively high annual averages due to the extremes in winter peak BC concentrations due to biomass combustion emissions. The average ratios of BC to PM were relatively similar across urban centres (for summer, winter and annual values), even for a range of different monitoring periods, and may be an empirical method for broad-scale assessment of other centres with PM monitoring but no BC data as yet.

Table 3.1 Black carbon concentrations measured at New Zealand urban monitoring sites.

Site (monitoring period)	PM size fraction	Averaging period	Black carbon (ng m^{-3})	BC:PM Ratio
Whangarei (2004-2012	PM_{10}	Summer	1147	0.10
		Winter	2527	0.18
		Annual	1691	0.15
Auckland (1998-2016)	$PM_{2.5}$	Summer	2726	0.39
		Winter	4437	0.44
		Annual	3495	0.43
Auckland (2001-2016)	PM_{10}	Summer	2961	0.19
		Winter	4689	0.25
		Annual	3679	0.21
Tokoroa (2015-2016)	PM_{10}	Summer	508	0.04
		Winter	4027	0.18
		Annual	1871	0.12
Hastings (2006-2007)	PM_{10}	Summer	958	0.09
		Winter	6598	0.18
		Annual	3311	0.16
Wainuiomata (2006-2013)	$PM_{2.5}$	Summer	167	0.06
		Winter	1571	0.24
		Annual	798	0.16
Masterton (2002-2004)	$PM_{2.5}$	Summer	256	0.07
		Winter	2491	0.19
		Annual	1410	0.15
Nelson (2008-2012)	$PM_{2.5}$	Summer	755	0.14
		Winter	6270	0.22
		Annual	3087	0.20
Nelson (2008-2012)	PM_{10}	Summer	605	0.05
		Winter	5775	0.18
		Annual	2723	0.12
Tahunanui (2008-2009)	PM_{10}	Summer	1009	0.07
		Winter	5903	0.21
		Annual	3034	0.14
Richmond (2013-2016)	PM_{10}	Summer	948	0.07
		Winter	6477	0.28
		Annual	3615	0.19
Christchurch (2013-2015)	$PM_{2.5}$	Summer	639	0.10
		Winter	4739	0.23
		Annual	2179	0.16
Timaru (2006-2007)	$PM_{2.5}$	Summer	1003	0.17
		Winter	7793	0.25
		Annual	3350	0.23
Dunedin (2010)	$PM_{2.5}$	Summer	1791	0.38
		Winter	2460	0.47
		Annual	2139	0.40
Alexandra (1999-2001)	PM_{10}	Summer	646	0.15
		Winter	5271	0.12
		Annual	2752	0.16

The following graphs illustrate the time-series and timelines of the BC datasets currently held. The datasets have been divided into North Island, Auckland, and South Island time-series with all graphs on the same scale for comparative purposes. Details of the monitoring locations are provided in Appendix 2.

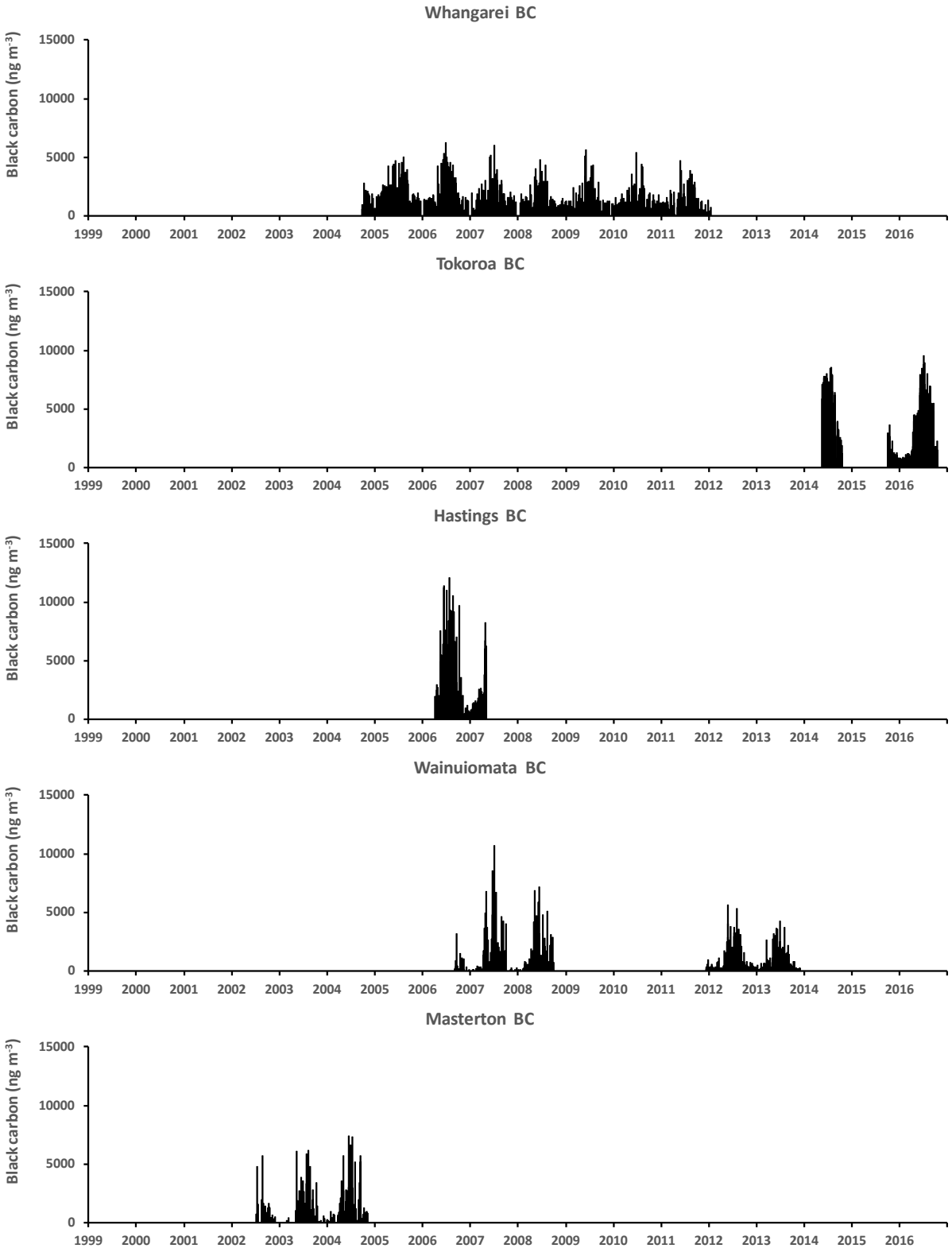

Figure 3.7 Black carbon concentrations measured at North Island monitoring locations.

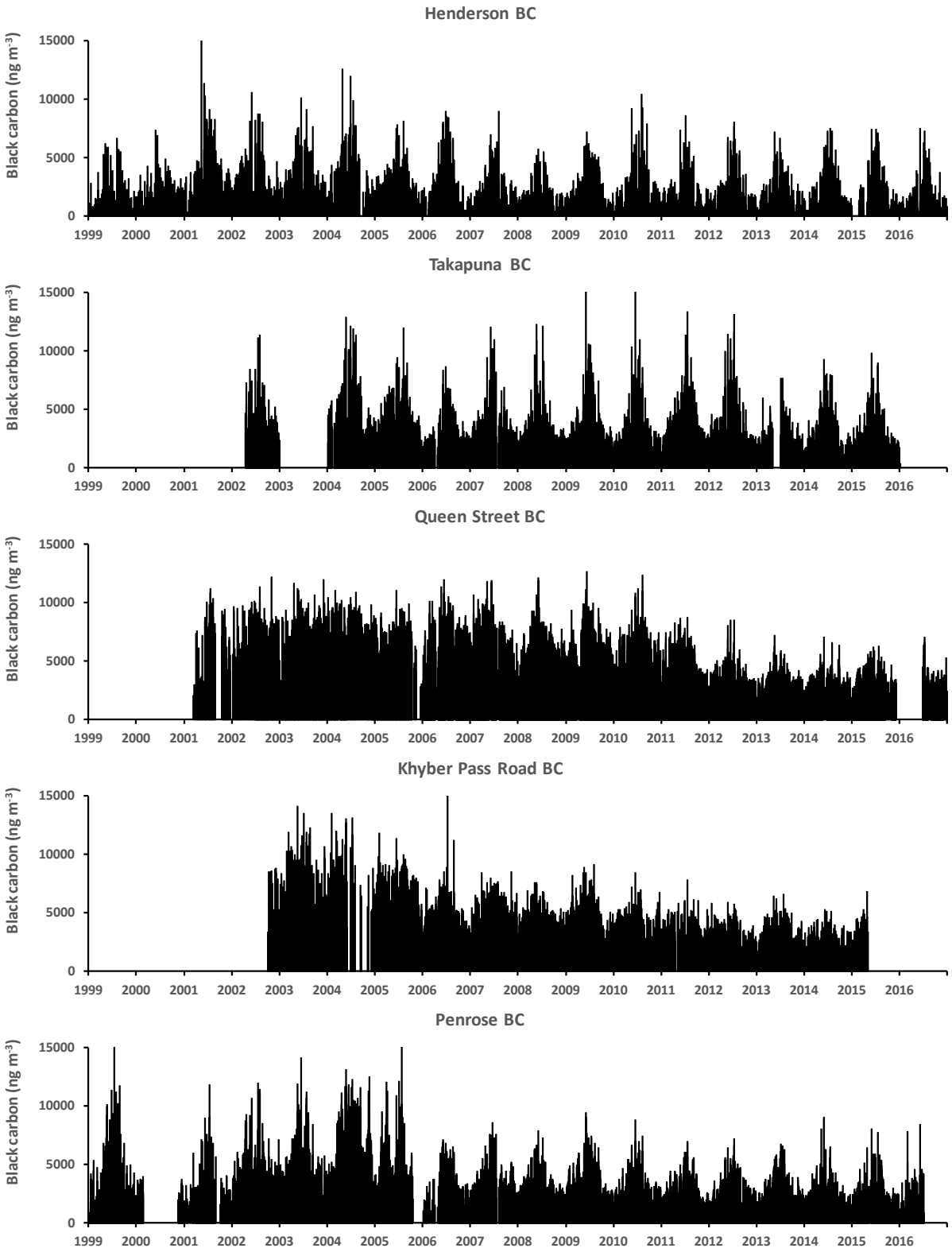

Figure 3.8 Black carbon concentrations measured at Auckland urban monitoring locations.

The Auckland dataset offers a remarkable record of BC concentrations with significant changes evident at the roadside monitoring locations heavily influenced by local traffic (Khyber Pass Road, Queen Street and Penrose). Note that gaps or missing periods in the times-series are due to periods where monitoring was not undertaken. Further discussion on the trends in BC concentrations is provided in Section 3.7.

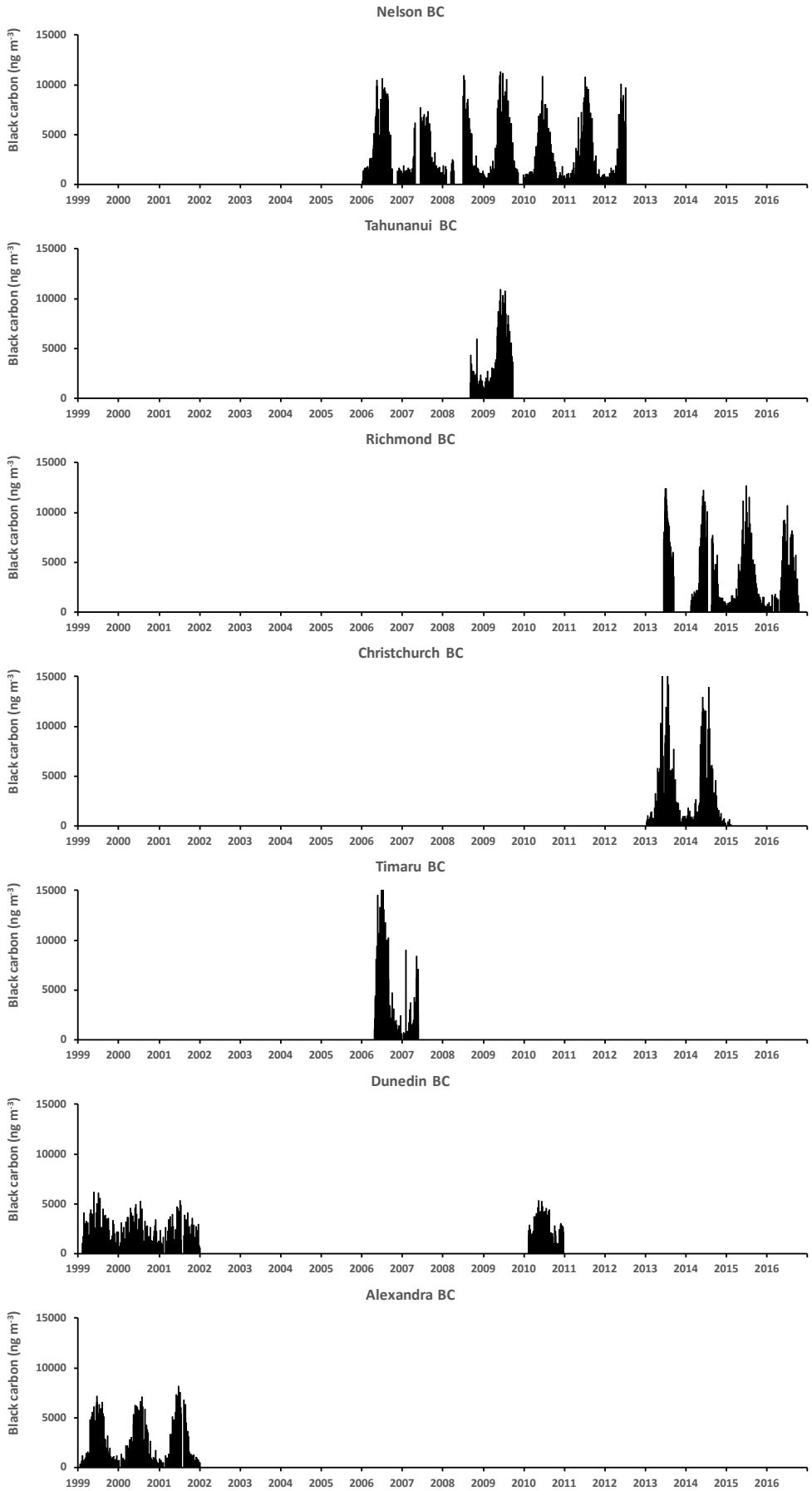

Figure 3.9 Black carbon concentrations measured at South Island monitoring locations.

3.5 Temporal Variations in Black Carbon Source Concentrations

The temporal variations in BC concentrations illustrate the seasonal and weekday/weekend differences in BC concentrations by emission source that reflects a combination of local source emissions activity, meteorological influences and behavioural characteristics such as commuter and commercial traffic patterns and domestic fire lighting practices.

3.5.1 North Island Locations

3.5.1.1 Whangarei

The Northland Regional Council Whangarei monitoring site (Davy and Ancelet 2014) was in the Whangarei CBD, an area of denser traffic, particularly with commercial deliveries by heavy duty diesel vehicles and public transport. Immediately to the northwest of the site is the Whangarei residential suburb of Avenues, an area of older housing that would be likely to use solid fuel fires for domestic heating during winter. Due to the nature of the samples from the Whangarei site, a fully resolved receptor modelling study was not possible and only the generalised temporal variations in BC concentrations are presented in Figure 3.10.

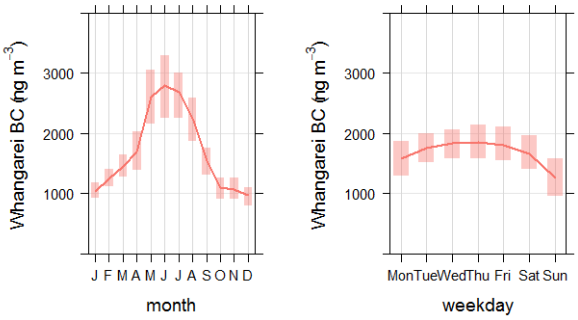

Figure 3.10 Temporal variations in black carbon concentrations measured at the Whangarei site. Shaded areas represent the 95% confidence intervals.

Figure 3.10 shows that there is a general background in BC concentrations all year and that concentrations were highest in winter with lower weekend concentrations (particularly Sunday) that likely reflects local combustion emission source activity (and consequent BC emissions).

3.5.1.2 Tokoroa

The Tokoroa monitoring site (Davy, Ancelet, Trompetter 2017) was located in a residential area away from major roads and therefore BC concentrations were dominated by winter domestic fire emissions.

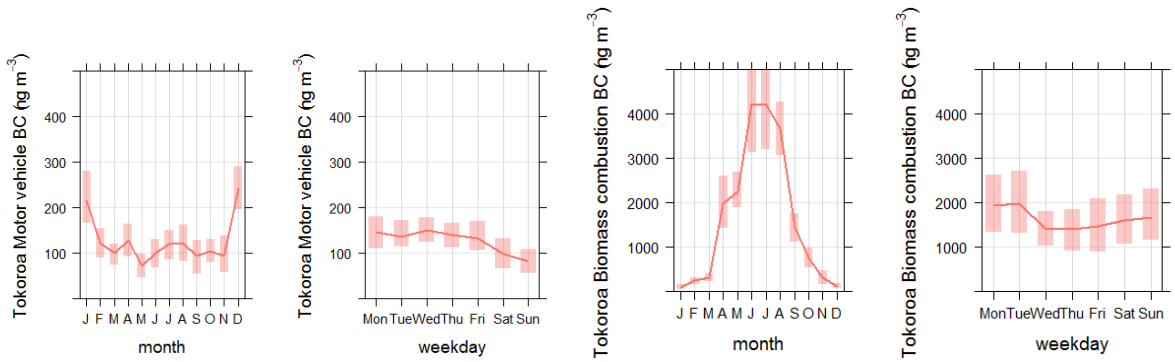

Figure 3.11 Temporal variations in black carbon concentrations by source measured at the Tokoroa site. Shaded areas represent the 95% confidence intervals.

3.5.1.3 Hastings

The Hastings monitoring site was situated at the St Johns Ambient Air Quality monitoring site located at St Johns College in Jervois Street, near the Hastings town centre. (Wilton et al. 2007). As such the data reflects a mix of residential and commercial (primarily transport) emissions activities.

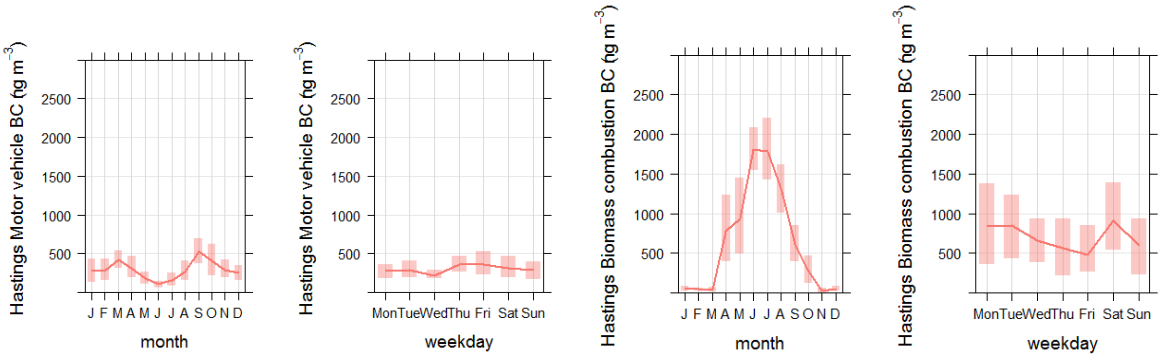

Figure 3.12 Temporal variations in black carbon concentrations by source measured at the Hastings site. Shaded areas represent the 95% confidence intervals.

3.5.1.4 Wainuiomata

Wainuiomata is a satellite suburb of Hutt City and is located in a valley basin relatively isolated from external air quality influences. The Greater Wellington Regional Council monitoring site was in a residential area away from major traffic influences (Davy et al. 2012). Local BC concentrations were highly influenced by winter domestic fire use as shown in Figure 3.13.

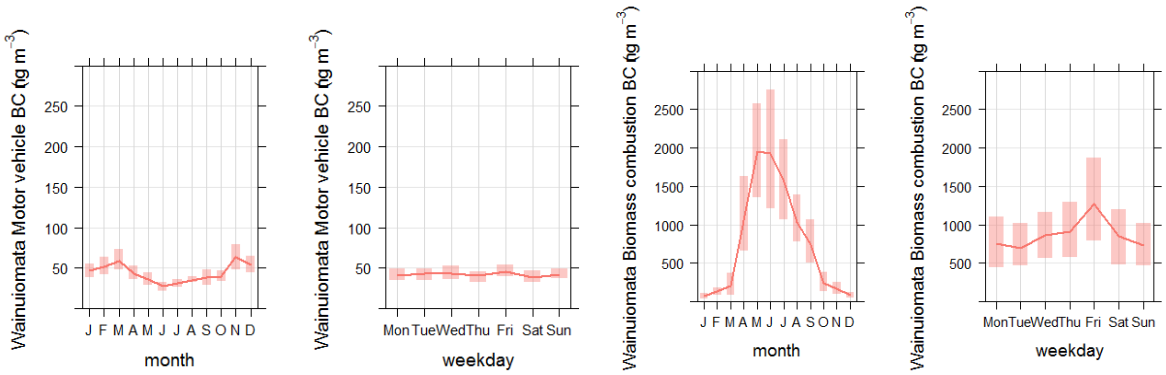

Figure 3.13 Temporal variations in black carbon concentrations by source measured at the Wainuiomata site. Shaded areas represent the 95% confidence intervals.

3.5.1.5 Masterton

The Greater Wellington Regional Council Masterton monitoring site was located in the grounds of Wairarapa College and at least 100m from the nearest road. Black carbon concentrations were strongly influenced by domestic fire emissions during winter (Davy et al. 2005).

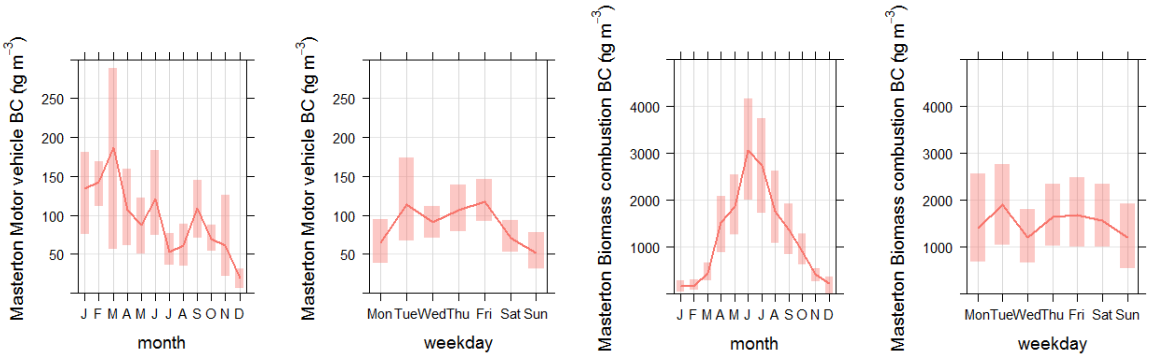

Figure 3.14 Temporal variations in black carbon concentrations by source measured at the Masterton site. Shaded areas represent the 95% confidence intervals.

3.5.2 Auckland City Locations

While it is clear from Figure 3.8 that there were differences between BC concentrations at the Auckland monitoring sites, this is mostly reflective of combustion emission activities in the vicinity of the air quality monitoring site (Davy et al. 2014). The primary drivers of these local variations in BC concentrations were local traffic density (Xie et al. 2015) (particularly with respect to heavy commercial vehicle activity) and the density of residential dwellings with a reliance on biomass combustion for winter space heating. The Auckland BC source data has been aggregated to represent a pan-urban perspective on the relative contributions of combustion sources to BC concentrations by dividing the data into two air quality monitoring site classes, peak traffic (Khyber Pass Road, Queen Street and Penrose) and peak residential (Takapuna and Henderson). These two classes are presented in Figure 3.15 and Figure 3.16 respectively.

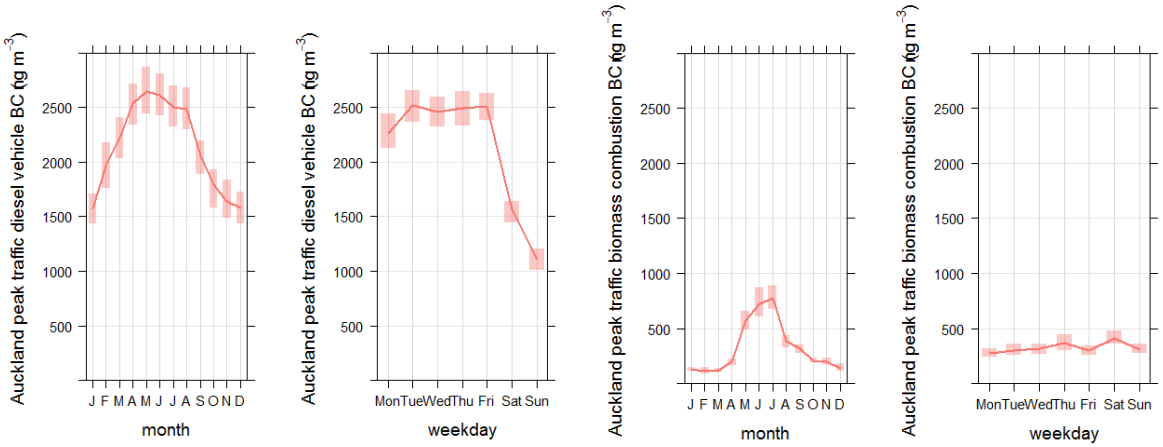

Figure 3.15 Temporal variations in black carbon concentrations by source measured at Auckland peak traffic sites. Shaded areas represent the 95% confidence intervals.

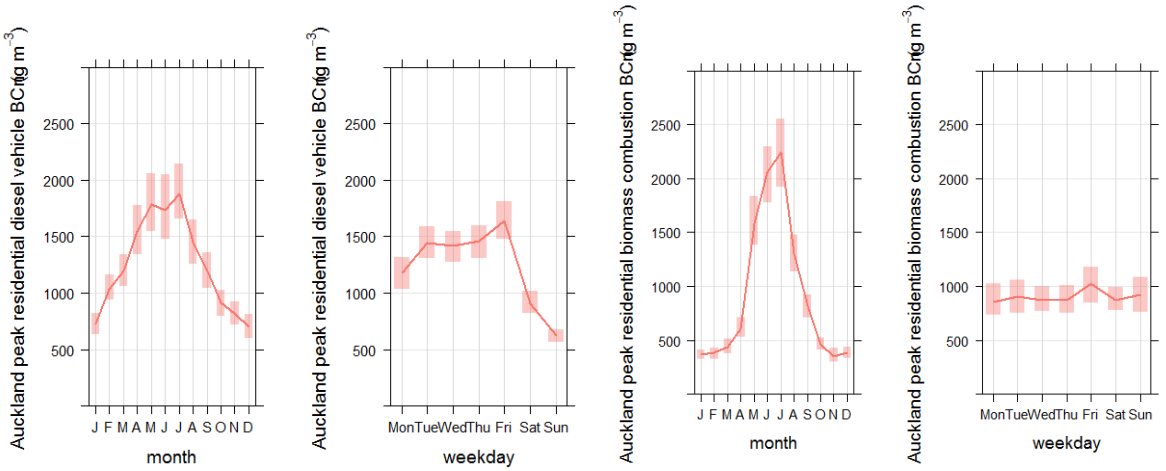

Figure 3.16 Temporal variations in black carbon concentrations by source measured at Auckland peak residential sites. Shaded areas represent the 95% confidence intervals.

Figure 3.15 and Figure 3.16 illustrate the relative influence of BC emission sources on the local monitoring site with domestic fire emissions of BC a significant contributor to atmospheric loadings at residential locations. Another interesting feature of the diesel vehicle contribution to atmospheric concentrations was that concentrations were slightly lower on Mondays (15% of Mondays are public holidays) and significantly lower for weekends.

3.5.3 South Island Locations

3.5.3.1 Nelson

The Nelson City Council monitoring site was located in a valley with a mix of commercial and residential activities near the central business district. While commercial activities and traffic have an impact at the location, BC concentrations were still dominated by winter domestic fire emissions (Ancelet, Davy, Trompetter 2013; Ancelet, Davy, et al. 2014b; Ancelet et al. 2015).

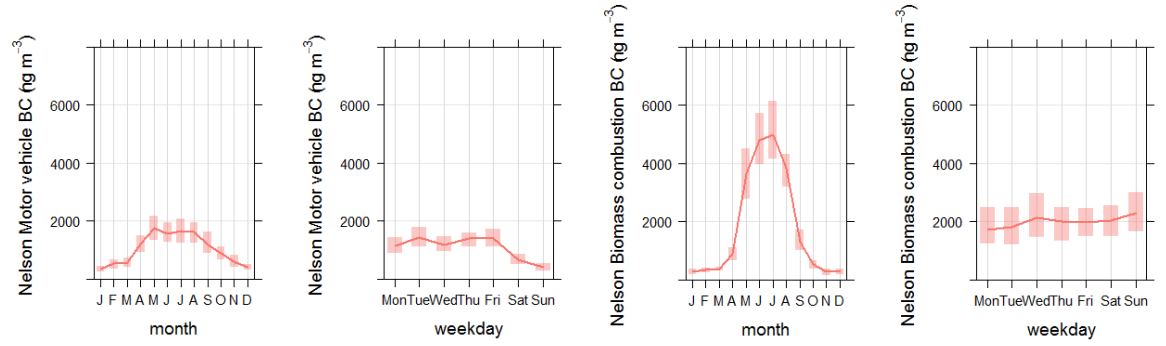

Figure 3.17 Temporal variations in black carbon concentrations by source measured at the Nelson site. Shaded areas represent the 95% confidence intervals.

3.5.3.2 Tahunanui

The Nelson City Council Tahunanui air quality monitoring site is located between an area of commercial/industrial activity and residential dwellings and therefore BC concentrations reflect the mix of these activities (Davy et al. 2010; Ancelet, Davy, Trompetter, Markwitz 2014). However, as shown in Figure 3.18, domestic fire emissions dominate ambient BC concentrations during the winter.

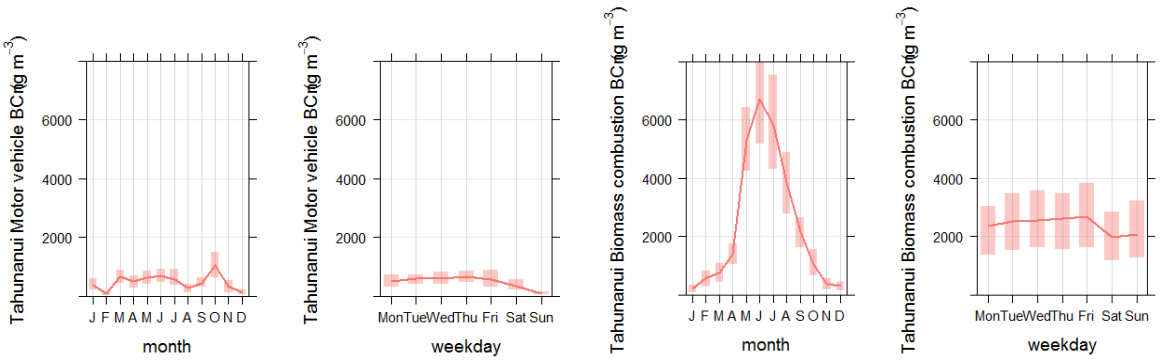

Figure 3.18 Temporal variations in black carbon concentrations by source measured at the Tahunanui site. Shaded areas represent the 95% confidence intervals.

3.5.3.3 Richmond

The Tasman District Council monitoring site on Oxford Street was at the interface of the Richmond commercial precinct and residential dwellings (Davy and Trompetter 2017) and therefore reflects a mix of commercial and private traffic sources as well as domestic fire missions of BC.

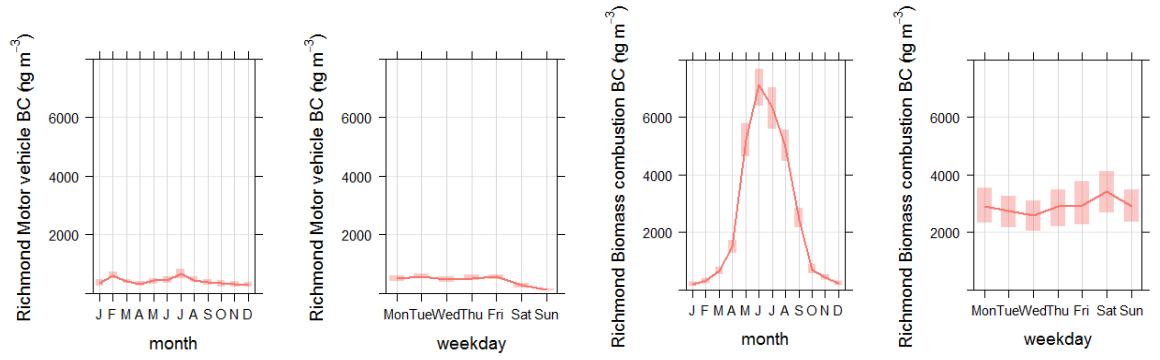

Figure 3.19 Temporal variations in black carbon concentrations by source measured at the Richmond site. Shaded areas represent the 95% confidence intervals.

3.5.3.4 Christchurch

Black carbon sampling was performed at the Environment Canterbury Coles Place monitoring site in St Albans, the primary long-term air quality monitoring site in Christchurch (Davy et al. 2016). The sampling site is located in a residential area adjacent to tennis courts at the end of a cul-de-sac. The immediate surrounding environment is dominated by older, medium to high-density residential dwellings. The closest arterial road, Cranford St (SH 74), is approximately 380 m to the east, and 240 m to the south is Edgeware Rd, a busy urban route.

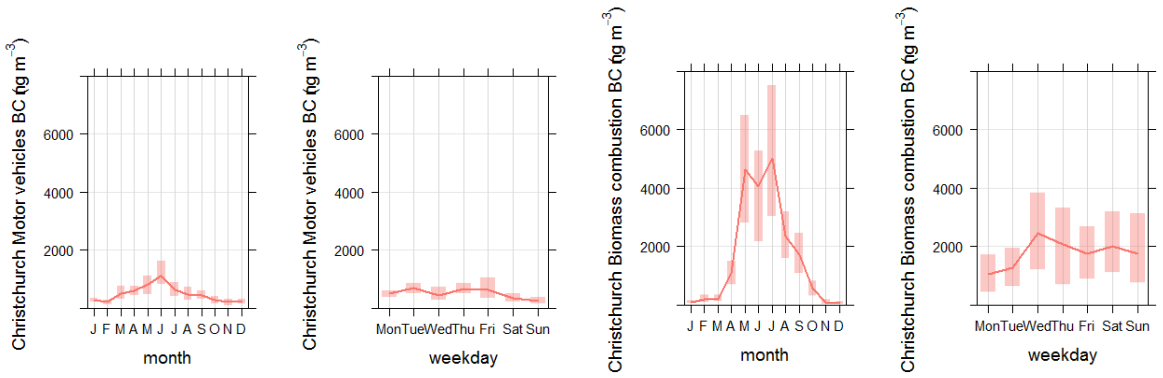

Figure 3.20 Temporal variations in black carbon concentrations by source measured at the Christchurch site. Shaded areas represent the 95% confidence intervals.

The relative distance to main roads and the immediate proximity of residential housing is reflected in the dominance of winter biomass combustion contributions to ambient BC concentrations at the Christchurch monitoring site.

3.5.3.5 Timaru

Particulate matter samples for BC analysis were collected at Environment Canterbury's Timaru air quality monitoring station located at Anzac Park, 1 km south of the CBD (Scott 2014). The station is situated in a residential area, a short distance from State Highway 1 and less than one kilometre from the coast (east) and port (north-east). As shown in Figure 3.21, the site at Timaru has recorded the highest winter monthly averages of BC of the New Zealand urban locations monitored to date.

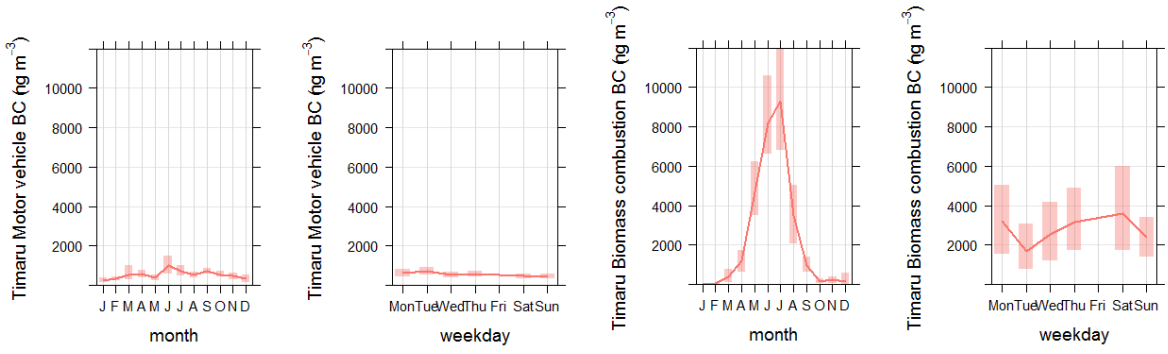

Figure 3.21 Temporal variations in black carbon concentrations by source measured at the Timaru site. Shaded areas represent the 95% confidence intervals.

Particulate matter concentrations at Timaru regularly exceed the PM_{10} NES (24-hour average and $PM_{2.5}$ AAQG (24-hour average) monitoring guideline during winter, primarily due to emissions from solid fuel fires for domestic space heating (Scott 2014).

3.5.3.6 Dunedin

Samples of airborne particles were collected at an ambient air quality monitoring station located on the corner of Albany Street and Anzac Avenue in central Dunedin. The Albany Street site is located in a mixture of commercial and residential activities with the port area and harbour 800m to the east. The influence of motor vehicle emissions of BC relative to emissions from biomass combustion activities at the Dunedin site is evident from the monthly and weekday averages as presented in Figure 3.22.

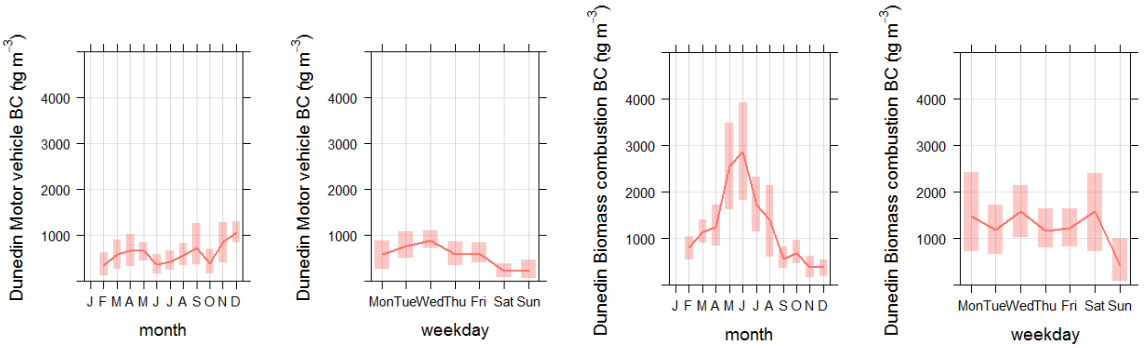

Figure 3.22 Temporal variations in black carbon concentrations by source measured at the Dunedin site. Shaded areas represent the 95% confidence intervals.

This is driven by a greater density of commercial activities and road traffic in the vicinity of the monitoring station.

3.6 Diurnal Patterns in Black Carbon Concentrations

In a series of studies designed to examine and explain the observed day-night patterns in winter particulate matter concentrations (Trompetter et al. 2010) and the contributing emission sources, hourly samples of PM were collected and the concentrations of BC were determined alongside elemental concentrations at Masterton, Alexandra, Nelson and Takapuna (Auckland) during the winters of 2010 to 2012. The receptor modelling results showed that peak biomass combustion BC contributions occur during early to late evening with a smaller peak in early morning due to relighting of fires for domestic heating purposes (Ancelet et al. 2012; Ancelet et al. 2014a; 2014b). Black carbon associated with motor vehicle emissions was found to follow a daytime pattern with peaks in the morning and afternoon associated with traffic density ('rush hour'). These differing BC emission patterns are clearly shown in Figure 3.23 for Takapuna during winter 2012 (6 to14 July) where the motor vehicle contributions to BC were the highest of all the study locations because of local traffic densities.

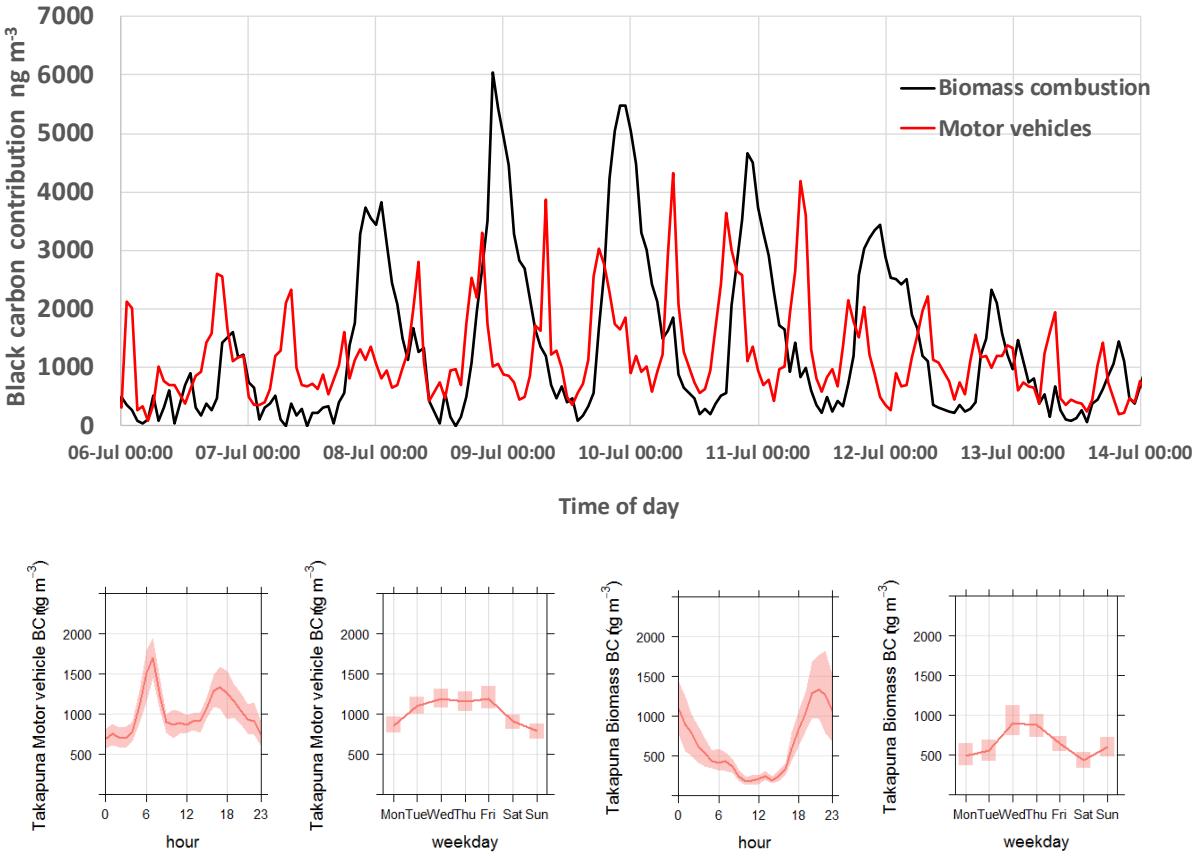

Figure 3.23 Diurnal variations in black carbon concentrations by source measured at the Takapuna site from 6 to 14 July 2012. Shaded areas represent the 95% confidence intervals.

The diurnal BC concentrations reflect the BC emission patterns of the different combustion sources which has implications for both human exposure and the transport and fate of BC in the atmosphere due to the change in meteorological conditions between night and day. Black carbon profiles in the atmosphere were also measured vertically and temporally using a portable aethalometer at the four New Zealand urban locations identified above (Trompetter et al. 2013). During winter, with clear skies and calm weather conditions, radiative cooling causes surface temperatures to fall quickly in the evenings. Vertical temperature and BC profiles show the formation of inversion conditions and the evolution of the boundary layer from a deep, well mixed convective layer into two distinct nocturnal layers: the stable boundary layer (SBL) and the higher residual layer (RL). The BC plots presented in Figure 3.24 show the

vertical extent and profile of BC in Nelson, which was mostly confined to a surface layer less than 50 m in height from the surface. During the night, the surface-based thermal inversion strengthens, causing the mixing height to decrease, reducing the volume of atmosphere that is available for BC to be dispersed into, which in turn exacerbates the observed BC pollution episodes at ground level. The measured profiles were consistent with typical PM_{10} diurnal cycles (Trompetter et al. 2010).

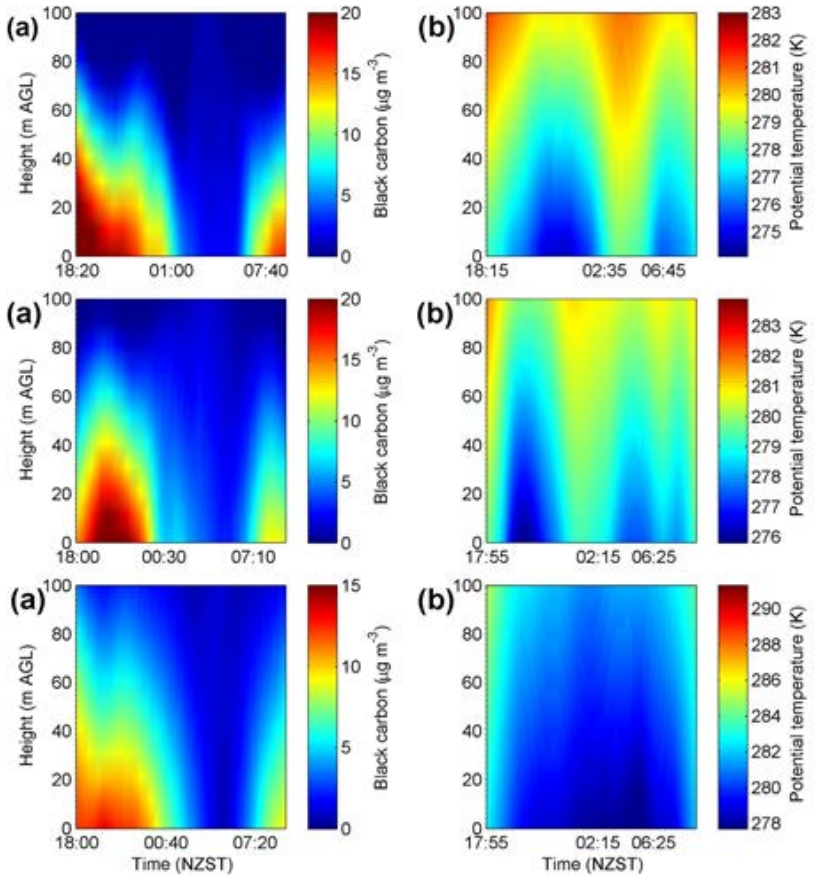

Figure 3.24 Results from Helikite flights in Nelson from 18th July 2011 (top), 19th July 2011 (middle) and 20th July 2011 (bottom) showing a) BC, b) potential temperature.

The BC concentrations and analysis indicated that inversion events in the confined urban valleys were the main factor contributing to the elevated concentrations during winter evenings, followed by the dispersion of pollutants by katabatic wind-flows, effectively clearing the boundary layer leading to decreased BC concentrations during the early morning. The evidence also suggests that rather than being dispersed into the general atmosphere, the winter emissions of BC may be deposited to the surrounding environment by gravitational settling and co-condensation with moisture. The relative importance of dispersion to the wider atmosphere versus more localised deposition of BC from winter biomass combustion emissions has yet to be determined but does have implications for any subsequent estimation of atmospheric warming potential.

3.7 Temporal Trends in Black Carbon Concentrations

Long-term temporal trends in BC concentrations are important when considering policy options or intervention strategies for reduction targets. For a trend analysis to be meaningful, the length of ambient BC monitoring record needs to be sufficient to smooth out inter-annual meteorological influences, particularly for biomass combustion sources associated with residential space heating as winters which have more cold and calm days can have a significant influence on peak (and average) ambient PM concentrations associated with source emissions. There are only a few long-term BC monitoring records from ambient air quality monitoring sites in New Zealand for which trends can be extracted, these are from the Whangarei, Auckland and Nelson monitoring sites.

The analysis of trends in the BC concentration and source contribution data are accompanied by confidence interval estimates for the observed trends. The following paragraph describes the basis of the TheilSen function and is taken from Carslaw 2015.

> *Given a set of n x, y pairs, the slopes between all pairs of points are calculated. Note, the number of slopes can increase by ≈ n^2 so that the number of slopes can increase rapidly as the length of the data set increases. The Theil-Sen estimate of the slope is the median of all these slopes. The advantage of the using the Theil-Sen estimator is that it tends to yield accurate confidence intervals even with non-normal data and heteroscedasticity (non-constant error variance). It is also resistant to outliers — both characteristics can be important in air pollution. As previously mentioned, the estimates of these parameters can be made more robust through bootstrap-resampling, which further adds to the computational burden, but is not an issue for most time series which are expressed either as monthly or annual means. Bootstrap resampling also provides the estimate of p for the slope. (Carslaw 2015)*

Only those trend results with statistical significance (p) above the 90th percentile confidence intervals have been considered in the current work. All TheilSen trend analyses were generated using deseasonalised (using the functionality available within *openair*) data to remove seasonal effects.

3.7.1 Trends in Black Carbon at Whangarei

The analysis of trends in the Whangarei BC concentration data (2004–2012) shows that year-on-year BC concentrations were decreasing (Figure 3.25).

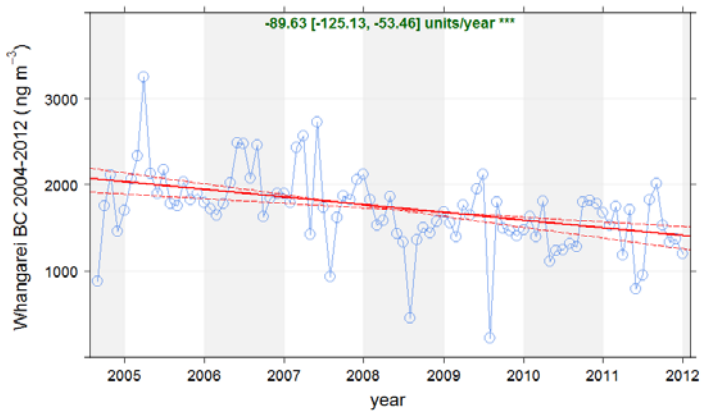

Figure 3.25 Trend analysis (deseasonalised) for Black Carbon concentrations at the Whangarei site. The solid red line indicates the trend estimate, while the dashed red lines indicate the 95% confidence intervals for the trend based on data resampling methods.

Figure 3.25 shows that BC decreasing at about 0.1 µg m^{-3} per year (99.9% confidence interval). The trends in BC concentrations on a seasonal basis it was found that the long-term decrease in BC was most significant during winter (99% CL) as shown in Figure 3.26.

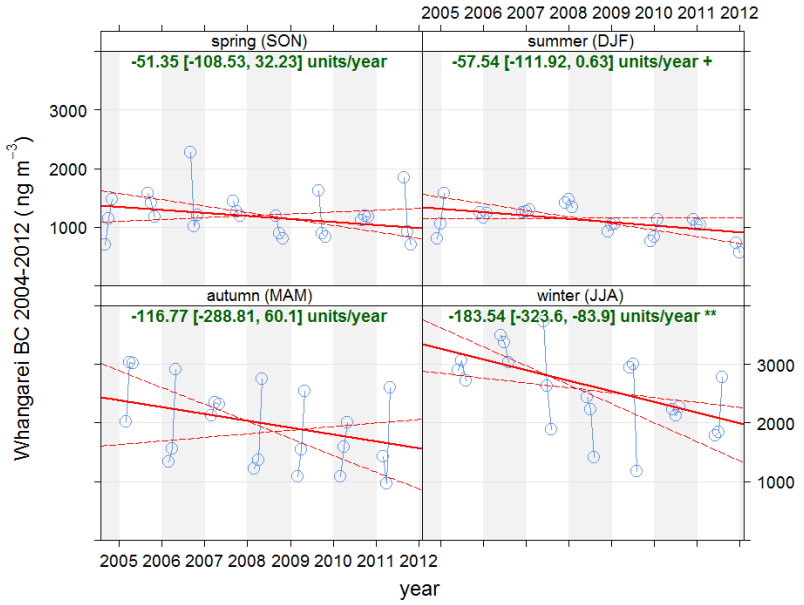

Figure 3.26 Seasonal trend analysis for Black Carbon concentrations at the Whangarei site. The solid red line indicates the trend estimate, while the dashed red lines indicate the 95% confidence intervals for the trend based on data resampling methods.

Interestingly, the data suggests that there has also been a significant (90%ile confidence interval) decrease in summer BC concentrations and this may reflect a reduction of BC emissions associated with motor vehicles.

3.7.2 Trends in Black Carbon at Auckland

A high-level approach using pan-Auckland BC concentrations (1998-2016) shows higher BC concentrations at peak traffic sites (Queen street and Khyber Pass Road) than in the peak residential sites (Takapuna and Henderson) as presented in Figure 3.27. Note that the specific time periods differ as datasets were matched to contiguous sampling for the site type. The compositional data shows that BC is a major component of $PM_{2.5}$ and that BC mass contributes around 40 % of Auckland $PM_{2.5}$ concentrations on average at both types of monitoring site. Black carbon concentrations also display a clear seasonality with peak BC concentrations during winter months (June-August).

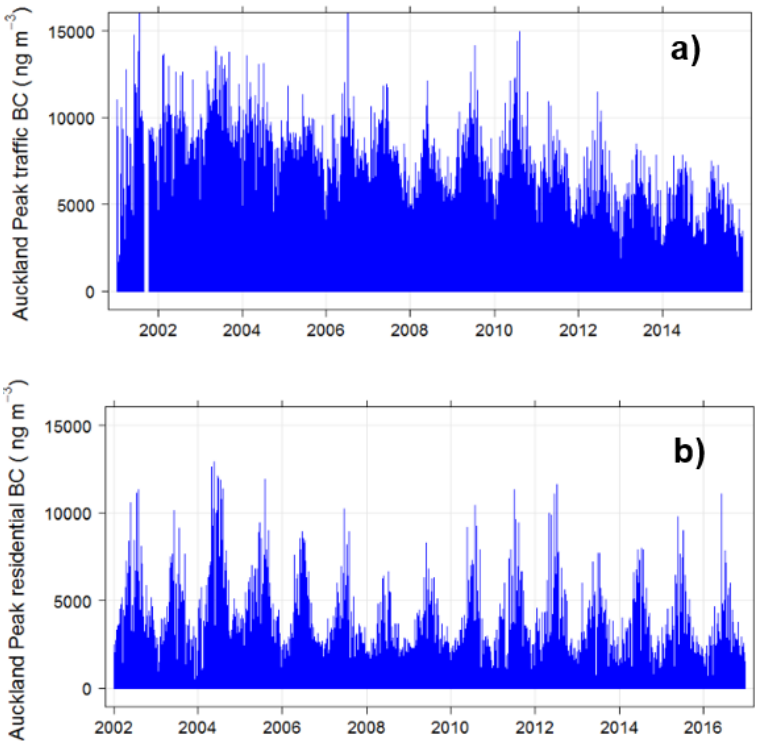

Figure 3.27 BC concentrations at (a) peak traffic and, (b) peak residential monitoring sites in Auckland.

All Auckland sites show a decreasing trend (statistically significant to the 99.9 % confidence intervals) in BC concentrations and the rate of decrease has been greater at peak traffic sites as shown in Figure 3.28.

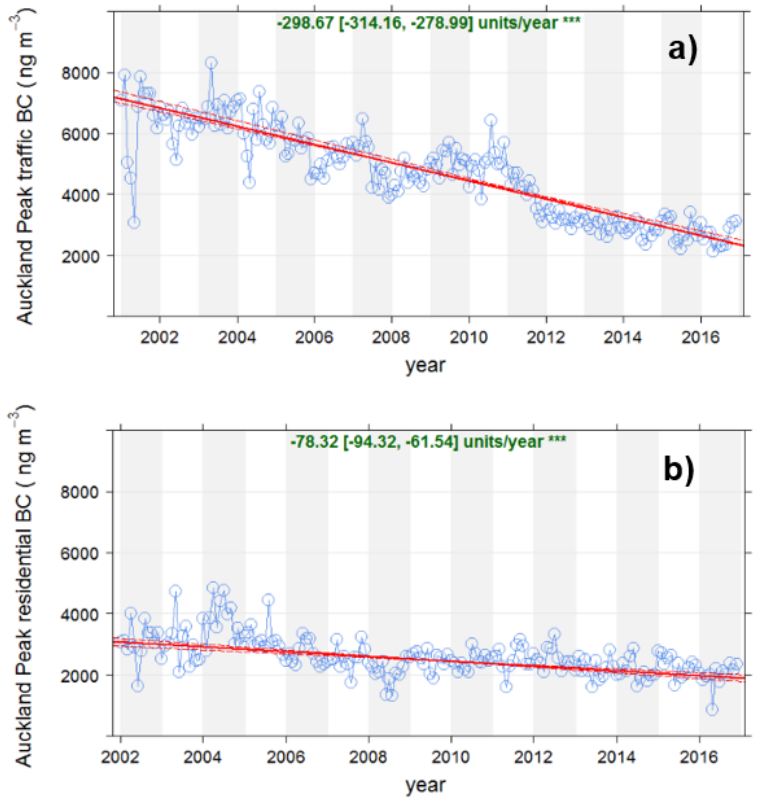

Figure 3.28 Long-term BC trends at (a) peak traffic and, (b) peak residential sites in Auckland. The solid red line indicates the trend estimate, while the dashed red lines indicate the 95% confidence intervals for the trend based on data resampling methods.

Receptor modelling of speciated PM filter samples from the Auckland monitoring sites (covering years 2006-2013) provided the means to apportion the BC concentrations to contributing sources (Petersen et al. 2009; Davy et al. 2014). The source contributions to BC at peak residential sites were dominated by residential wood combustion and diesel vehicle emissions (38 % and 47 % respectively). Diesel fuelled vehicle emissions were the most significant contributor (66 %) to BC concentrations at peak traffic sites (Queen Street and Khyber Pass Road). It was found that the observed decreasing trend in pan-Auckland BC concentrations were driven by a reduction in apportioned diesel vehicle BC emissions, while interestingly, the apportioned residential wood burning contributions to BC appeared to be slowly increasing (at 99.9 % confidence intervals) as presented in Figure 3.29.

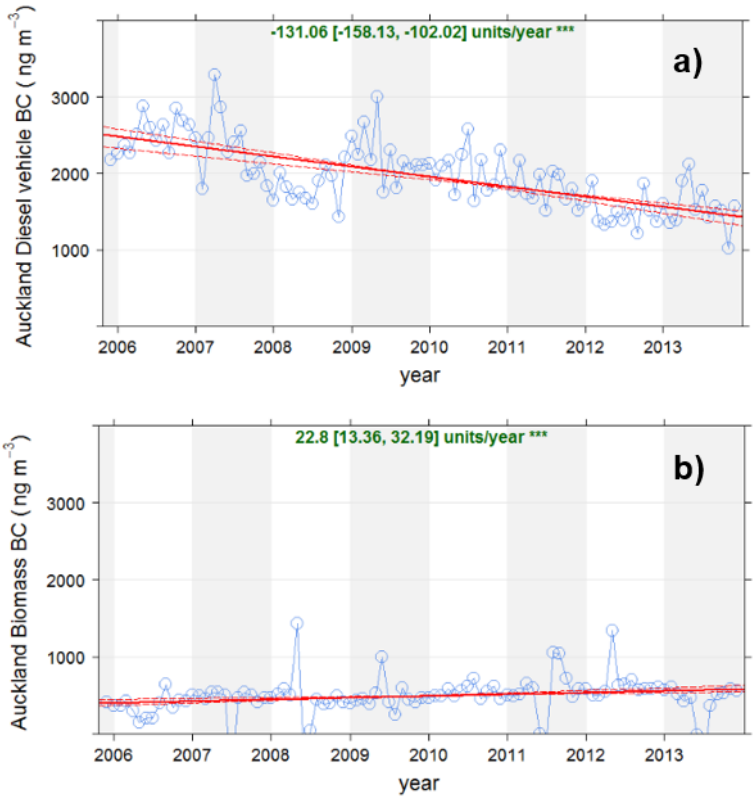

Figure 3.29 Trends in BC associated with (a) diesel vehicle emissions and (b) residential wood combustion in Auckland. The solid red line indicates the trend estimate, while the dashed red lines indicate the 95% confidence intervals for the trend based on data resampling methods.

The decreasing trend in BC concentrations at a particular Auckland monitoring site were dependent on the relative influence of motor vehicle emissions at the site, with factors such as the proximity of the monitoring site to the nearest roadway, local traffic density (particularly with respect to heavy duty diesel vehicles) and prevailing wind direction all playing a part. Over the monitoring period there was several step-changes in automotive fuel composition in New Zealand, particularly due to the Petroleum Products Specifications Regulations 2002 which dictated the reduction of sulphur in diesel and petrol over a period of time as summarised in Table 3.2.

Table 3.2 Key dates for the reduction of sulphur in automotive fuels as specified in the Petroleum Products Specifications Regulations 2002.

Year	Regular petrol (Sulphur ppm)	Premium petrol (Sulphur ppm)	Diesel (Sulphur ppm)
1998	500	500	3000
Petroleum Products Specifications Regulations 2002			
1 May 2007	150	150	50
1 January 2008	50	50	50
1 January 2009	50	50	10

The key dates identified in Table 3.2 have been marked on the trend analysis plot of sulphur concentrations over the years 2006 – 2010 as presented in Figure 3.30. This shows that the reduction in sulphur concentrations largely occurred during this period (95 % confidence interval) with no statistically significant trend in sulphur concentrations evident for the years 2010 – 2014 as shown in Figure 3.31.

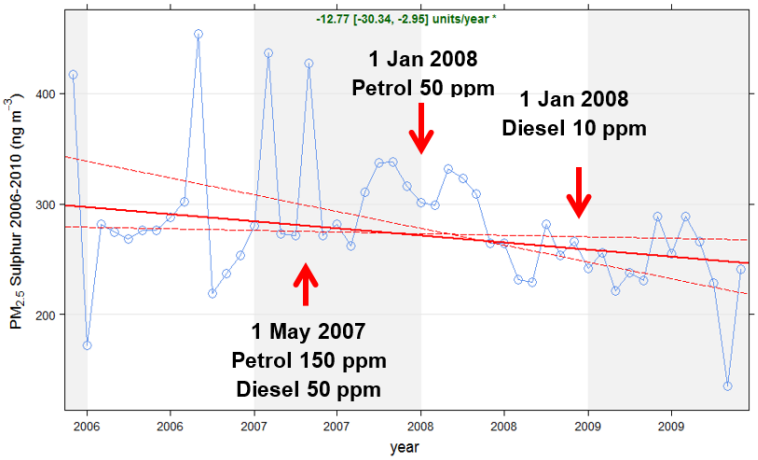

Figure 3.30 Trend analyses for 2006-2010 showing a decrease in sulphur in all Auckland $PM_{2.5}$ samples (statistically significant at the 95 % confidence limits).

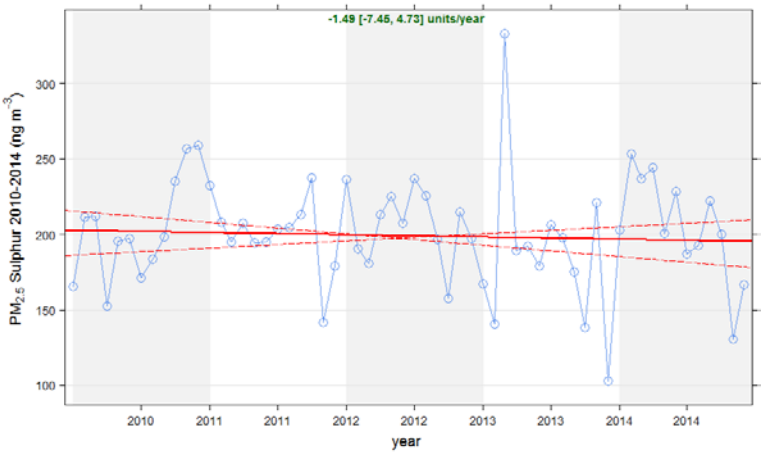

Figure 3.31 Trend analyses for 2010-2014 showing no statistically significant trend over the period for sulphur in all Auckland $PM_{2.5}$ samples.

It is likely that the reduction in sulphur content in automotive fuels is also in part responsible for the observed reduction in diesel powered vehicle tailpipe emissions. The reduction of sulphur containing aerosol is a demonstrable impact of policy (and regulation) for improving urban air pollution.

Interestingly, the long-term trend for the ratio of BC to total $PM_{2.5}$ concentrations has remained remarkably stable over the Auckland dataset as shown in Figure 3.32 and Figure 3.33 for the Khyber Pass Road and Takapuna monitoring sites respectively. The Khyber Pass Road site had a slight decrease in the BC:$PM_{2.5}$ ratio (95% CI) over the 2006 - 2015 period, with the average ratio at 41%.

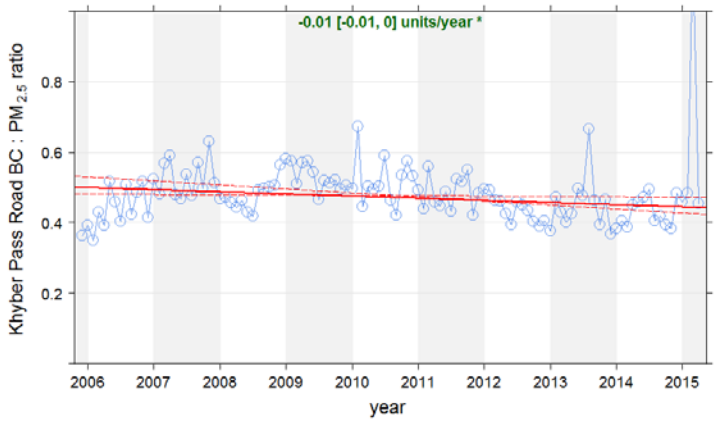

Figure 3.32 Trend analysis (deseasonalised) for BC:$PM_{2.5}$ ratio at the Khyber Pass Road site. The solid red line indicates the trend estimate, while the dashed red lines indicate the 95% confidence intervals for the trend based on data resampling methods.

Whereas for the Takapuna site, the BC:$PM_{2.5}$ ratio has remained stable at about 40% over the 2006 – 2016 period with no statistically significant trend evident.

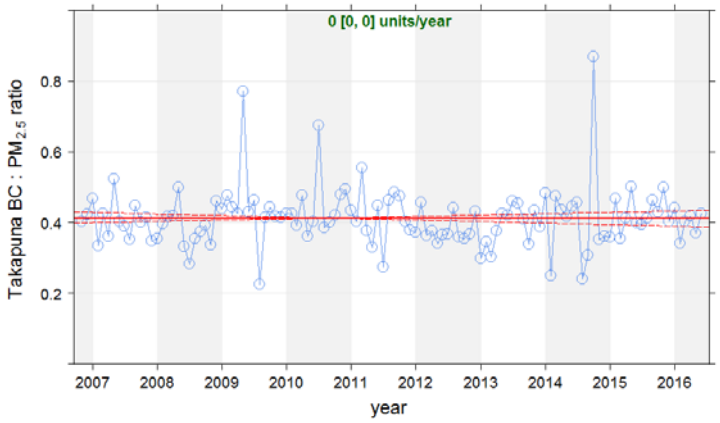

Figure 3.33 Trend analysis (deseasonalised) for BC:$PM_{2.5}$ ratio at the Takapuna site. The solid red line indicates the trend estimate, while the dashed red lines indicate the 95% confidence intervals for the trend based on data resampling methods.

The relatively stable BC:$PM_{2.5}$ ratio found for the Auckland sites means that $PM_{2.5}$ was also decreasing commensurately with the BC concentrations and demonstrates the relative influence diesel vehicle emissions have on BC and $PM_{2.5}$ concentrations in urban Auckland.

3.7.3 Trends in Black Carbon at Nelson

The analysis of trends in air pollutant concentrations is critical for assessing source activity and the effects of pollution mitigation strategies and policy intervention measures to reduce air pollution concentrations. Since PM_{10} concentrations in Nelson have exceeded the NES during the winter for many years, the Nelson Air Plan contains an air quality target for PM_{10} of 50 µg m^{-3} (24-hour average). The Nelson City Council operative air plan also includes measures to reduce emissions of PM_{10} into the local airshed, such as a ban on the outdoor burning of

rubbish, a ban on the use of open fires, the phasing out of older burners and restrictions on the installation of solid fuel burners to achieve compliance with the NES.

The receptor modeling for PM samples collected at the St Vincent Street site (2008–2012) only included those filters (i.e. Teflon) that were able to be analysed using IBA techniques. However, the filter based monitoring programme at the site initially began in 2006 with PM_{10} sampled onto quartz filters. The PM_{10} quartz filter set have been analysed for black carbon (BC) concentrations and the analysis of trends in the Nelson BC concentration data (2006–2012) showed that year-on-year BC concentrations were decreasing at 113 ng m^{-3} per year (99.9 % confidence limits), as shown in Figure 3.34.

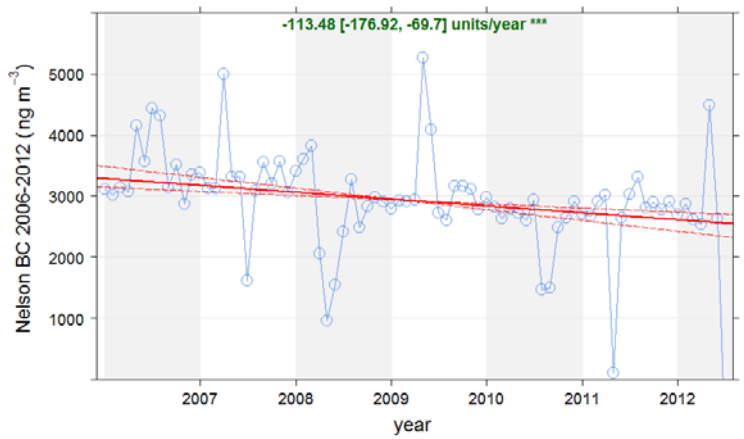

Figure 3.34 Trend analysis (deseasonalised) for Black Carbon concentrations at the Nelson site. The solid red line indicates the trend estimate, while the dashed red lines indicate the 95% confidence intervals for the trend based on data resampling methods.

The trends in Nelson BC were explored further by examining the average seasonal trends, which show (Figure 3.35) that much of the decrease in concentrations of BC (242 ng m^{-3} per year, 95 % confidence limits) has occurred during winter months (June, July and August). As with the Whangarei BC data, the Nelson BC data suggests that there has also been a significant (99.9 % confidence limits) decrease in summer BC concentrations and this may reflect the decreasing trend in diesel vehicle BC emissions that was observed for Auckland monitoring sites.

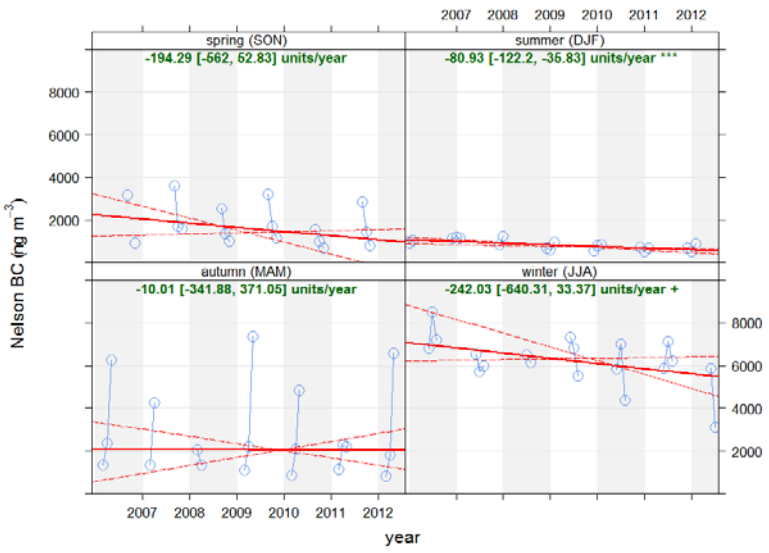

Figure 3.35 Seasonal trend analysis for Black Carbon concentrations at the Nelson site. The solid red line indicates the trend estimate, while the dashed red lines indicate the 95% confidence intervals for the trend based on data resampling methods.

3.8 Summary of Spatial and Temporal Patterns and Trends in Black Carbon Concentrations

The BC monitoring data for New Zealand shows that BC concentrations vary both temporally and spatially. Receptor modelling results indicate that diesel vehicle emissions and biomass combustion are the primary sources of BC in New Zealand urban settings and that the highest concentrations are associated with areas of greatest combustion emissions density such as adjacent to busy roads or residential locations with a high prevalence of solid fuel fires for domestic space heating. There was also a general north-south increase in biomass combustion contributions to ambient BC concentrations due to a combination of increasing use of solid fuel fires for residential space heating and environmental confinement factors (meteorology and topography) limiting the dispersion of emissions. The highest concentrations of BC were recorded during winter months also for these reasons. Figure 3.36 (Auckland) and Figure 3.37 (rest of NZ) present average BC concentrations by emission source for each of the monitoring locations.

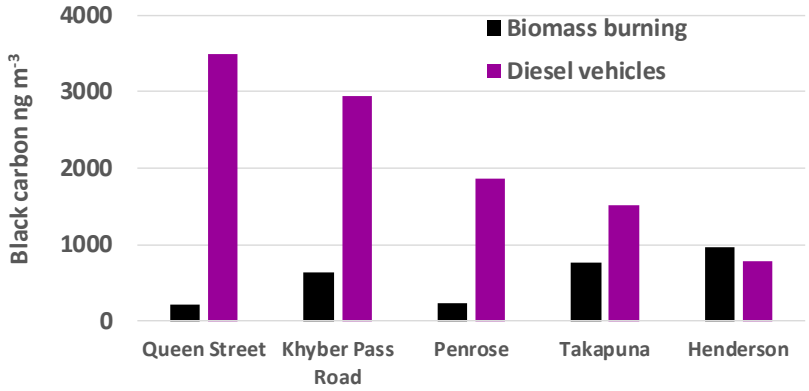

Figure 3.36 Average black carbon concentrations by source at Auckland monitoring sites.

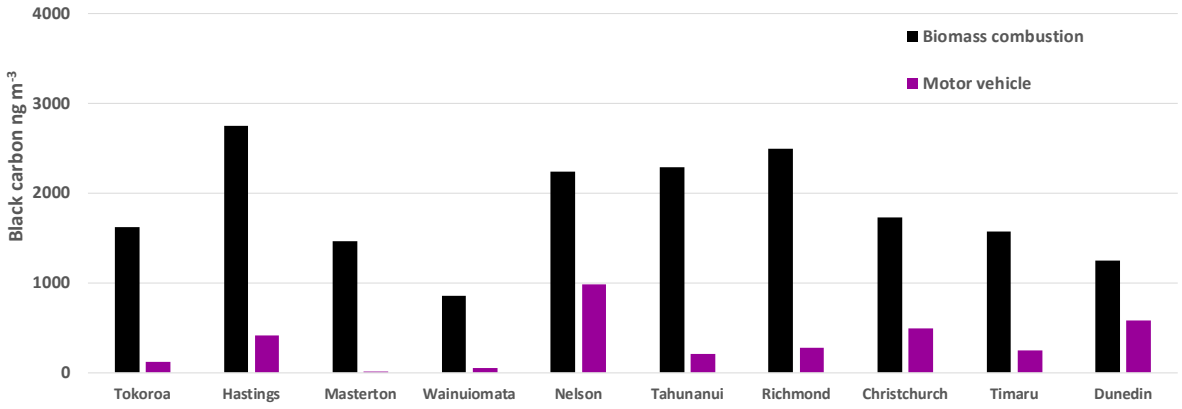

Figure 3.37 Average black carbon concentrations by source at New Zealand monitoring sites.

Trend analysis of BC concentration data from the Whangarei, Auckland and Nelson monitoring sites showed that BC concentrations were decreasing year on year and the extensive Auckland dataset indicated with high confidence that this was primarily due to the reduction of BC emissions from diesel fuelled vehicle which was attributed to improvements in engine technology and fuel formulation. For Nelson, a decreasing trend in in BC concentrations during winter was likely to be the result of proactive policies for removing open fires and old wood burners from residential dwellings in the airshed leading to reductions in emissions of BC associated with biomass combustion.

3.8.1 International Black Carbon Concentrations and Observed Trends

Black carbon concentrations have been measured routinely or as targeted campaigns in many countries across the globe. Table 3.3 provides BC concentration data from countries around the globe (adapted from (USEPA 2012) and includes data from the New Zealand monitoring sites for comparison. It shows that, relative to European and US cities, larger NZ urban areas with significant local traffic and smaller urban areas with extreme winter BC concentrations, have generally higher annual average concentrations of BC.

Across Europe and the United States, urban BC concentrations have been decreasing over time which has been largely attributed to improvements in diesel fuelled vehicle emissions and moving from high-carbon fossil fuels (e.g. residual fuel and coal) to lower carbon forms (natural gas) and electricity for residential heating. For example, in a study of carbonaceous aerosols from 78 monitoring sites across Spain, Xerol *et al* found decreasing annual trends for carbonaceous aerosols between 1999 and 2011 at a large number of air quality monitoring stations, most probably reflecting the impact of the EURO4 and EURO5 diesel engine standards in reducing the diesel PM emissions (Querol et al. 2013). In the United States it was found that patterns in seasonal and weekly BC concentrations and energy consumption trends together indicated that reducing wintertime emissions (namely substituting natural gas and electricity for heavy fuel oil in the residential sector) and decreasing emissions from diesel vehicles, contributed to lower ambient BC concentrations (Kirchstetter et al. 2017).

Table 3.3 Black carbon concentrations from international and New Zealand networks.

Region	Networks	Year	Method* Type	Black carbon µg m^{-3}	
				Urban sites	Rural/Remote sites
United States	CSN/ IMPROVE	2005–2007	T[1]	0.3 to 2.5 (~200 sites)	0.1 – 0.6 (~150 sites)
	SLAMS	2007	LA[2]	0.3 to 3.0 (~ 45 sites)	
Canada	NAPS	2003–2009	T	0.9 – 1.8 (12 sites)	0.4 – 0.8 (4 sites)
Europe	EMEP	2002–2003	T	1.4 – 1.8 (2 sites)	0.2 – 1.8 (12 sites)
Europe	EUSAAR	2006	T	1.5 (2 sites)	0.1 – 0.7 (4 sites)
United Kingdom	BC Network	2009	LA	1.0 – 2.9 (19 sites)	
China	CAWNET	2006	T	9.3 – 14.2 (5 sites)	0.3 – 5.3 (13 sites)
Nepal	NCO–P	2006–2008	LA		0.16 (1 site)
Global Background (NOAA GMD Sites)	Mauna Loa	1990–2006	LA		0.01 – 0.02
	Point Barrow	1988–2007	LA		0.02 – 0.07
	South Pole	1987–1990	LA		0.002 – 0.004
Other Arctic Sites	Alert (Canada)	1989–2008	LA		0.04 – 0.1
	Zeppelinfjell (Svalbard, Norway)	2002–2009	LA		0.02 – 0.06
United Kingdom	Black Smoke (BS)	2006	LA	5.0 – 16.0 (12 sites)	
NZ Locations	**Network**	**Year**		**Annual Average range**	
Whangarei	NRC	2004–2012	LA	1.1 – 2.1	
Takapuna (Auckland)	AC	2006–2016	LA	3.0 – 3.3	
Khyber Pass Road (Auckland)	AC	2006–2015	LA	4.1 – 4.7	
Penrose (Auckland)	AC	2006–2016	LA	2.3 – 2.9	
Henderson (Auckland)	AC	2006–2016	LA	1.3 – 2.2	
Patumahoe (Auckland)	AC	2010	LA		0.5
Tokoroa	WRC		LA	2.3	
Hastings	HBRC	2006–2007	LA	3.3	
Wainuiomata	GWRC	2006–2008	LA	1.0 – 1.2	
Masterton	GWRC	2002–2004	LA	1.6 – 1.8	
Nelson City	NCC	2008–2012	LA	2.7 – 4.1	
Tahunanui (Nelson)	NCC	2008–2009	LA	3.1	
Richmond	TDC	2013–2016	LA	3.2 – 4.4	
Christchurch	CRC	2013–2015	LA	2.3 – 2.6	
Timaru	CRC	2006–2007	LA	3.6	
Dunedin	ORC	2010	LA	2.1	
Alexandra	ORC	2008–2009	LA	1.6 – 1.8	

4.0 ACCOUNTING FOR BLACK CARBON: EMISSIONS INVENTORIES

Emissions inventories are regarded as one of the essential tools for evaluating, managing and regulating air pollution (Mobley and Cadle 2004). Emissions inventories provide an estimate of the quantity of a contaminant including particulate matter emitted by a source and the combined emissions from all sources (MfE 2001), and is generally termed a 'bottom-up' approach. An emissions inventory can provide valuable information on the quantities of pollutants emitted from sources that may be contributing to air pollution in areas where poor air quality is an issue.

In practice, emissions inventories involve gathering activity data for various source categories in a region of interest (for example; tonnes of raw material processed; units manufactured by an industrial source; or vehicle kilometres travelled (VKT) by motor vehicles). This activity data is then multiplied by some emissions factor specific to the pollutant being inventoried and appropriate to the source being considered, examples of this are gram of pollutant/kilogram of raw material consumed for industrial processes or gram of pollutant/VKT for motor vehicles. Emissions inventory values can be subject to many uncertainties as a result of obtaining information from a wide range of sources, and the approximations and use of empirical models in their compilation (Mobley and Cadle 2004). Inventories also do not take into account the effect of varying topography or meteorology may act to reduce or enhance dispersion. These uncertainties and averaging of both emissions factors and activity data across a source category often reduces the utility of emissions inventories for air quality management purposes. Quite often, output from an emissions inventory is on a tonnes of pollutant/year basis. Temporal resolution may be improved to a tonnes/pollutant/typical winter or summer day, or alternatively, a weekday/weekend difference. However, as the estimations and temporal resolution of emissions inventories are improved there is a consequent increase in the cost of compiling the inventory.

Internationally, global, regional and national BC emissions inventories have been produced demonstrating relative consistency for the primary sources of BC in the atmosphere, namely fossil fuel (diesel) and biomass combustion (Cooke and Wilson 1996; Liousse et al. 1996; Streets et al. 2001; Bond et al. 2004; Novakov and Hansen 2004; Junker and Liousse 2008; Chow et al. 2010; Kondo et al. 2011; Wang, Tao, Shen, et al. 2012; Wang, Tao, Wang, et al. 2012; Montelongo-Reyes et al. 2015).

The following sections provide comments on current BC emissions inventory methodologies for the various combustion categories along with the uncertainties involved.

4.1 Industrial Combustion Facilities

Estimates of BC emissions from dedicated industrial combustion plant used for generating heat can be relatively straightforward for classes of facility (gas, coal, diesel, residual oil, biomass) or individual units as these can be stack-tested under operating conditions or may already have the data as part of plant design or resource consent conditions. In most cases combustion conditions will be maximised for efficiency to minimise fuel costs, but facilities such as gas flaring (mainly associated with gas and oil extraction, refining facilities or landfills) form a different category. The open-flame nature of gas flaring distinguishes it from industrial point-sources; the high temperature, flame control, and spatial compactness distinguishes gas flaring from both biomass burning and domestic fuel-use (Fawole et al. 2016). Therefore, emission inventories for the soot yield from gas flaring should consider the variation of fuel gas composition and combustion characteristics.

The high-temperature nature of industrial combustion facilities coupled with the height of the stack enables some of the BC to escape further into the free troposphere aiding long-range transport, atmospheric residence times and therefore enhance the potential for climate impacts.

4.2 Motor Vehicle Emissions

Emissions of pollutants from motor vehicles in New Zealand are generally covered by the vehicle emissions prediction model (VEPM), which is an average speed model that predicts emission factors for the New Zealand fleet under typical road, traffic and operating conditions. VEPM provides tailpipe exhaust emission factors for CO, HC, NO_X, CO_2 and PM, as well as particulates from brake and tyre wear[2]. Black carbon emissions are not specifically covered by an emission factor in VEPM, but are clearly an important and substantial component (60 – 90%) of the motor vehicle tailpipe PM emissions. The main factors determining the level of emissions are the structure of the vehicle fleet and the level of vehicle emission controls (Kholod et al. 2016). According to the European Environment Agency emissions guidebook[3], BC/PM ratios vary significantly for vehicles across emission classes., These ratios vary from 0.55 for Euro 0 vehicles to 1.0 for Euro 5 for light-duty vehicles. The BC/PM ratio for heavy duty vehicles (buses and trucks) is 0.5 for Euro 0 vehicles and 0.75 for Euro V vehicles. The Auckland ambient BC source apportionment dataset supports this, with diesel vehicle $PM_{2.5}$ BC/PM ratios ranging from 0.6 to 0.9 on a mass basis depending on monitoring site location.

One of the uncertainties for diesel powered vehicle BC emission factors is that, while the BC emission measurements are generally carried out in laboratory based dynamometer systems, real-life tailpipe emissions can vary significantly due to varying loads and road gradients, particularly for heavy commercial vehicles that account for the majority of Auckland urban BC.

4.3 Biomass Combustion

As identified in Chapter 3, BC emissions during winter from biomass combustion appliances used for residential space heating are a major source of BC in New Zealand urban atmospheres. Measurement of New Zealand wood burner emissions to develop emissions factors for PM (Scott 2005; Smith et al. 2008; Wilton 2012) have generally shown user-dependent variability in PM emissions for a given model or class of appliances, which in turn results in significant uncertainty for emission factors. As BC was not measured in those studies, the inference from the results is that the uncertainties for BC emissions would be on a similar scale. Work by Davy et al (Davy et al. 2009a) indicated that average BC emissions may only be 5% of total PM emissions from wood burners with the majority released as organic carbon (OC) compounds resulting from low-temperature pyrolysis, although actual emissions will vary significantly throughout the burn cycle. A recent study (Crimmins 2017) compared the bottom-up emissions inventory approach for residential wood burning emissions of BC in Auckland with the top-down source apportionment of BC concentrations to derive region-wide emission factors for BC that reduced the inherent uncertainty. The approach relied on the comparatively more robust emissions from on-road vehicle exhaust BC emissions to derive a region-wide dispersion coefficient for the subsequent derivation of biomass combustion BC emissions.

[2] Vehicle emissions prediction model (VEPM 5.1) user guide v1.0, NZ Transport Agency June 2013

[3] https://www.eea.europa.eu/publications/emep-eea-guidebook-2016

4.4 Off-Road Sources of Black Carbon Emissions

Reference to off-road sources of BC emissions covers a broad range of activities and includes stationary plant (mainly in the construction industry), excavation and demolition vehicles, farm and forestry vehicles, aircraft, shipping, fishing and smaller marine craft. Some of these activities may have a significant local impact on BC concentrations, for example construction activities and shipping emissions in central Auckland (Davy, Ancelet, Trompetter, et al. 2017), while others will be more diffuse. Most of these activities are likely to involve combustion of diesel fuels and fuel usage statistics indicate that off-road activities account for around 40% of diesel consumption in New Zealand[4]. A US study found that, as on-road engine emissions have been controlled, the relative importance of off-road sources has grown. For example, in 1970 approximately 90% of BC emissions were from on-road sources; by 2010, off-road engines were estimated to account for 37 ± 20% of total mobile source contributions to BC in the Los Angeles area (McDonald et al. 2015). The US study highlights both the success of efforts to control on-road emission sources, and the importance of considering off-road engine and other source contributions when assessing future BC emissions and ambient air quality trends.

[4] Estimated from http://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-data-modelling/statistics/oil

5.0 SUMMARY AND RECOMMENDATIONS

5.1 Black Carbon Concentrations in New Zealand

Black carbon concentrations in airborne particulate matter have been measured in samples collected from New Zealand urban air quality monitoring sites, primarily on a monitoring campaign basis (1-2 years) except for Auckland city where a continuous 20-year monitoring record was available. It was found that peak BC concentrations were highest (10-15 μg m^{-3}) at NZ urban monitoring sites (irrespective of the size of the urban area) during winter due to BC emissions associated with the use of solid fuel fires for residential space heating and environmental confinement factors (meteorology and topography), while the influence of motor vehicle related BC emissions resulted in higher annual average (2- 5 μg m^{-3}) BC concentrations in urban centres with high traffic densities relative to the local air quality monitoring site location. At monitoring sites with sufficient data (Whangarei, Auckland and Nelson) the long-term trends showed that BC concentrations were generally decreasing and this was largely due to reductions in motor (diesel fuelled) vehicle emissions of BC, except at Nelson where local policy initiatives to remove open-fire places and replacement of old wood burners with newer, more efficient models also appears to have had a significant effect on reducing local BC concentrations during winter.

5.2 Potential Health Effects

It has long been suspected that individual components and sources contributing to PM mass may have more impact on health-related outcomes (mortality and morbidity) for exposed populations than others. Being a product of combustion emissions and with a sub-micron particle size range, BC has been a prime candidate PM component for which the adverse health effects may be higher compared to $PM_{2.5}$ in terms of effect per μg m^{-3} (Li, Henze, et al. 2016). Li and co-workers have estimated the US national mortality and morbidity attributable to anthropogenic BC exposure based on 2010 data (annual averages). They estimated approximately 14,000, and up to 130,000 deaths, with many hundreds of thousands more cases of BC-related illness attributable to anthropogenic BC, finding that the health impact estimates are highly sensitive to the risk estimates drawn from published epidemiological studies. The uncertainties are likely to reduce as longer-term BC concentration data becomes available and population exposure estimates improve. The BC annual average concentration data for the US ranged from background to 3 μg m^{-3} in more polluted cities (Li, Henze, et al. 2016) (see also Table 3.2).

The annual average BC concentration data for New Zealand urban areas (Table 3.1 and Table 3.2) lies at the upper end of the US BC data and therefore the health risk for exposed NZ urban populations may be commensurately higher. Interestingly, the US study reported that the ratio of BC to $PM_{2.5}$ (annual averages) ranged from 5-10% of the average US urban $PM_{2.5}$ mass, whereas the New Zealand data indicates that the annual average ratio (BC:$PM_{2.5}$) is 15-45% with the highest in Auckland, our most populous city. This result is probably unsurprising since motor vehicle and biomass combustion sources dominate $PM_{2.5}$ concentrations in New Zealand. Grahame et al found that in models with multiple species, BC was more often associated with adverse health effect outcomes than were other $PM_{2.5}$ species, and that where BC is coupled with PAHs and other contaminants, such as wood burning communities then adverse health outcomes are likely to be considerably higher (Grahame et al. 2014). Therefore, for New Zealand it is probable that health effects attributable to BC are likely to be synonymous with those for $PM_{2.5}$ mass.

5.3 Climate Impacts of NZ BC Emissions

The BC concentrations for New Zealand urban locations presented in the previous sections were all from samples of aerosol collected within the first 3 metres above ground level except for the vertical BC concentration profiles from the near-surface nocturnal boundary layer described in Section 3.6. The *climate*[5] forcing effects due to BC in the atmosphere result from complex interactions through the total atmospheric column which cannot be estimated from surface measurements alone. Atmospheric BC concentrations for climate forcing calculations are usually estimated by coupling BC emissions with atmospheric transport models to account for dispersion, atmospheric distributions and removal mechanisms (Li, Liao, et al. 2016). Also, because of transport and chemical and microphysical transformation after emission, atmospheric aerosol becomes a complex array of atmospheric particles. Pure BC aerosol rarely exists in the atmosphere alone as it is just one component of this mixed aerosol and varies with emission source type (Bond et al. 2013). Therefore, to assess the climate impacts of New Zealand BC emissions, modelling of atmospheric transport and distribution mechanisms would need to be undertaken as well as effectively accounting for BC emissions in the first place as described in Chapter 4. Broadly, the declining concentrations of BC observed in New Zealand urban centres may have had the benefit of mitigating some of the BC associated atmospheric warming potential.

New Zealand has an unusual BC emissions profile and differs to comparable urban centres in Europe and North America due the prevalence of winter BC emissions from biomass combustion for residential space heating and a lesser influence from industrial and power generation emissions. Further work is required to determine the fate of the winter biomass combustion BC emissions since emissions occur largely at night and studies (Grange et al. 2013; Trompetter et al. 2013) suggest that this BC is cleared from the atmospheric column, potentially due to local deposition rather than widespread dispersion to the atmosphere that would result in warming effects.

[5] Climate forcing refers to a generic term encompassing all types of forcing quantifying a perturbation to the Earth's energy balance in W m^{-2} and described in detail by Bond TC, Doherty SJ, Fahey DW, Forster PM, Berntsen T, DeAngelo BJ, Flanner MG, Ghan S, Kärcher B, Koch D, et al. 2013. Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres*. 118(11):5380-5552. doi:10.1002/jgrd.50171.

5.4 Recommendations

The analysis of black carbon concentrations and sources in New Zealand has highlighted several areas where current information on BC was deficient for a complete analysis of BC emissions and the environmental fate of BC aerosol. The following recommendations cover areas where further information would benefit our understanding:

1. While the concentrations and emission sources of BC in urban settings are relatively well characterised, there are gaps in the quantification of off-road source emissions (estimated at 40% of diesel consumption) and emissions from industrial combustion facilities. An emissions inventory approach is likely be the most effective method of accounting for, and comparing the relative importance of different BC emission sources.
2. Furthermore, to assess the climate impacts of New Zealand BC emissions, modelling of atmospheric transport and distribution mechanisms of those BC emissions would need to be undertaken in order to calculate the aerosol forcing. This would require an understanding of the nature of the BC emission source (emission rate, emission height, temporal variation in emissions) and is therefore somewhat dependent on the information generated by a BC emissions inventory.
3. The environmental fate of night-time BC emissions from domestic solid fuel fire use needs to be explored further since this source is a major contributor to New Zealand urban BC concentrations. Research suggests that local deposition may be a significant removal mechanism rather than widespread dispersion into the atmospheric column where interaction with the earth's climate system can take place.

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APPENDICES

A1.0 BLACK CARBON MEASUREMENT

Black carbon (BC) has been studied extensively, but it is still not clear to what degree it is elemental carbon (EC (or graphitic) C(0)) or high molecular weight refractory weight organic species or a combination of both (Jacobson et al. 2000). Current literature suggests that BC is likely a combination of both, and that for combustion sources such as petrol and diesel fuelled vehicles and Biomass burning (wood burning, coal burning), EC and organic carbon compounds (OC) are the principle aerosol components emitted (Jacobson et al. 2000; Fine et al. 2001; Watson et al. 2002; Salma et al. 2004).

Determination of carbon (soot) on filters was performed by light reflection to provide the BC concentration. The absorption and reflection of visible light on particles in the atmosphere or collected on filters is dependent on the particle concentration, density, refractive index and size. For atmospheric particles, BC is the most highly absorbing component in the visible light spectrum with very much smaller components coming from soils, sulphates and nitrate (Horvath 1993; 1997a). Hence, to the first order it can be assumed that all the absorption on atmospheric filters is due to BC. The main sources of atmospheric BC are anthropogenic combustion sources and include biomass burning, motor vehicles and industrial emissions (Cohen et al. 2000). Cohen and co-workers found that BC is typically 10–40% of the fine mass ($PM_{2.5}$) fraction in many urban areas of Australia.

When measuring BC by light reflection/transmission, light from a light source is transmitted through a filter onto a photocell. The amount of light absorption is proportional to the amount of black carbon present and provides a value that is a measure of the black carbon on the filter. Conversion of the absorbance value to an atmospheric concentration value of BC requires the use of an empirically derived equation (Cohen et al. 2000):

$$BC\ (\mu g\ cm^{-2}) = (100/2(F\varepsilon))\ \ln[R_0/R] \qquad \textbf{A1.1}$$

where:

ε is the mass absorbent coefficient for BC ($m^2\ g^{-1}$) at a given wavelength;

F is a correction factor to account for other absorbing factors such as sulphates, nitrates, shadowing and filter loading. These effects are generally assumed to be negligible and F is set at 1.00;

R_0, R are the pre- and post-reflection intensity measurements, respectively.

Black carbon was measured at GNS Science using the M43D Digital Smoke Stain Reflectometer. The following equation (from Willy Maenhaut, Institute for Nuclear Sciences, University of Gent Proeftuinstraat 86, B-9000 GENT, Belgium) was used for obtaining BC from reflectance measurements on Nucleopore polycarbonate filters or Pall Life Sciences Teflon filters:

$$BC\ (\mu g\ cm^{-2}) = [1000 \times LOG(R_{blank}/R_{sample}) + 2.39] / 45.8 \qquad \textbf{A1.2}$$

where:

R_{blank}: the average reflectance for a series of blank filters; R_{blank} is close (but not identical) to 100. GNS always use the same blank filter for adjusting to 100.

R_{sample}: the reflectance for a filter sample (normally lower than 100).

With: 2.39 and 45.8 constants derived using a series of 100 Nuclepore polycarbonate filter samples which served as secondary standards; the BC loading (in µg cm^{-2}) for these samples had been determined by Prof. Dr. M.O. Andreae (Max Planck Institute of Chemistry, Mainz, Germany) relative to standards that were prepared by collecting burning acetylene soot on filters and determining the mass concentration gravimetrically (Trompetter 2004).

A2.0 SITE SUMMARY AND METADATA

Table A2.1 New Zealand PM speciation and BC monitoring sites.

Location	Sites	Time Period	Frequency	Size Fraction	Location Lat; Long	Quality Comment
Northland	Whangarei	2004-2012	1 day-in-6	PM10	-35.7252; 174.3177	Screening/trend
Wellington Region	Masterton	2002-2004	1 day-in-3,	PM2.5, PM10-2.5	-40.9523; 175.6465	AQM
	Masterton (2 sites)	Winter 2010	Hourly	PM2.5, PM10-2.5	-40.9593; 175.6531	Research
	Upper Hutt	2000-2002	Variable	PM2.5, PM10-2.5	-41.1308; 175.0426	Research
	Wainuiomata	2006-2008, 2011-	1 day-in-3	PM2.5, PM10-2.5	-41.2681; 174.9534	AQM
	Seaview	2002-2004, 2005-2007	1 day-in-3	PM2.5, PM10-2.5	-41.2405; 174.9140	AQM
	Wairarapa (Masterton, Carterton, Featherston)	Winter 2009	Daily	PM2.5, PM10-2.5		Screening
	Mt Victoria Tunnel	Summer 2009		PM2.5, PM10-2.5	-41.3035; 174.7892	Research
	Baring Head	1996-1998		PM2.5, PM10-2.5	-41.4082; 174.8714	Research
	Raumati	Winter 2010	12-hourly	PM2.5, PM10-2.5	-40.9321; 174.9799	AQM
Auckland Region	Kingsland	2004-2007	1 day-in-3	PM2.5, PM10	-36.8732; 174.7471	AQM
	Takapuna	2006-	1 day-in-3	PM2.5, PM10	-36.7803; 174.7489	AQM
	Takapuna (3 sites)	Winter 2012	Hourly	PM2.5, PM10-2.5	-36.7803; 174.7489	AQM
	Queen Street	2006-onwards	1 day-in-3	PM2.5	-36.8476;174.7655	AQM
	Queen Street	2006-onwards	Daily	PM10	-36.8476; 174.7655	AQM
	Penrose	2006-onwards	1 day-in-3	PM2.5, PM10	-36.9045; 174.8156	AQM
	Khyber Pass	2006-onwards	1 day-in-3	PM2.5, PM10	-36.8662; 174.7705	AQM
	Henderson	2006-onwards	1 day-in-3	PM10	-36.8681; 174.6284	AQM
	Patumahoe	2010	Daily	PM2.5, PM10-2.5	-37.2046; 174.8639	AQM
	Johnstone Hills tunnel	Jun-11	3-hourly	PM2.5, PM10-2.5	-36.5353; 174.6800	Research
Nelson	Tahunanui	2008-2009	1 day-in-3	PM10	-41.2949; 173.2431	AQM
	Nelson City	2006-2012	1 day-in-6,	PM2.5, PM10	-41.1642; 173.1624	AQM
	Nelson City (3 sites)	Winter 2011	Hourly	PM2.5, PM10-2.5		Research
Marlborough	Blenheim	2007	1 day-in-3	PM2.5, PM10-2.5	-41.5268; 173.9561	AQM
Otago	Dunedin	2010	1 day-in-3	PM2.5, PM10-2.5	-45.8689; 170.5177	AQM
	Alexandra (3 sites)	Winter 2011	Hourly	PM2.5, PM10-2.5	-45.2534; 169.3912	Research
Canterbury	Christchurch	2001-2002	Daily	PM2.5	-43.5112; 172.6337	
	Timaru	2006-2007	1 day-in-3	PM2.5	-44.4046; 171.2496	
	Woolston	2013-2014	2-hourly	PM2.5, PM10-2.5	-43.5572; 172.6811	Research
	Christchurch (Coles Place)	2013-2015	1 day-in-3	PM2.5, PM10-2.5	-43.5112; 172.6337	AQM
	Christchurch (Coles Place, Woolston, Riccarton) high resolution 3-site study	Winter 2014	2-hourly	PM2.5, PM10-2.5	-43.5112; 172.6337	Research
Hawkes Bay	Hastings	2006-2007	1 day-in-3	PM2.5, PM10	-39.6385; 176.8574	AQM
	Meanee Rd	2006+2008	1 day-in-2 (screening survey)			Screening
	Napier	2008-2009	1 day-in-3	PM2.5, PM10-2.5		
	Awatoto	2016-2017	1 day-in-3	PM2.5, PM10-2.5	-39.5459; 176.9192	AQM
	Marewa Park	2017-	1 day-in-3	PM2.5, PM10-2.5	-39.5002; 176.8971	AQM
Southland	Invercargill	Winter 2014	Hourly	PM2.5, PM10-2.5	-46.4305; 168.3711	AQM
Waikato	Tokoroa	Winter 2014	Daily	PM10	-38.2216; 175.8589	Screening
	Tokoroa	October 2015- October 2016	Daily	PM10	-38.2216; 175.8589	AQM
Bay of Plenty	Rotorua	October 2014 -	1 day-in-3	PM2.5, PM10-2.5	-38.1625; 176.2571	Research
Tasman	Richmond	2013 - 2016	1 day-in-3	PM10	-41.3396; 173.1833	AQM
	Richmond	2015 - 2016	Daily	PM2.5	-41.3396; 173.1833	AQM

A2.1 Site Descriptions and Metadata

A2.1.1 Whangarei Monitoring Site

Size-resolved PM_{10} samples were collected at an ambient air quality monitoring station located on top of the roof of the Northland Regional Council building at 35 Water Street, Whangarei (Lat: –35.725255; Long: 174.317721°, elevation: 6 m). Figure A2.1 presents the site location on a map of the local area.

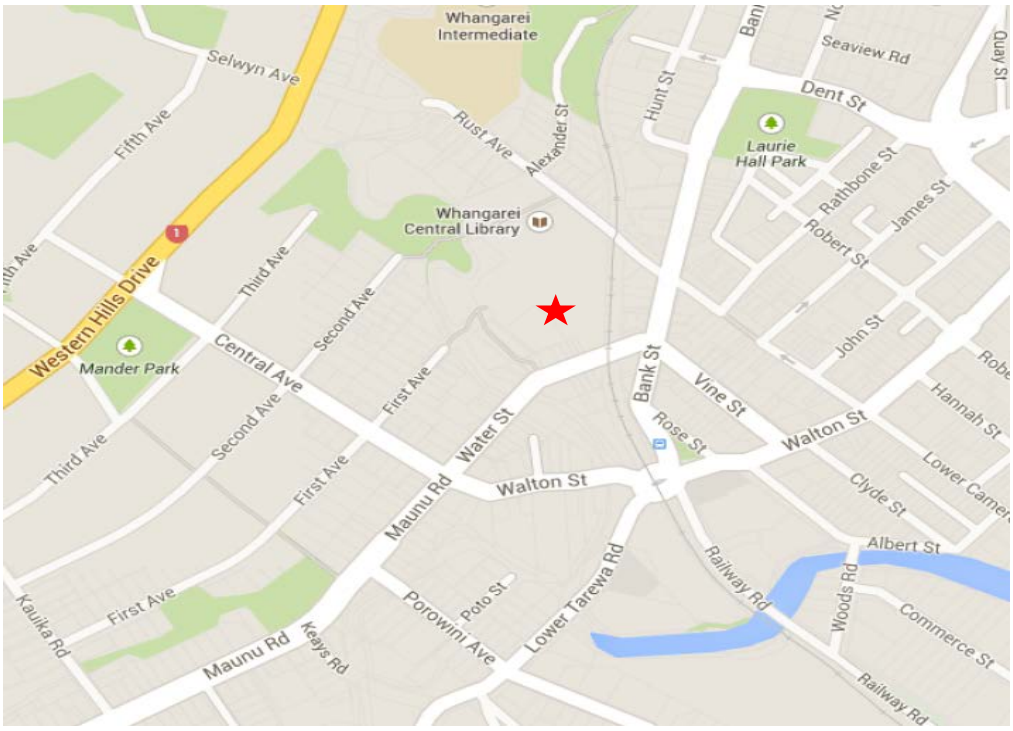

Figure A2.1 Map showing the location of the Water Street monitoring site (★) (source: Wises Maps www.wises.co.nz).

Water Street is located on the northwestern edge of the Whangarei CBD. The site was approximately 50 m from the nearest road and surrounded by open space or buildings no more than two stories high. To the northwest of the site is the Whangarei residential suburb of Avenues with bush clad hills further north and west. To the south and southwest the land opens out into the port area and Whangarei Harbour. The city of Whangarei essentially sits in the confluence of two valleys that drain into the harbour.

A2.1.2 Auckland Monitoring Sites

Samples of airborne particles were collected at five ambient air quality monitoring stations located across the Auckland isthmus as shown in Figure A2.2. Full details and site metadata are contained in (Davy, Ancelet, Trompetter, et al. 2017).

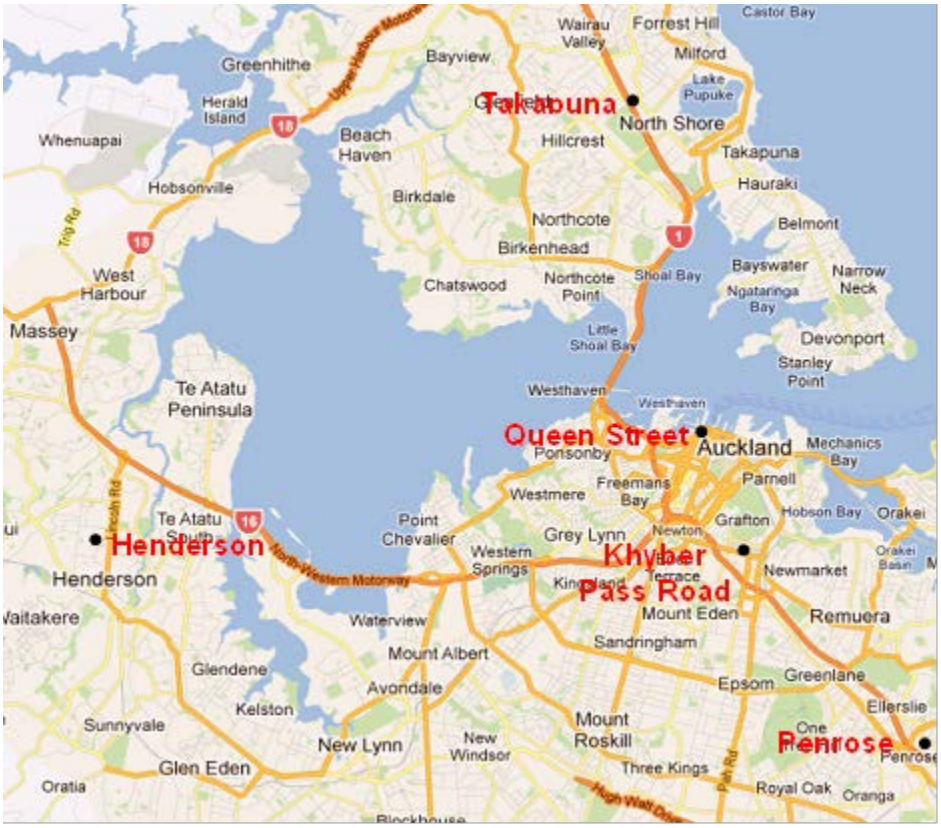

Figure A2.2 Location of the five monitoring sites (●) included in the Auckland receptor modelling study (source: Wises Maps www.wises.co.nz).

A2.1.3 Tokoroa Monitoring Site

Daily PM_{10} sampling was undertaken by Waikato Regional Council (WRC) from September 2015 until October 2016 at their air quality monitoring station at 80 Billah Street in Tokoroa (NZTM: N5765821; E1850246). The site is classified as residential and is located next to a large water reservoir. The surrounding terrain is flat and Tokoroa lies in a valley that slopes down from southeast to the northwest. Continuous PM_{10} concentrations for compliance monitoring purposes are recorded at the site using an FH62 beta-attenuation monitor (Thermo-Fisher), and data on wind direction and speed (Vector A101M and W200P) and temperature (PT100) are also collected at the site. 24-hour PM_{10} samples for analysis were collected onto Teflon filters (Tisch Environmental SF18040) at the site using a sequential Partisol system (Thermo-Fisher 2025). A total of 361 samples (plus field and lab blanks) were collected over this period. All PM sampling and systems maintenance at the air quality monitoring site was carried out by WRC, and as such, WRC maintains all records of equipment, flow rates and sampling methodologies used for the PM sampling regime. Filter conditioning, weighing and re-weighing for PM_{10} gravimetric mass determinations were carried out by Hill Laboratories Limited.

Figure A2.3 Location of the Billah Street monitoring site in Tokoroa (▲) (source: Waikato Regional Council).

A2.1.4 Hastings (St Johns College) Monitoring Site

Hastings is a small urban area located approximately 20 kilometres south of Napier in Hawke's Bay on the east coast of the North Island of New Zealand. Figure A2.4 illustrates the distance and direction to sea, neighbouring areas and the largely flat topography of the immediate area.

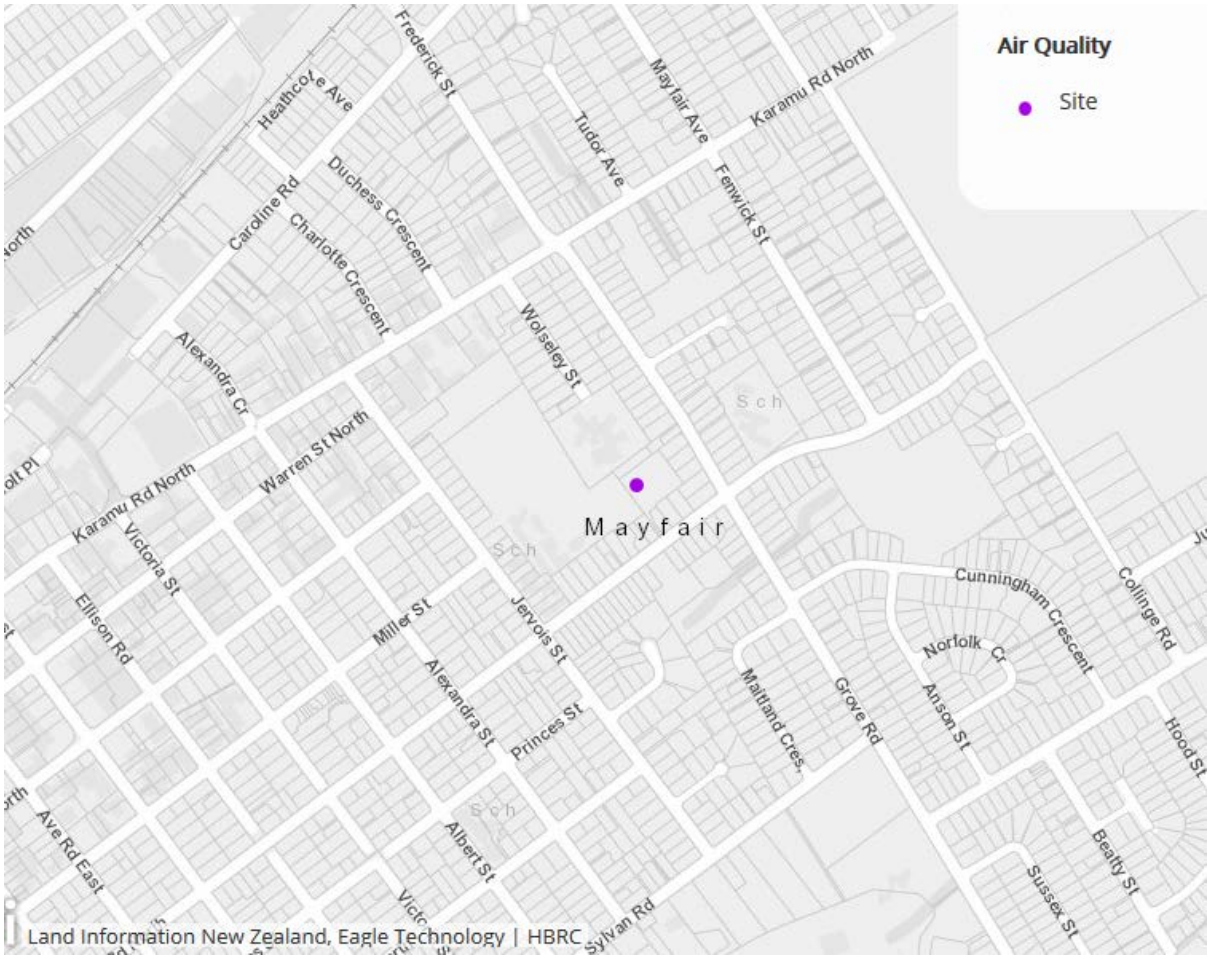

Figure A2.4 Hastings monitoring site location (source: Hawkes Bay Regional Council).

The ambient sampling monitoring equipment was situated at the St Johns Ambient Air Quality monitoring site located at St Johns College in Jervois Street, Hastings (Figure A2.4) (lat. -39.6385; long. 176.8574).

A2.1.5 Wainuiomata Monitoring Site, Wellington

Samples of airborne particles were collected at an ambient air quality monitoring station located within the grounds of the Wainuiomata Bowling Club, off Moohan Road, Wainuiomata (Lat: -41.2681o, Long: 174.9534). Figure A2.5 shows the site location on a map of the local area.

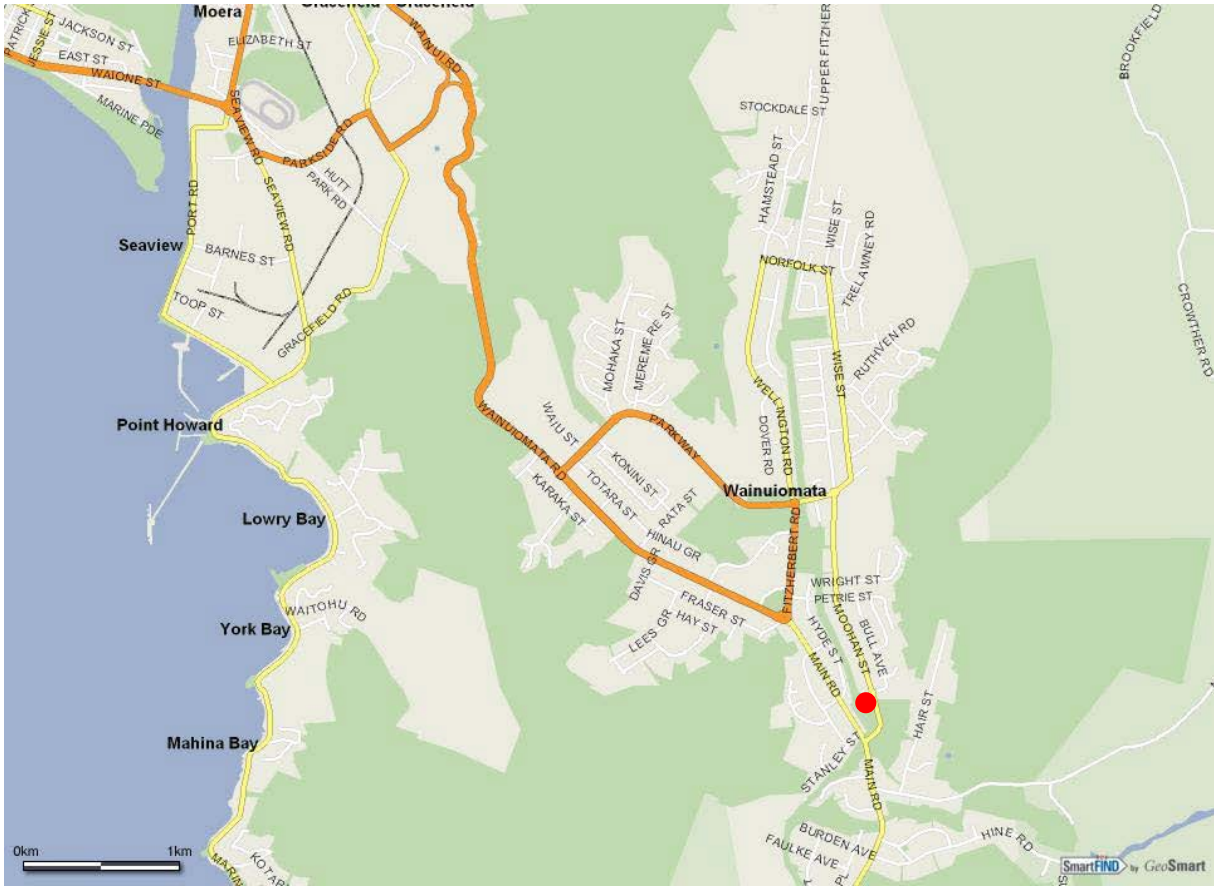

Figure A2.5 Map showing location of Wainuiomata monitoring site (●) (source: Wises Maps www.wises.co.nz).

Wainuiomata is located in a valley basin surrounded by hills 200 m high to the north and west, to the east the hills rise into the Rimutaka Range up to 800 m high. The south end of Wainuiomata narrows to a constricted valley which runs 20 km down to the ocean. Wellington City is 15 km to the southwest across the hills and harbour.

A2.1.6 Masterton Monitoring Site

An ambient air quality monitoring station is located within the grounds of Wairarapa College, in Masterton (lat. -40.9523; long. 175.6465, elevation 100 m) and has been operating since October 2002. Co-located at the site are continuous CO, NOx and PM_{10} (TEOM) analysers and a PM10 high-volume sampler as a reference method. Various meteorological parameters were also monitored at the site. Figure A2.6 is a map of the local area surrounding the monitoring site.

Figure A2.6 Local map of area around Wairarapa College monitoring site (●).

Masterton is a rural town with a population of approximately 20,000 that services the surrounding farming community. Masterton is located on the flat river plain of the Wairarapa Valley which is approximately 20 km wide. The Wairarapa College site was at least 150m from the nearest road and approximately 1 km from the central business district of Masterton. The land around the school site was flat and surrounded by open space or school and residential buildings no more than two storeys high.

A2.1.7 St. Vincent Street, Nelson Monitoring Site

Size-resolved PM samples (PM_{10} and $PM_{2.5}$) were collected at an ambient air quality monitoring station located on a property off of St. Vincent Street, Nelson (Lat: –41.164150°, Long: 173.162447°, elevation: 5 m). Figure A2.7 presents the site location on a map of the local area.

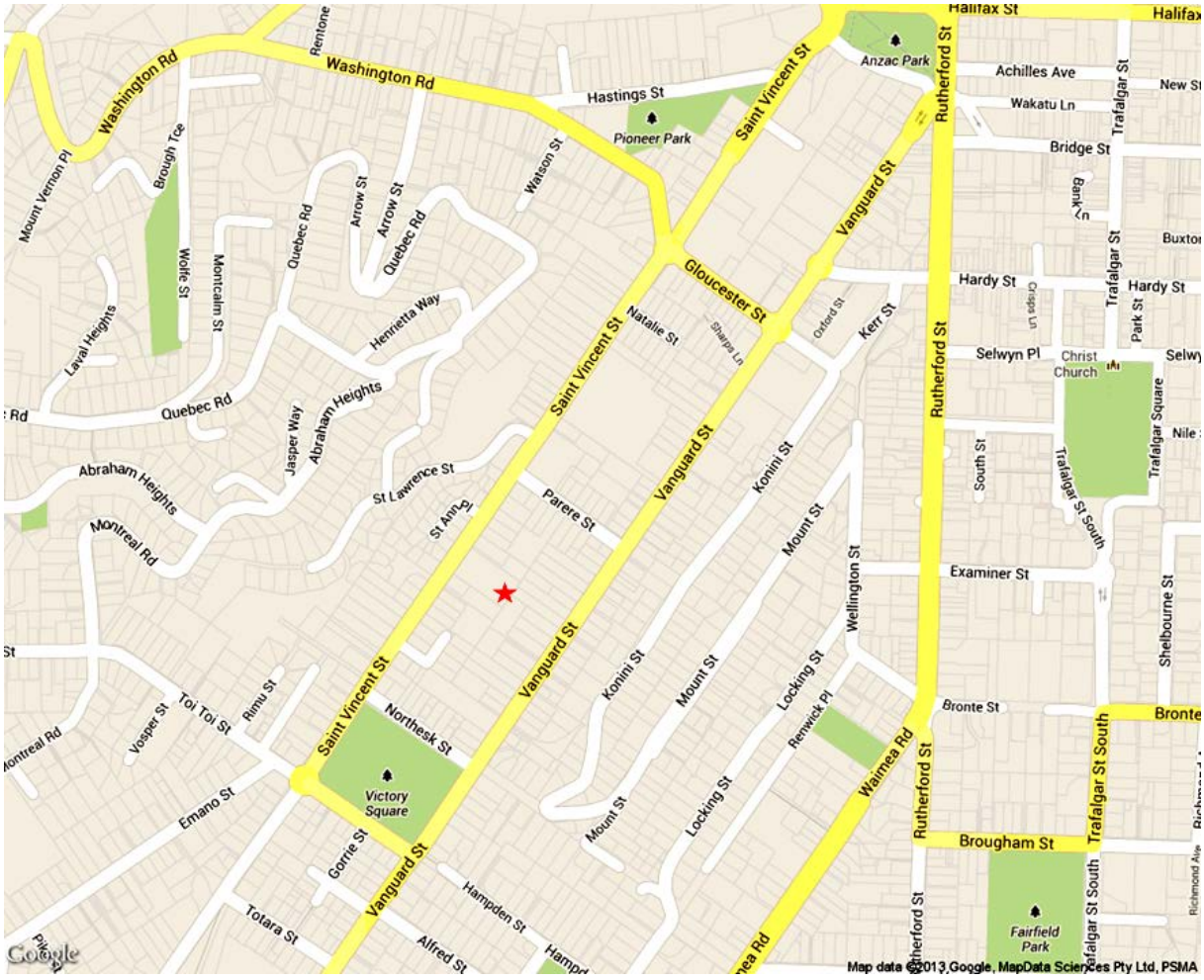

Figure A2.7 Map showing the location of the St. Vincent Street monitoring site (★) (source: Wises Maps www.wises.co.nz).

St. Vincent Street is located near (within 600 m) the Nelson CBD. The site was approximately 90 m from the nearest road and surrounded by open space or buildings no more than two stories high.

A2.1.8 Tahunanui Monitoring Site, Nelson

Samples of airborne particles (PM_{10}) were collected at an ambient air quality monitoring station located on a property off Blackwood Street, Tahunanui (Lat: -41.2949o, Long: 173.2431, elevation 5 metres). Figure A2.8 shows the site location on a map of the local area.

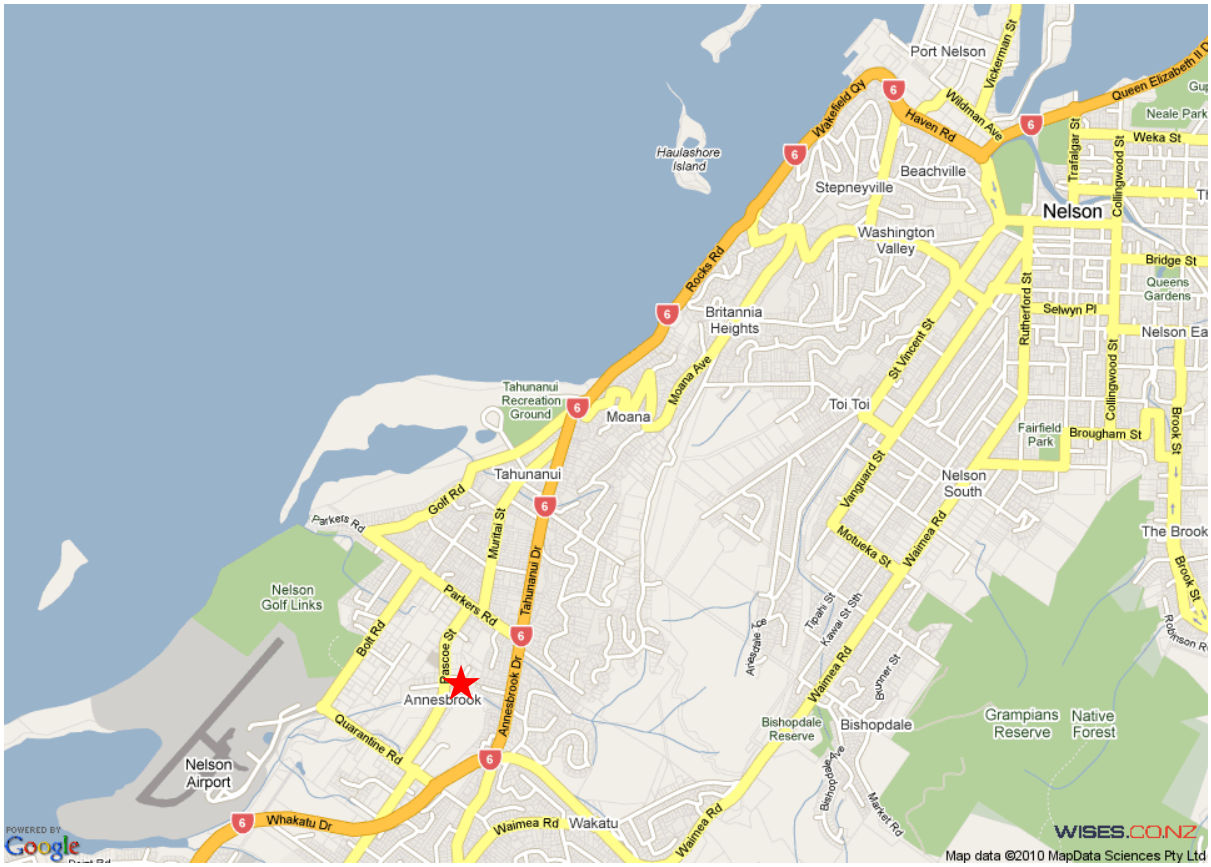

Figure A2.8 Map showing location of Tahunanui monitoring site (★) (source: Wises Maps www.wises.co.nz).

Tahunanui is located on a narrow coastal plain bordered by hills to the east (200-300 m high) to the north lies Tasman Bay and to the west is the Waimea Inlet. To the southwest is the Waimea Plain. The Blackwood Street site lies on the border between industrial activities to the south and west with Nelson Airport located on the edge of the Tahunanui Inlet west of the monitoring site. Residential activities predominate immediately to the east and north, with State Highway 6 (Annesbrook Drive) 200 m east of the site.

A2.1.9 Oxford Street Monitoring Site, Richmond

$PM_{2.5}$ and PM_{10} samples were collected at an ambient air quality monitoring station located at 56 Oxford street, Richmond (Lat: 41°20'21.46 S; Long: 173°10'58.65 E; elevation: 13 m). Figure A2.9 presents the site location on a map of the local area.

Figure A2.9 Map showing the location of the Richmond monitoring site (source: TDC).

Oxford Street is located near the Richmond CBD and the monitoring site was less than 400 m from State Highway 6, the major roadway into and out of Nelson. The site was in a residential area and was surrounded by buildings no higher than two stories. Aside from its immediate environment, the monitoring site was surrounded by hills and farmland, and was less than 5 km south of Tasman Bay.

A2.1.10 St Albans, Christchurch Monitoring Site

Particulate matter sampling was performed at the Coles Place monitoring site (operated by Environment Canterbury) in St Albans, Christchurch (Lat: –43.304255°; Long: 172.380231). The site is the primary long-term air quality monitoring site in Christchurch. The sampling location is presented in Figure A2.10.

Figure A2.10 Location of the Christchurch monitoring site (●) (source: Google Maps).

As shown in Figure A2.10, the sampling site is located in a residential area adjacent to tennis courts at the end of a cul-de-sac. The immediate surrounding environment is dominated by older, medium to high-density residential dwellings. The closest arterial road, Cranford St (SH 74), is approximately 380 m to the east, and 240 m to the south is Edgeware Rd, a busy urban route.

A2.1.11 Timaru Monitoring Site

Environment Canterbury's Timaru city air quality monitoring station is located at Anzac Square, Parkside (Figure A2.11) (lat. -44.4046; long. 171.2496. The station is situated in the south-eastern corner of the park, a short distance from State Highway 1 (100 m west), Rose St (20 m east), the coast (<1 km east) and port (<1 km east).

Figure A2.11 Location of the Timaru air quality monitoring site (source: Environment Canterbury).

A2.1.12 Dunedin Monitoring Site

Samples of airborne particles were collected at an ambient air quality monitoring station located on the corner of Albany Street and Anzac Avenue in Dunedin (Lat: -45.8689; Long: 170.5177). The Albany Street site is located in a mixture of commercial and residential activities with the port area and harbour 800m to the east. Figure A2.12 provides an aerial photo of Dunedin and its immediate environs.

Figure A2.12 Aerial view of Dunedin monitoring site (★) (source: Google Maps 2011).

Buildings around the Dunedin monitoring site range from single storey up to 7 or 8 storeys which provides for complex terrain that will affect wind speed and direction as measured at the monitoring site. The local topography around the Albany Street air quality monitoring site is flat with hills rising to the north and west and the Dunedin CBD to the southwest.

A2.1.13 Alexandra Monitoring Site

The Alexandra monitoring site was located at the Alexandra Girl Guides centre (lat. -45.2534; long. 169.3912) and was approximately 50 m from the nearest road (Figure A2.13. The site was an ambient air quality monitoring station used for compliance monitoring by the Otago Regional Council. The land around the site was flat and surrounded by open space or buildings no more than two stories high.

Figure A2.13 Aerial view of Alexandra monitoring site (★) (source: Google Maps 2011).

www.gns.cri.nz

Principal Location

1 Fairway Drive
Avalon
PO Box 30368
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 31312
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4657