Foreword

The Otago region experiences very good air quality most of the year, however, there are times, especially during the winter, when residents can suffer from high levels of air pollution from smoke as we still rely on the use of solid fuel such as coal and wood to heat our houses, schools and workplaces. Industries in some locations also contribute to smoke in the air.

National Environmental Standards (NES) for ambient air quality in New Zealand were initially introduced by the Ministry for the Environment (MfE) in September 2005, and amended in 2011. Otago's main pollutant is the small suspended particles (PM10) found in smoke, which is measured using a network of monitors operating in towns around the region.

ORC is committed to improving air quality and creating a healthier environment. Our Regional Policy Statement provides for the sustainable management of the air resource and the Regional Plan: Air sets out the policies, rules and objectives for enhancing the quality of air.

In addition to analysing the air quality monitoring network results, occasionally studies are carried out to improve our understanding of local air quality problems. This report looks at the air quality of Dunedin in more detail and shows how air quality varies in different parts of the town.

Executive summary

Air pollution, particularly in winter, is a concern to communities throughout Otago. Poor air quality is due to elevated levels of PM_{10}, which are very small particles suspended in the air. Three factors affect air quality – how much pollution is put into the atmosphere, the weather, and the topography of an area. How these factors relate to one another determines whether air quality is good, fair, or poor.

The main source of PM_{10} in Dunedin, similar to other towns in Otago, is smoke from solid fuel burners. That's why wintertime PM_{10} levels are generally higher than those measured during summer. In addition, the temperature inversions that commonly form in winter create conditions that discourage dispersion, allowing PM_{10} to accumulate. Cold night-time air sinking down the sides of hills also serves to keep smoky air close to ground level.

The ORC has been monitoring air quality at various locations around Dunedin over the last 12 years. During this time, monitoring technology has improved greatly allowing us to sample the air on an hourly basis. While Dunedin is similar to other Otago towns, there are some important differences that make the city's PM_{10} patterns different and more complex.

During a typical year, daily PM_{10} levels average about 21µg/m^3. High daily values, those above 50µg/m^3, happen about six times and can occur any time of the year. Most of them fall on either a Monday or a Tuesday. This pattern probably reflects the contribution of industrial emissions in the city.

Central Dunedin enjoys relatively good air quality throughout the year, with the vast majority of days (85%) having low levels of PM_{10} (less than 35µg/m^3). This is due, in no small part, to the city's proximity to the sea and the unique setting of the harbour, which provides a significant wind corridor. In parts of the city that are sheltered from the wind, such as North East Valley and Kaikorai Valley, PM_{10} levels can often be elevated.

The 2005 Air Emission Inventory identified that 8% of the total Dunedin emissions were from industrial and commercial air discharges, with the remaining 92% from domestic solid fuel heating appliances. The geographic distribution of these emission sources helps form the PM_{10} 'signature' of Dunedin neighbourhoods. Different parts of the city have differing emission rates, so it's not surprising that various part of the city will experience different levels of air quality. It is quite possible to have poor air quality in one area, while 'over the hill' the air quality may be quite good.

In 2009, the ORC undertook a study to understand the patterns of PM_{10} around the city. NIWA was contracted to use their mobile air quality monitoring system and travel the streets for several days and nights during winter. The monitor in central Dunedin is used to report daily values to the Ministry for the Environment, and while it does represent the centre city's air quality, it may not be a good predictor of air quality in other parts of the city.

Work towards improving Dunedin's air quality continues, as does our effort to understand the complex nature of the city's air quality patterns.

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1. Introduction

Air quality has been monitored in central and suburban Dunedin since 1997. From 1997 to 2006, single twenty-four hour samples were taken every third day in winter and less frequently during the rest of the year. In 2005, the Ministry for the Environment introduced National Environmental Standards for Air Quality (AQNES), which limit the allowable level of PM_{10} (fine particles suspended in the air) to 50 micrograms per cubic metre of air. The original low-resolution, labour-intensive monitors were replaced with continuous, automated monitors. This state-of-the-art technology samples and computes PM_{10} every hour, allowing a much closer examination of PM_{10} patterns.

The major source of PM_{10} emissions in Dunedin, similar to most Otago towns, is smoke from domestic solid fuel burners. In Dunedin, other important sources include commercial and industrial emissions, vehicle emissions, and some natural sources such as sea salt and pollen. The air quality on any given day is the result of the interaction between these emissions, the weather, and the topography of an area. While Dunedin is similar to other Otago towns in some respects, there are some important differences that make the city's PM_{10} patterns different and more complex.

From 2006 on, the ORC has used the continuous monitor located in central Dunedin to report PM_{10} values for the AQNES. This site is located in the campus zone, with industrial and residential zones nearby. No single monitor can represent such a large and diverse city; so, in 2009, the ORC contracted NIWA to conduct a 'real-time' spatial monitoring programme. The purpose of the study was to define the spatial variability of PM_{10} around the city to provide a context for the results from the central Dunedin monitor.

This report describes and compares the PM_{10} patterns found across the city and also discusses the geographic distribution of various emission sources. A summary of the NIWA spatial monitoring project is provided and the complete NIWA report is included as Appendix 1.

2. PM_{10} patterns in Dunedin

2.1. Monitoring sites in Dunedin

Since 1997, the ORC has deployed a varying configuration of monitors in and around Dunedin. Early monitors were often used as screening tools to identify areas with potential air quality problems. Currently, the only monitor running is located along Albany Street in central Dunedin. The table below depicts where and when monitoring has taken place and a map of locations is shown in Figure 1. The colour of the dot indicates which type of monitor was used.

Table 1 Past and current PM_{10} monitors in Dunedin, showing the year's run

Site	Type of Monitor	Years Monitored													
		97	98	99	00	01	02	03	04	05	06	07	08	09	10
North East Valley (North Road)	hi-vol														
Central Dunedin (Albany Street)	hi-vol														
Central Dunedin (Albany Street)	BAM 1020														
Kaikorai Valley (Taieri Road)	mini-vol														
South Dunedin (Macandrew Road)	hi-vol														
South Dunedin (Bayview Road)	mini-vol														
Green Island (Irmo Street)	mini-vol														

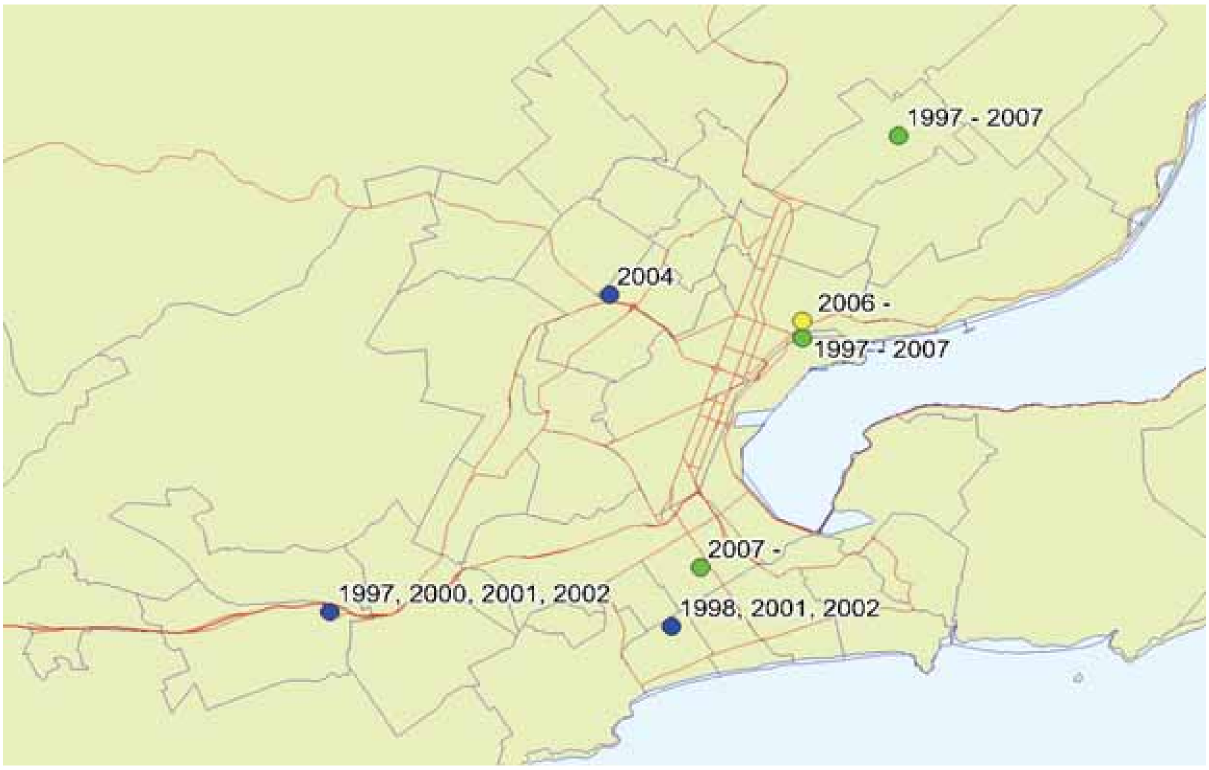


Figure 1 Locations of past and current PM_{10} monitoring in Dunedin by type of monitor

2.2. Central Dunedin PM_{10} patterns

Using just the past five years of continuous data, a typical yearly pattern is derived and shown in red in the graph below. Daily PM_{10} values generally fall between 15 and 40µg/m^3, with an average annual value of about 21µg/m^3. High values can occur any time of the year. This pattern reflects the contribution of industrial and commercial emissions in the city. By comparison, this is a very different pattern to that seen in Alexandra (blue line), where domestic heating emissions during winter make up the vast majority of PM_{10}.

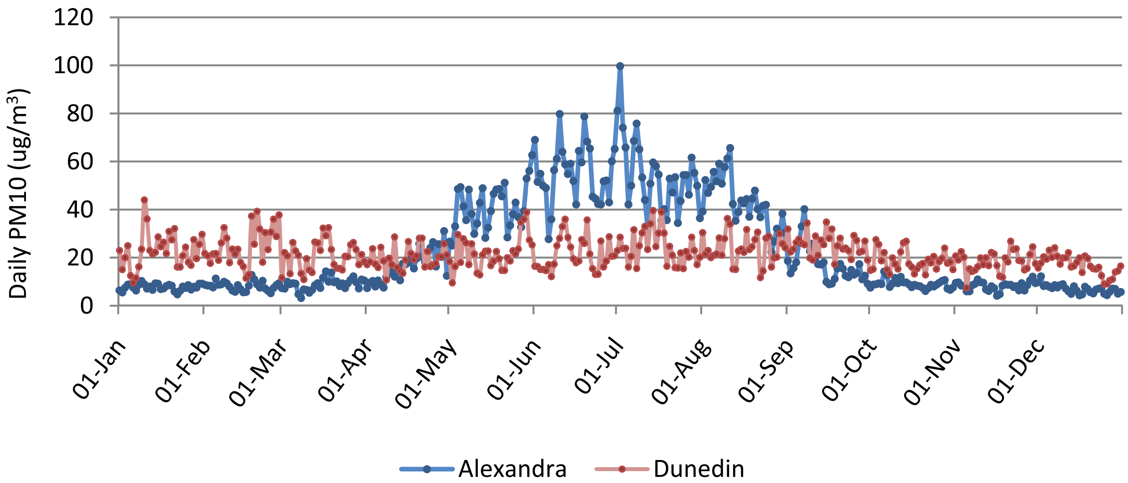


Figure 2 **Averaging five years of data, these graphs represent a typical air quality year in Alexandra and central Dunedin**

The graph below shows that the variability in the winter averages (blue bars shown on left axis) from year to year seems to have decreased. The maximum values for each year (red diamonds shown on right axis) appear to have increased over the last four years. Note that some of the difference seen in these annual patterns may be because of the change in monitor technology during 2005. Also, in 2005, the sampling frequency increased from every third day to everyday. Continued monitoring will reveal the strength of the trends. The values are given in Table 2.

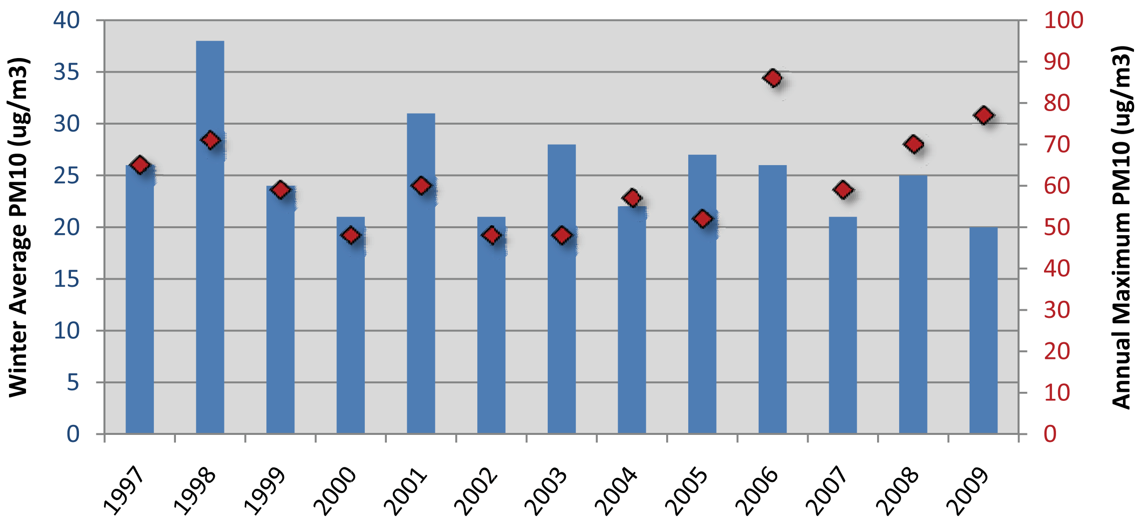


Figure 3 **Winter average and annual maximum PM_{10} values in central Dunedin**

Table 2 **Values of winter average and annual maximum PM_{10}. All units are in µg/m³**

Year	1997	98	99	00	01	02	03	04	05	06	07	08	09
Ave*	26	38	24	21	31	21	28	22	27	26	21	25	20
Max**	65	71	59	48	60	48	48	57	52	86	59	70	77

* Winter average ** Annual maximum

On a weekly timescale, the data show that of the 35 high-pollution days that have occurred at the central Dunedin site since 1997, half have fallen either on a Monday or a Tuesday. Only one has been reported as occurring on a Sunday. The graph below shows the distribution of the high-pollution days.

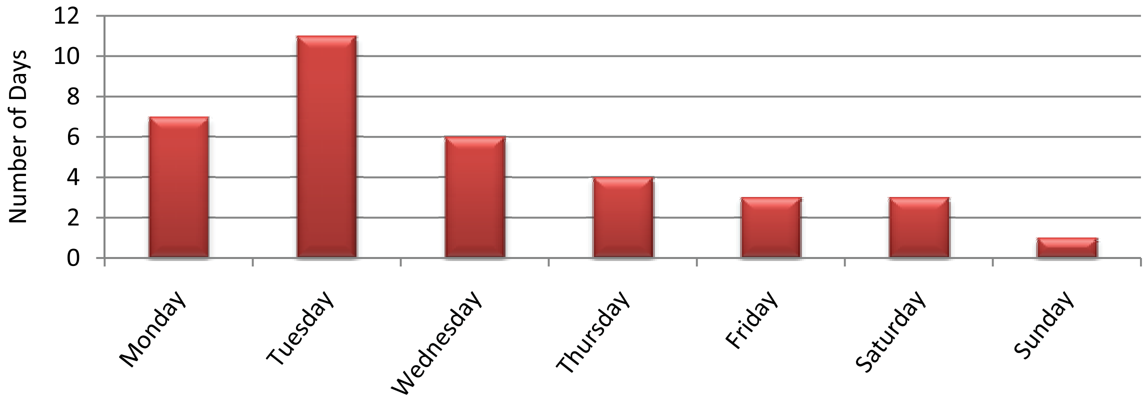


Figure 4 **Most high-pollution days in central Dunedin have occurred early in the week**

On a daily scale, winter weekday PM_{10} levels increase in the morning and remain elevated throughout the day, peaking from 3 to 4pm. After that, they gradually taper off to a minimum during the early morning hours. Winter weekends have their maximum in the evening. The graph below shows these distinctive patterns.

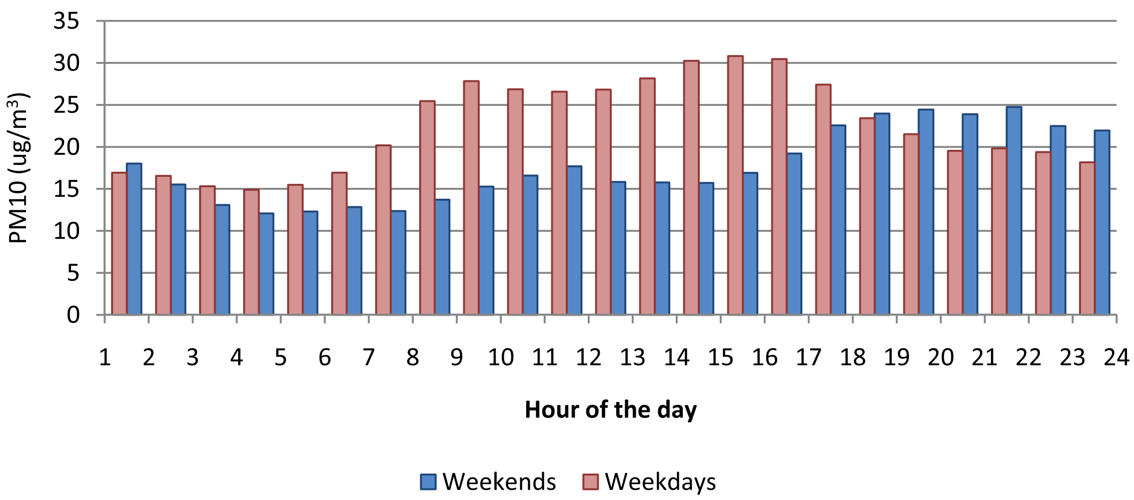


Figure 5 **Representative winter weekday and weekend days in central Dunedin**

All of these patterns point to the combined contribution of domestic heating and industrial emissions to central Dunedin's unique PM_{10} 'signature'. Compared to other towns in the region, Dunedin enjoys relatively good air quality throughout the year. Overall, the majority of days (83%) have low levels of PM_{10} (less than 35µg/m^3), with only a small percentage of days (3%) having PM_{10} levels greater than 50µg/m^3.

2.3. Comparisons to other monitoring sites in Dunedin

South Dunedin

A comparison of the intermittent monitoring done in South Dunedin with the central Dunedin site shows that the relationship between the two sites is not simple (Figure 6). They generally follow a similar pattern with, on average, the central Dunedin site recording higher values than those in South Dunedin.

However, at each site, high-pollution days generally occur on days when the other site does not experience a high-pollution day; and moderate values can occur on days when low values occur at the other site. This suggests that the sites are subject to more localised sources and/or meteorological conditions on high-pollution days.

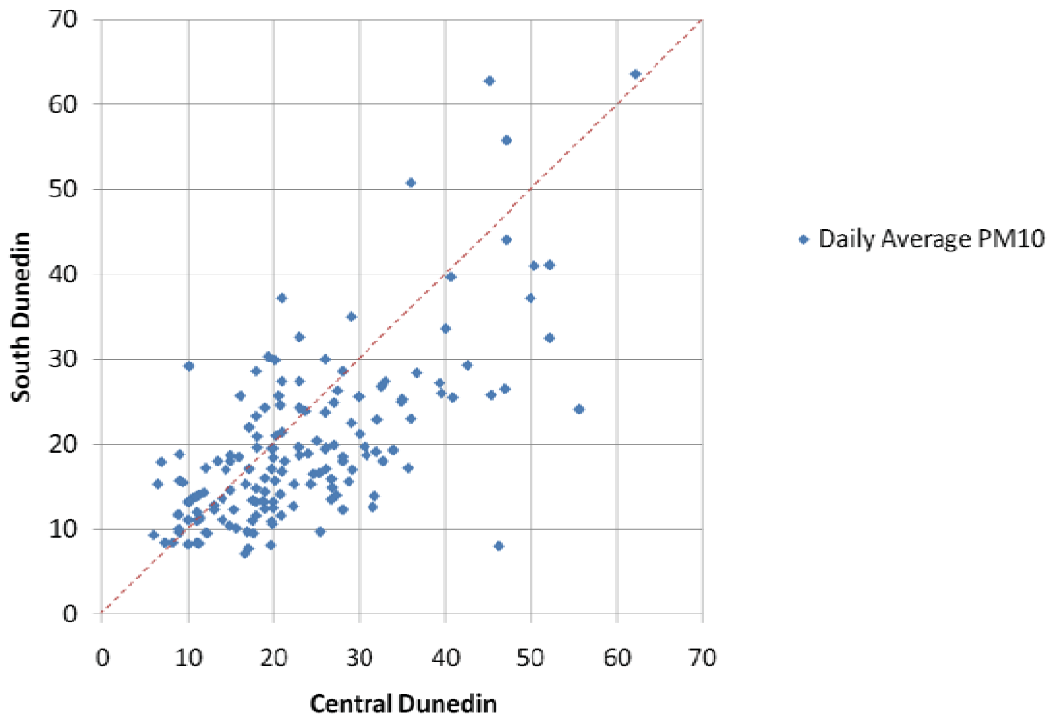


Figure 6 Comparison of daily average PM_{10} from central and South Dunedin from May 2007—August 2009 (161 paired values). All units are micrograms per cubic metre of air

North East Valley (NEV)

Comparison of the North East Valley data with the central Dunedin data from 2002 to 2007 (Figure 7) shows generally lower levels of PM_{10} are recorded in North East Valley, especially during the non-winter months. This is not always the case though, with moderate values recorded at NEV on days when Albany Street showed low levels of PM_{10}, and vice versa.

The NEV monitor may not have been ideally placed to pick up the highest concentrations of PM_{10}. Therefore, the highest PM_{10} levels may have been under-represented. Also, differences in PM_{10} levels at different heights up the valley sides are poorly understood, and residents living in these areas may experience higher or lower values due to the capping effect of inversion layers.

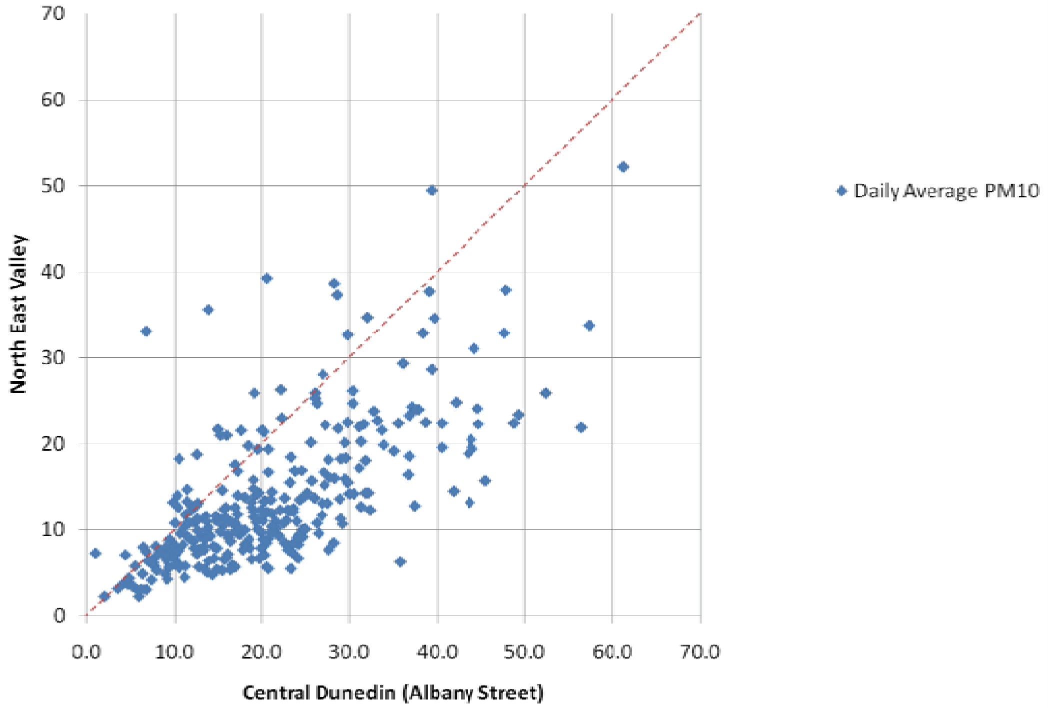


Figure 7 **Comparison of daily average PM_{10} from hi-vol monitoring in central Dunedin and North East Valley from January 2002 – April 2007 (307 paired values). All units are micrograms per cubic metre of air**

Others site comparisons (Minivol monitors)

In addition to the comparison of the long-term sites, the data from the mini-vol screening monitors were analysed to look at the strength of the relationships between these sites and the central Dunedin site. Table 3 gives the Pearson's correlation coefficient (r), an indicator of the strength of the relationship between the sites. While it must be kept in mind that these are based on a relatively small number of samples, as might be expected, there is a positive relationship between most sites (i.e. when one site recorded high values, it is likely that the other site did too).

Table 3 **Pearson's correlation coefficients – winter only (the green highlighting shows positive correlations, with darker shading indicating stronger correlation; where there are no overlapping data, the square is left blank)**

	Central Dunedin	NEV	Green Island	Kaikorai Valley	Mosgiel	South Dunedin
Central Dunedin	1	0.67	0.57	0.81	0.38	0.40
NEV	0.67	1	0.56	0.75	0.63	0.39
Green Island	0.57	0.56	1	-	0.41	0.27
Kaikorai Valley	0.81	0.75	-	1	0.62	-
Mosgiel	0.38	0.63	0.41	0.62	1	0.41
South Dunedin	0.40	0.39	0.27	-	0.41	1

The South Dunedin site shows the weakest correlation to all the other sites, while the Green Island, North East Valley, and central Dunedin sites show slightly stronger correlations to each other. There is a small sample size at the Kaikorai Valley site (10); however, it does show a strong positive correlation with central Dunedin.

As shown by the R^2 values in Table 4, these relationships are not strongly linear (i.e. you cannot predict what one will be from the other). The lower the R^2 values, the weaker the linear relationship, with Kaikorai Valley the only site to have more than a 50% correlation to another site.

The low R^2 values observed for most sites make the Albany Street site a poor predictor of the air quality in these other areas of town. This higher degree of independence indicates that the emissions and/or the meteorological conditions differ between areas. This will no doubt be due to different or localised emission sources and/or from varying exposure to wind speeds and directions in each individual area.

Table 4 R^2 values from linear regression of paired sites

	Central Dunedin	NEV	Green Island	Kaikorai Valley	Mosgiel	South Dunedin
Central Dunedin	1	-	0.32	0.65	-	0.16
NEV	-	1	0.31	0.56	-	0.06
Green Island	0.32	0.31	1	-	0.17	0.06
Kaikorai Valley	0.65	0.56	-	1	0.38	-
Mosgiel	-	-	0.17	0.38	1	0.17
South Dunedin	0.16	0.16	0.06	-	0.17	1

The plots below show the paired daily average values from each site and those made in central Dunedin. (The North East Valley site has been excluded as it was covered earlier in Figure 7). Kaikorai Valley shows similar levels to those in central Dunedin, with no consistent variation (Figure 8). Green Island (Figure 9) shows mostly higher values compared to those in central Dunedin. South Dunedin shows a spread of values (the reason for low R^2), with no trend either way (Figure 10).

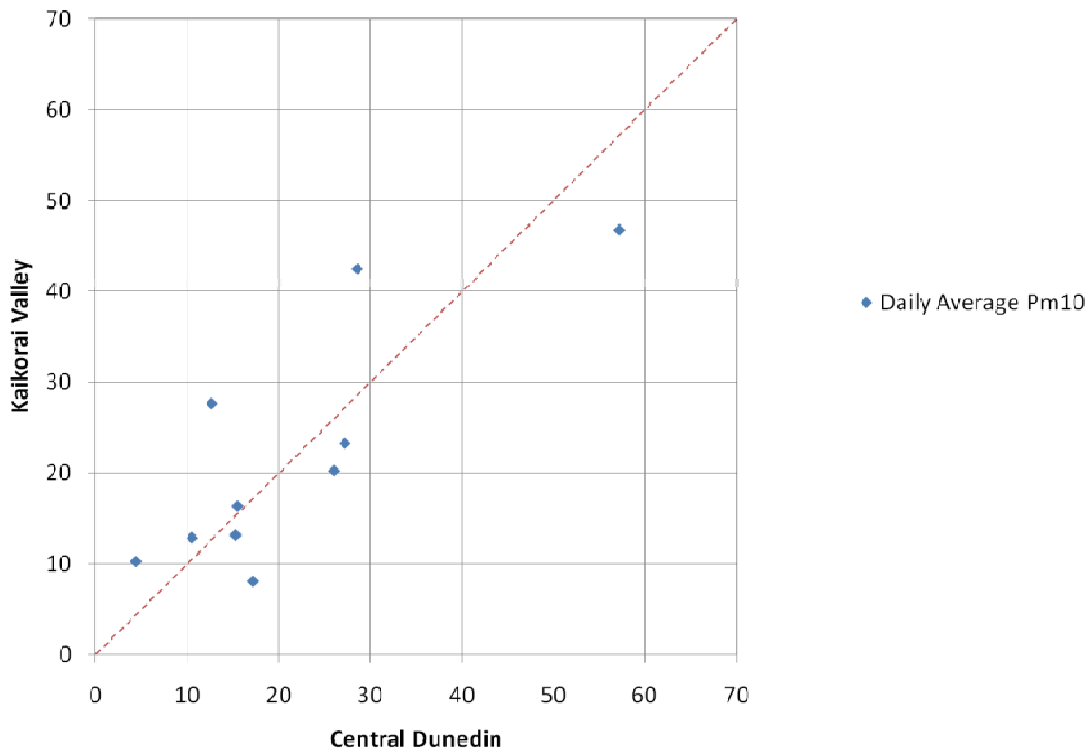


Figure 8 Comparison of daily average PM_{10} from central Dunedin and Kaikorai Valley (10 paired values). All units are micrograms per cubic metre of air

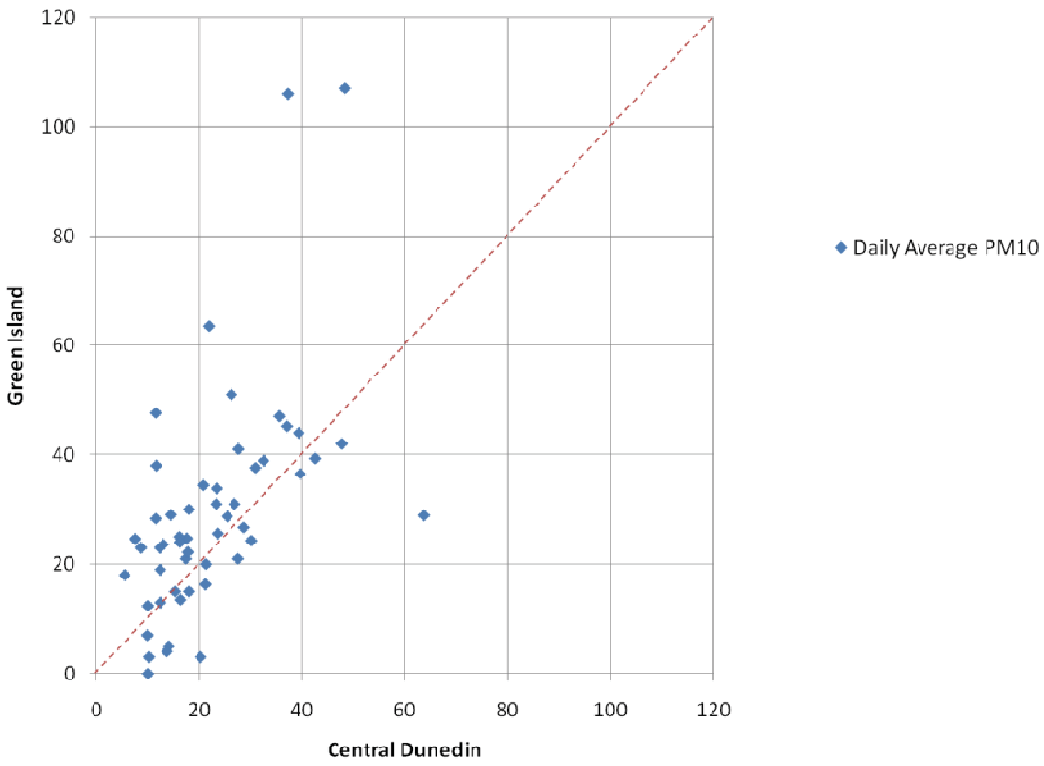


Figure 9 **Comparison of daily average PM_{10} from central Dunedin and Green Island (101 paired values). All units are micrograms per cubic metre of air**

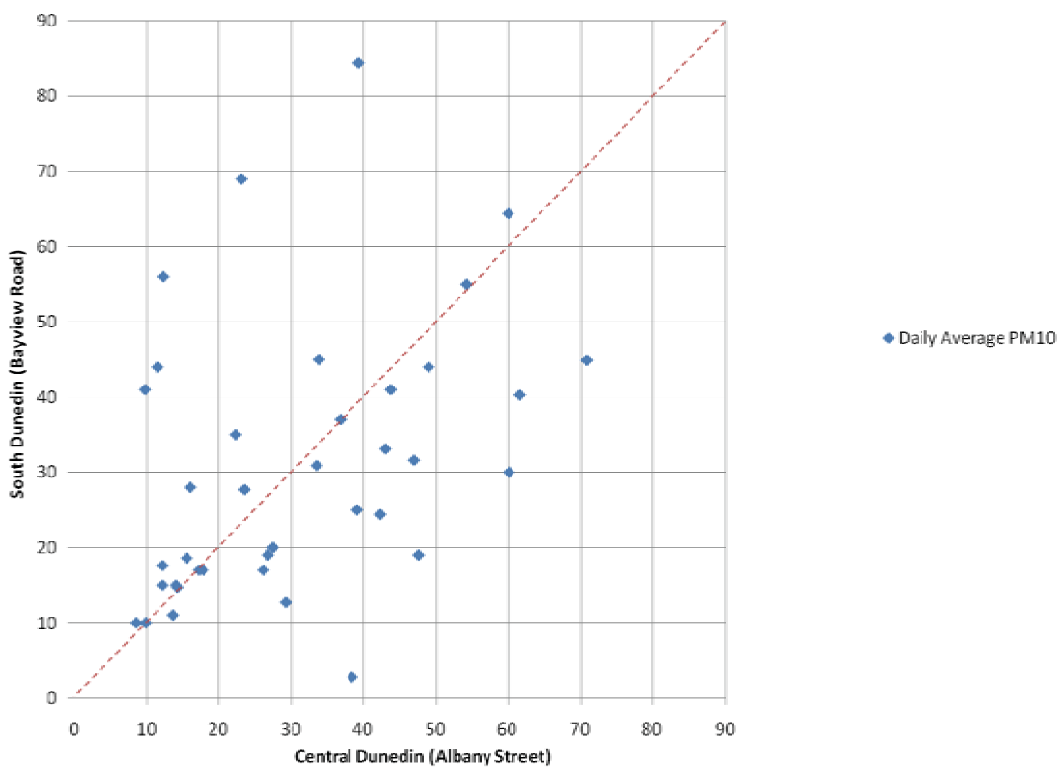


Figure 10 **Comparison of daily average PM_{10} from central Dunedin and South Dunedin at Bayview Road (85 paired values). All units are micrograms per cubic metre of air**

3. Emission patterns in Dunedin

Results of monitoring have shown that PM_{10} levels can often vary in different parts of the city. One reason for this variation is that emission levels vary around Dunedin. This section describes the emission patterns found in Dunedin.

The Air Emission Inventory (ORC, 2005) identified that 8% of the total Dunedin emissions were from industrial and commercial air discharges, and 92% (of the total) were from solid fuel domestic heating appliances. While these numbers are still likely to be relevant today on a Dunedin-wide scale, they are not necessarily representative of the situation in every part of town. For example, in some areas where there are no commercial or industrial air discharges, domestic heating may account for 100% of PM_{10} emissions. In other areas, where there are clusters of industrial and commercial discharges, these emissions may outweigh the domestic contribution.

PM_{10} emissions can be divided into two groups: fine (<2.5µm), which are from combustion sources (fires, engines, boilers etc); and coarse (2.5-10µm), which are from mechanical sources such as sea salt, suspended dust, pollen, suspended road and industrial material.

Since the two groups are spatially varied, it is useful to examine the geographic distribution of home-heating methods and consented discharges to air.

3.1. Spatial patterns of land use

The pattern of land-use zoning across the city is shown below in Figure 11. The map shows that, apart from the central city area, industrial land is confined to the base of Kaikorai Valley, Green Island and the northern part of South Dunedin. The central Dunedin monitoring site, which is located on Albany Street site, is in an area of mixed land-use, including industrial, campus, residential and port.

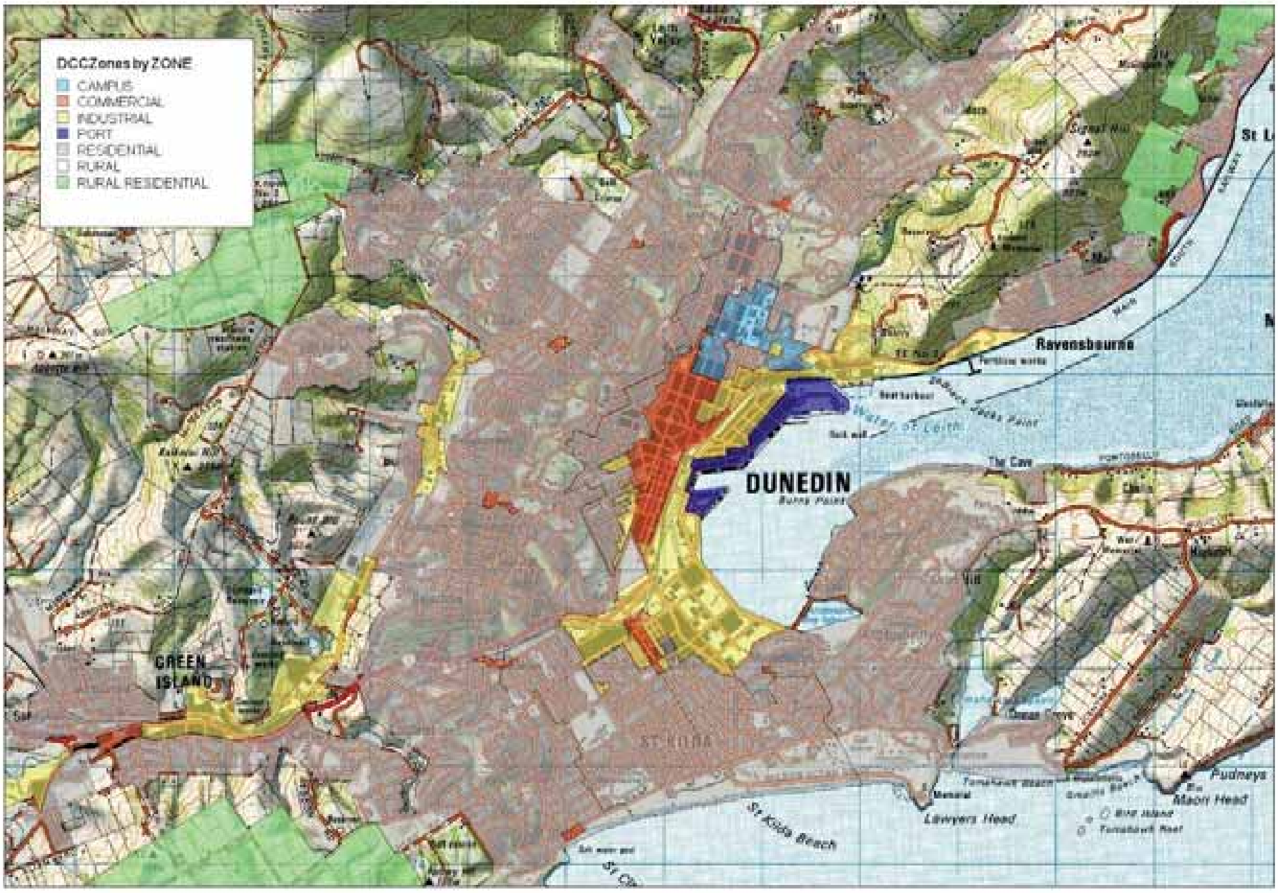


Figure 11 **Land use across the main Dunedin urban area (taken from DCC zoning)**

3.2. Spatial patterns of home-heating emissions

Patterns of fuel use

The 2006 census of NZ included questions on the types of fuel used to heat individual dwellings, aggregated by both census area units (CAU) and meshblock units (smaller-sized units). The following series of plots show the relative use of each of the main methods of heating by census area units[1]. (Note that the Harbourside and Caledonian units, on the south-western edge of the harbour, do not have any dwellings so they show up as white in all plots.)

As shown in Figure 12, the rate of wood use for home heating is between 40% and 70% throughout most of Dunedin. Areas in the central city and north Dunedin have markedly lower rates of wood use (less than 20%), and in the case of the University CAU, it is under 10%. Closer to the edge of the urban area, rates of wood use are higher.

The same pattern is shown in the rate of coal usage: the areas in the central city and north Dunedin have much lower rates (Figure 13). The highest rates are found in the Brockville, Halfway Bush, Concord, and along the edges of the harbour.

[1] These percentages are for heating used anywhere in the house, not just the main form of heating, as was found in the Air Emission Inventory (2005); hence the higher values presented.

The use of gas (both bottled and mains supply) is between 10% and 30% in most areas (Figure 14). This is included here to show the variation of this fuel, but it does not contribute significantly to PM_{10}.

In comparison, the rate of electricity usage is almost uniformly high, between 80-100% in all but the rural areas, as shown in Figure 15.

Figure 16 shows that in most areas less than 1 percent of dwellings are not heated at all, but in the central city units, this figure climbs to 2%-3% and in north Dunedin to 7%.

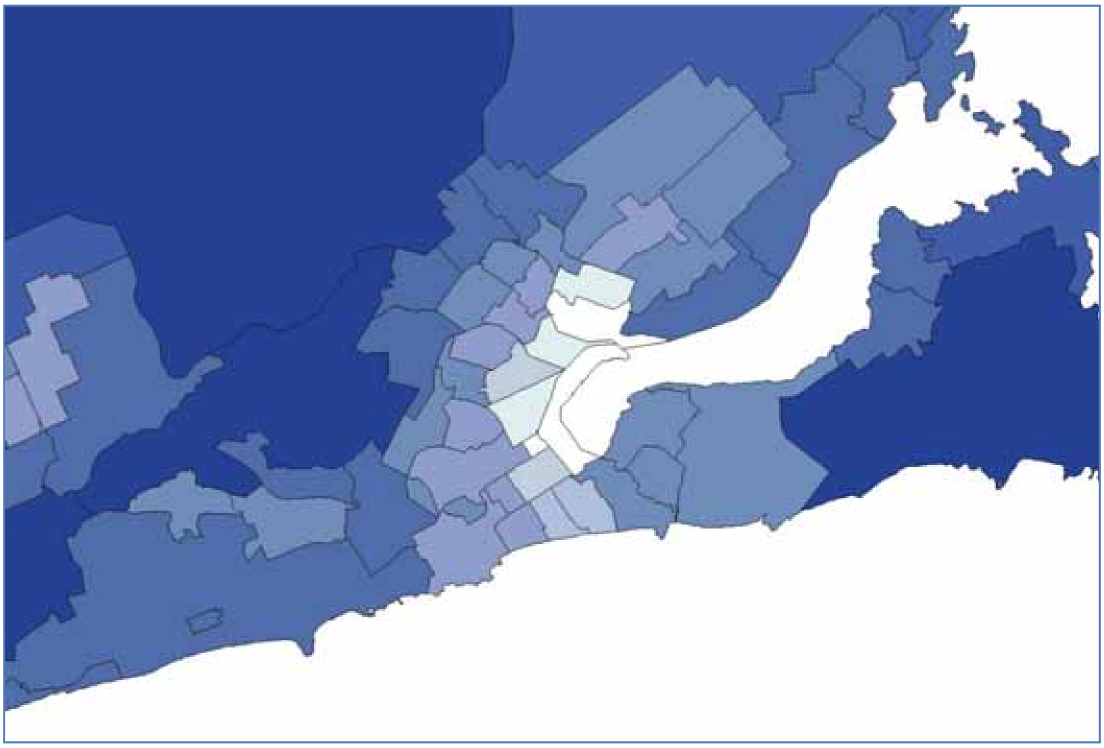
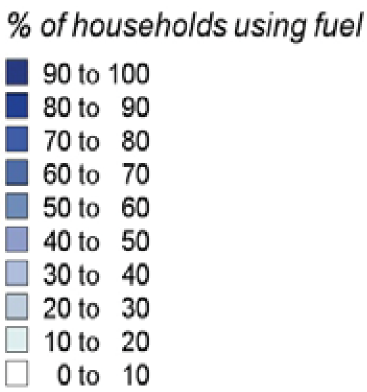


Figure 12 Percentage of households that use wood for heating



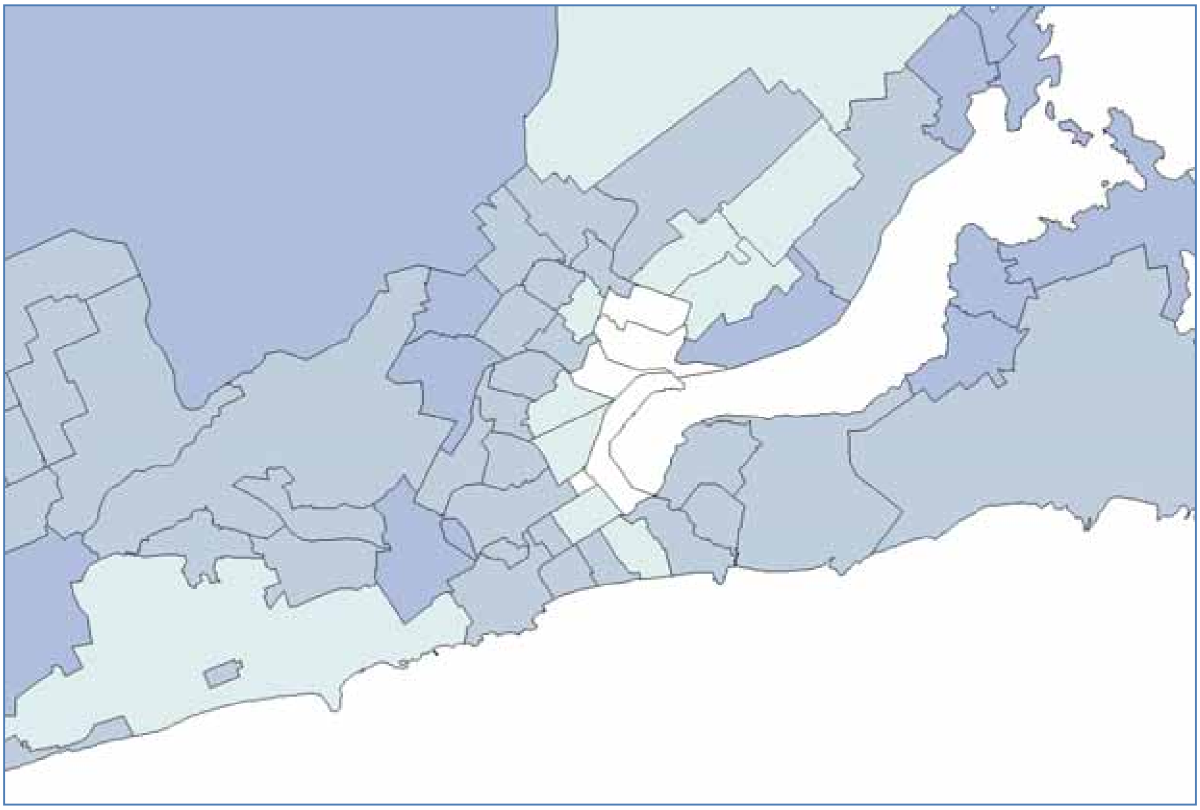
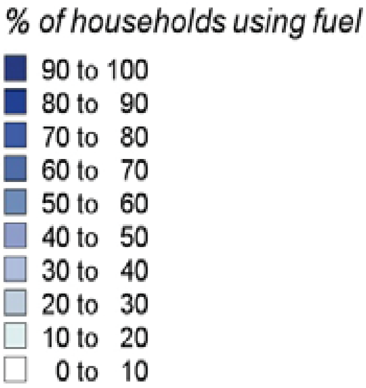


Figure 13 **Percentage of households that use coal for heating**



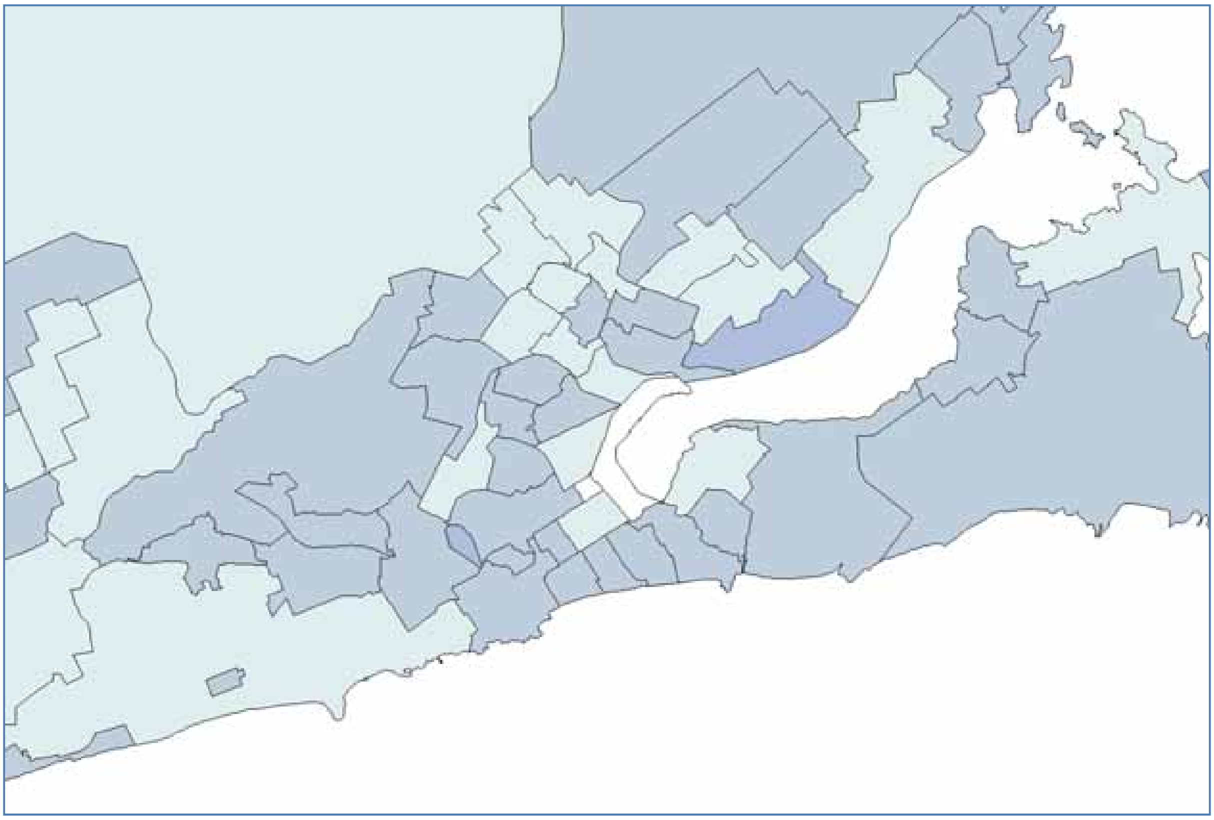
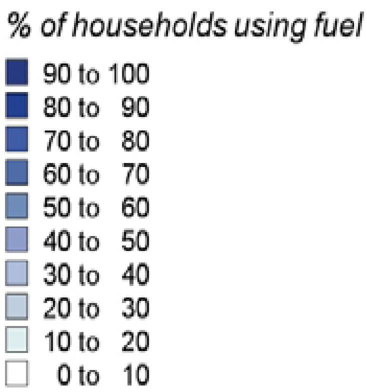


Figure 14 **Percentage of households that use gas (both bottled and mains) for heating**



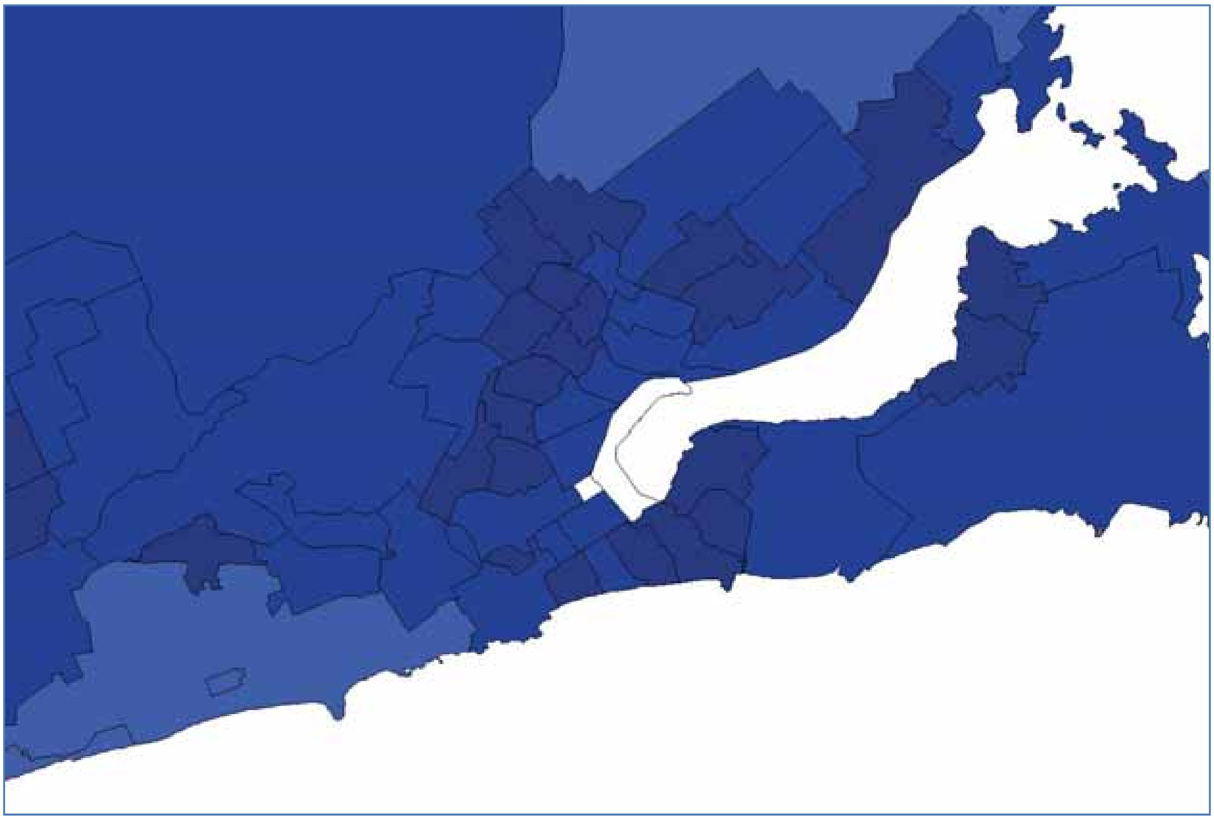
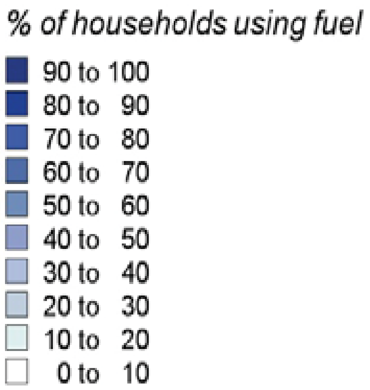


Figure 15 **Percentage of households that use electricity for heating**



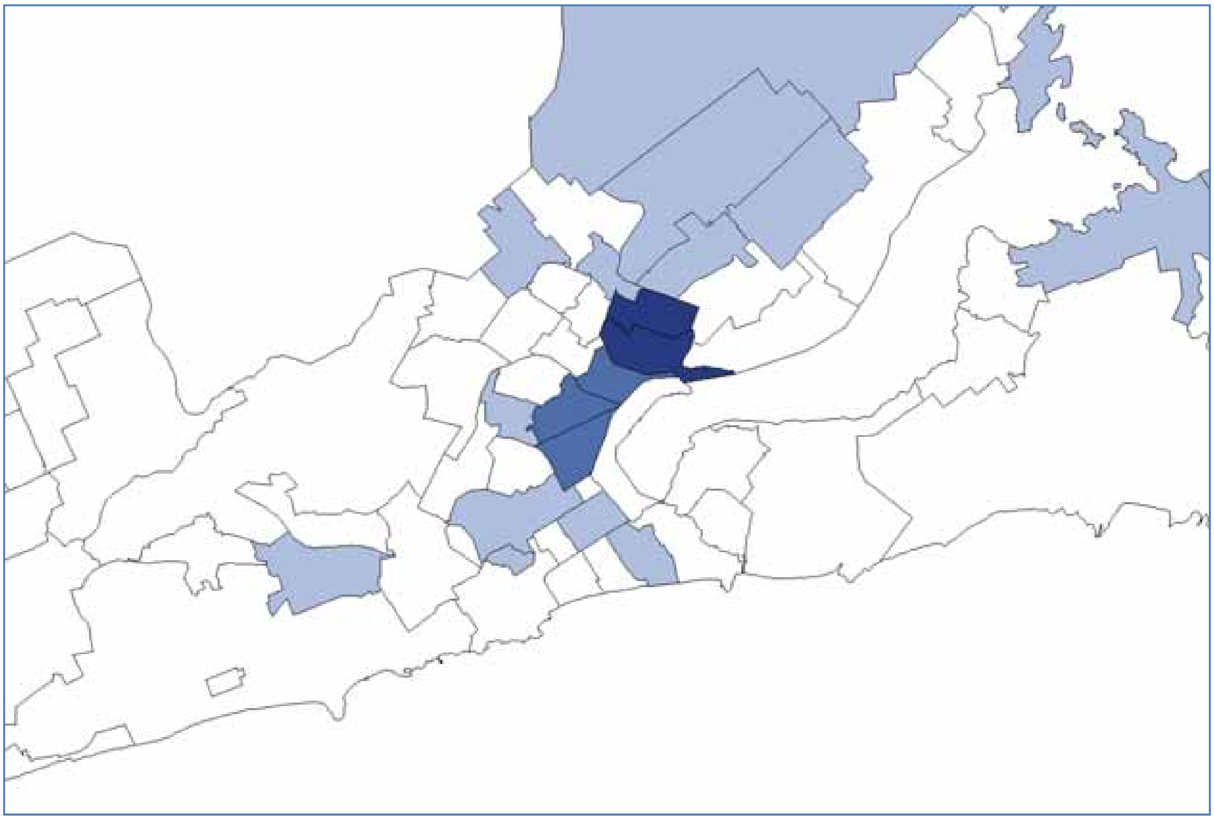
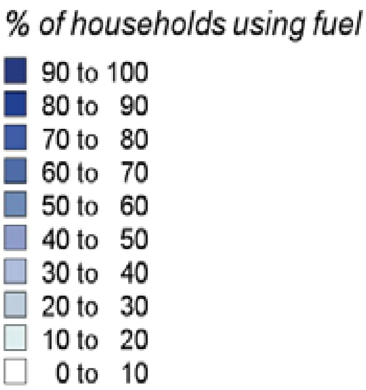


Figure 16 Percentage of households that use no fuels for heating



Density of emissions

While it is useful to look at the relative percentage of fuel use in different areas, the density of emissions is more closely linked to the concentration of PM_{10} experienced in the atmosphere. In a given area, a higher density of emission sources will emit a larger total amount of PM_{10} than in the same-sized area with fewer emission sources. Since PM_{10} is measured as a concentration, particulates from both areas will have to disperse in the same amount of air. All other factors being equal, the PM_{10} concentration will be higher from the higher density area.

One meaningful description of the density of domestic-heating PM_{10} emissions is the number of home-heating fires per unit area. In Figure 17, the total number of households using wood to heat their homes has been used as a proxy for the density of domestic-heating emissions[2]. This shows that the highest densities are in Mornington, Corstorphine East and Waldronville. The central and north Dunedin areas have lower densities of home-heating emissions.

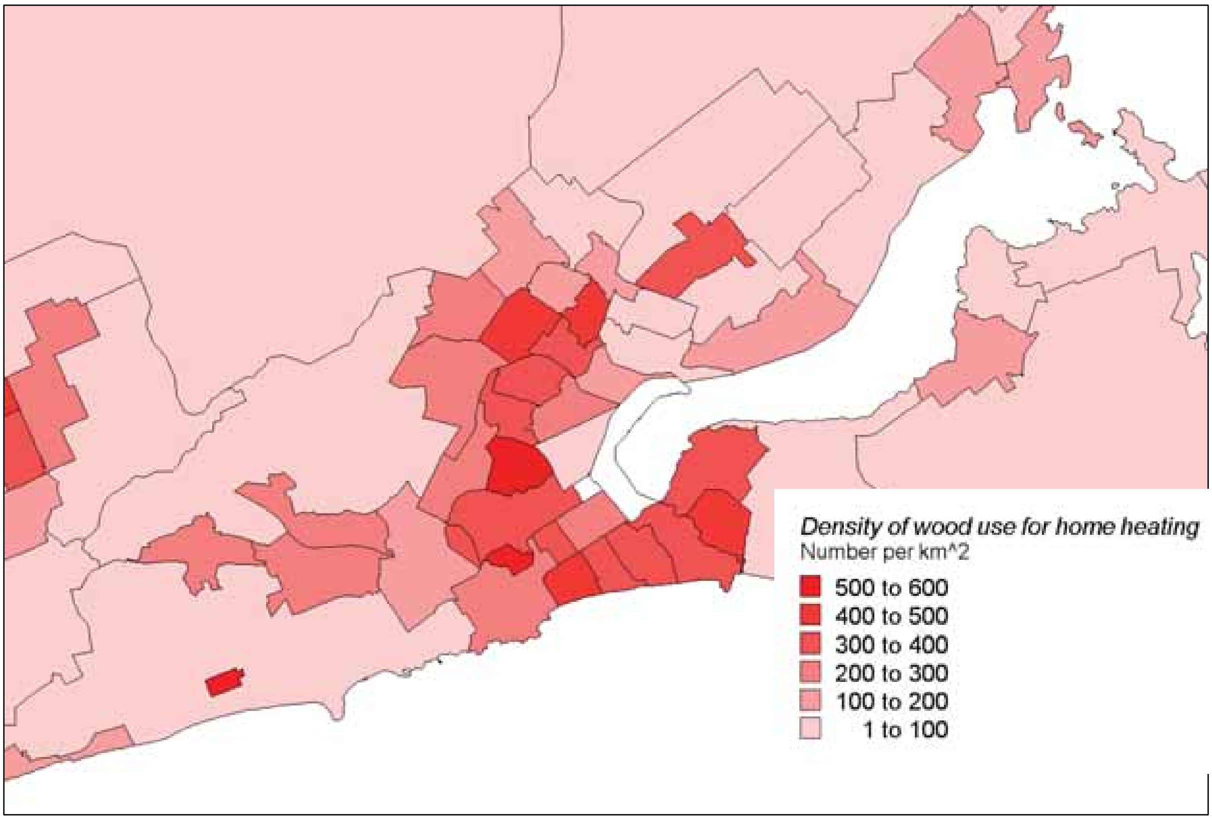


Figure 17 Density of wood burners used for home heating

3.3. Location of discharges to air in Dunedin

As Figure 18 shows, most of the consented air discharges are clustered around the central Dunedin area, as well as in the bottom of Green Island and along the Hillside Road corridor in South Dunedin. While not all the marked discharges contribute significant amounts of PM_{10}, the figure is indicative of the pattern of industrial PM_{10} discharges in Dunedin.

[2] This assumes that the proportion of the coal use and woodburner/multifuel type and age is uniform.

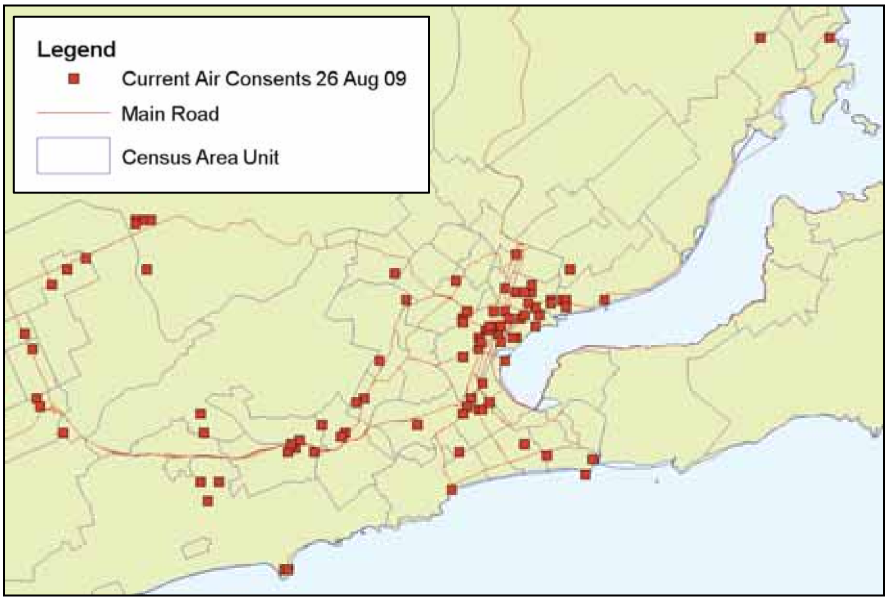


Figure 18 **Location of consented discharges to air in Dunedin, as of August 2009**

3.4. Emission Inventory for the central Dunedin monitor

The 2005 Air Emission Inventory identified that only 8% of the total daily PM_{10} load is from industrial and commercial sources. Focusing on the area that could be considered to contribute PM_{10} in the vicinity of the Albany Street monitor (Figure 19), the contribution from these sources increases to 22% on an average winter's day[3]. The reason for this is that many of the large commercial discharges of PM_{10} are clustered in the central Dunedin area.

In addition, as presented earlier in Figures 12 and 13, the northern central Dunedin area in close proximity to the monitor (from the Botanical Gardens to Stuart Street) has a much lower rate of wood and coal use (and by far the highest rate of no fuels used) than other areas in the city. Therefore, it is clear that the area of central Dunedin in the vicinity of Albany Street is more influenced by industrial and commercial emissions than are other areas of town. This also fits well with the observed pattern of daily, weekly, and yearly PM_{10} patterns.

[3] This is a conservative estimate and assumes down-valley flows that will bring domestic heating emissions from the suburbs into the central Dunedin area during the night-time period.

Figure 19 Area units included in the 2005 Air Emission Inventory for PM_{10} at Albany Street. The monitor is shown as a yellow dot and the area units are shaded white

4. The spatial monitoring programme in Dunedin

Mapping the geographic distribution of emission sources and their relative densities provides valuable information about the potential magnitude of PM_{10} levels around the city. In 2009, NIWA was contracted to perform a 'real-time' spatial monitoring programme in an effort to quantify PM levels in various parts of the city.

The rationale for the study was to provide a spatial context for the central Dunedin monitor. Monitoring was designed to reveal how representative the central Dunedin site was to the city, and to try and ascertain the extent of the area covered by the site's results.

As well as monitoring PM_{10}, the programme monitored PM_1 (ultra-fine particles) and black carbon (BC), an indicator of source type. A high ratio of $BC:PM_1$ will indicate areas where the dominant emission type is fossil fuels (coal), as opposed to wood-burning activities. Mobile measurements were taken using continuously recording sensors. The sensors were mounted on the top of a vehicle that traversed several set routes in the Dunedin area between 25 May and 4 June 2009. The main central Dunedin route is shown in Figure 20. Other routes encompassed north Dunedin, South Dunedin, and a southern motorway route.

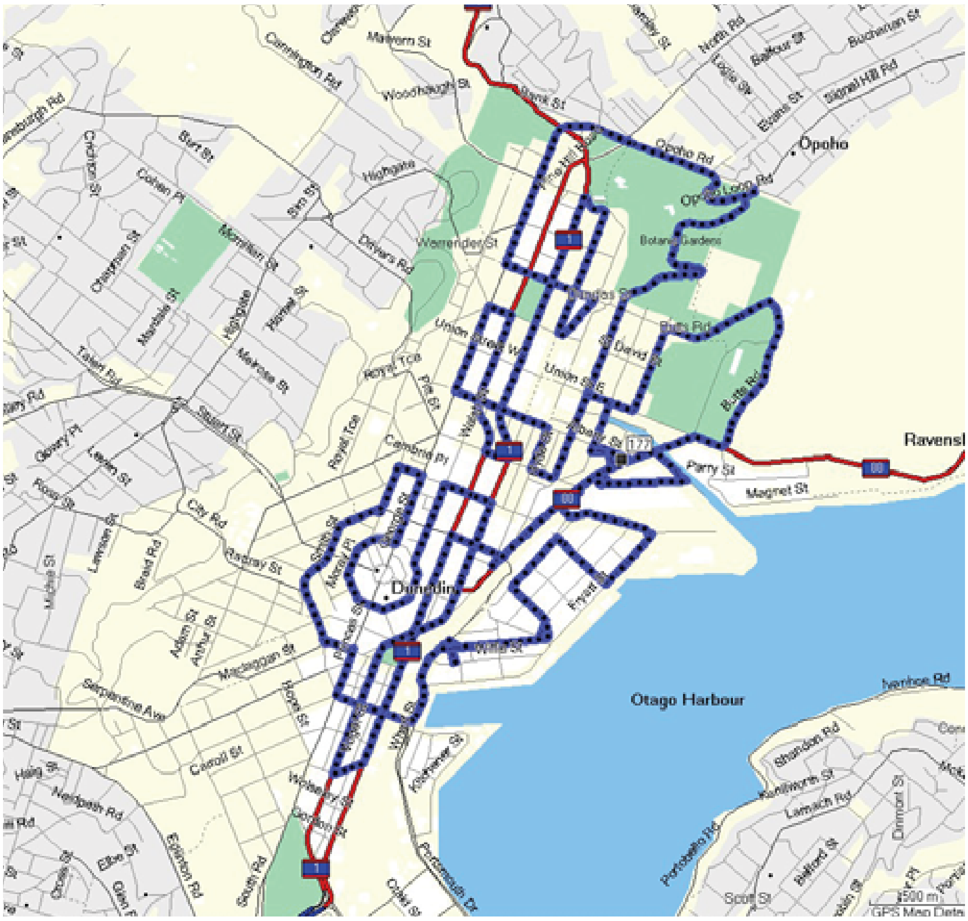


Figure 20 Central Dunedin route

4.1. Results of the spatial monitoring study

Each day exhibited different PM_{10} patterns, as weather conditions and emission patterns changed. Comparing one day to another, it was wind speed that generally controlled the mean ambient concentrations of PM_{10}, with calmer days having higher levels.

The concentration of PM_{10} varied across the central Dunedin area, as expected, with a wide range of emission sources. Figure 21 shows the average PM_{10} values recorded on the second day of monitoring in central Dunedin (25 July). On this day, as on the other three days that exhibited high concentrations of PM_{10}, the Albany Street monitor appears to be in an area of higher concentrations, with averages not exceeding those in the vicinity of the monitor.

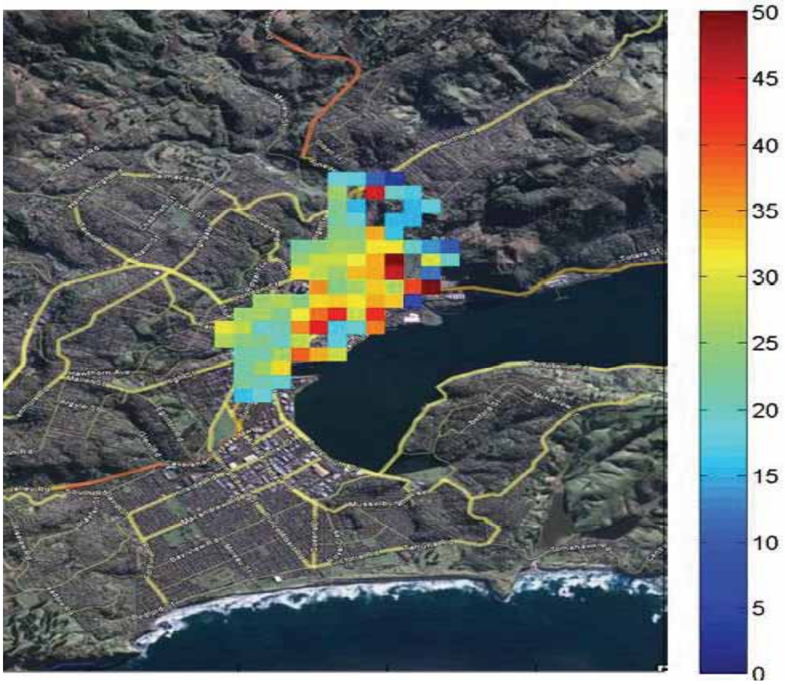


Figure 21 PM_{10} concentrations (µg/m³) measured across central Dunedin on 25 May

As a contrast, on 3 June the concentrations are uniformly low (Figure 22). Again, the monitor appears representative of the central Dunedin area.

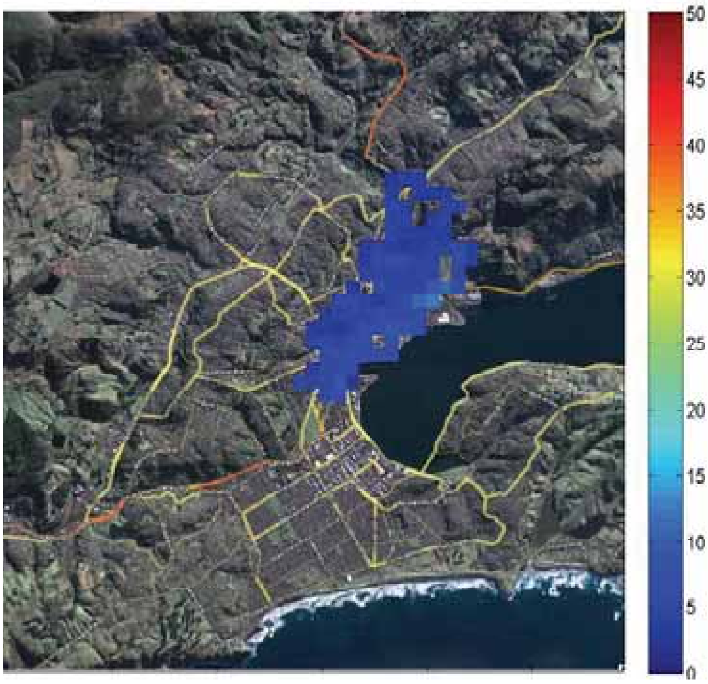


Figure 22 PM_{10} concentrations (µg/m³) measured across central Dunedin on 3 June

Across the greater Dunedin area, variability in PM_{10} levels becomes more apparent. For example, Figure 23 shows measurements taken on 2 June across central Dunedin, Kaikorai Valley, Green Island, and Mornington. These measurements indicate that there were significantly higher concentrations recorded in Green Island than in central Dunedin.

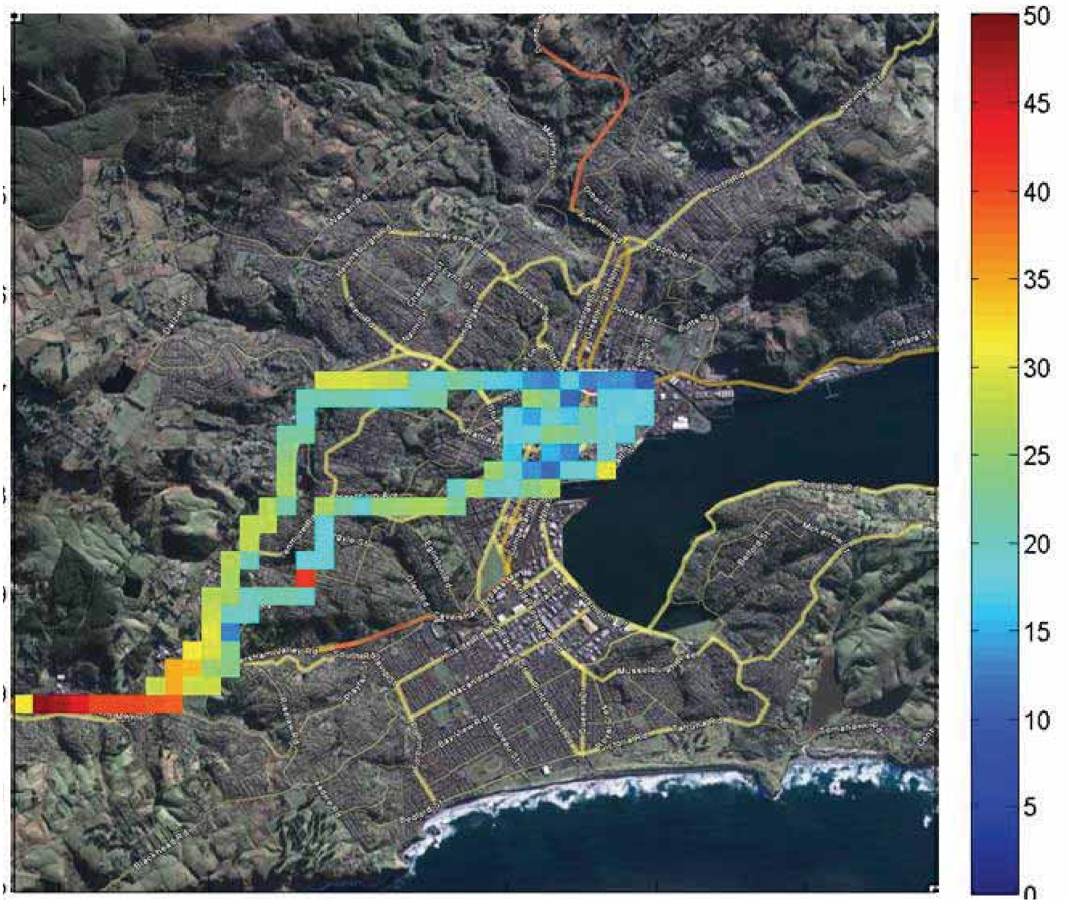


Figure 23 **PM_{10} concentrations ($\mu g/m^3$) measured across central Dunedin, Green Island, Kaikorai Valley, and Mornington on 2 June**

Sampling in central and northern Dunedin on 27 May yielded the results shown in Figure 24. The highest values are concentrated in central and northern Dunedin, not tapering off until the upper reaches of the Leith and North East Valleys.

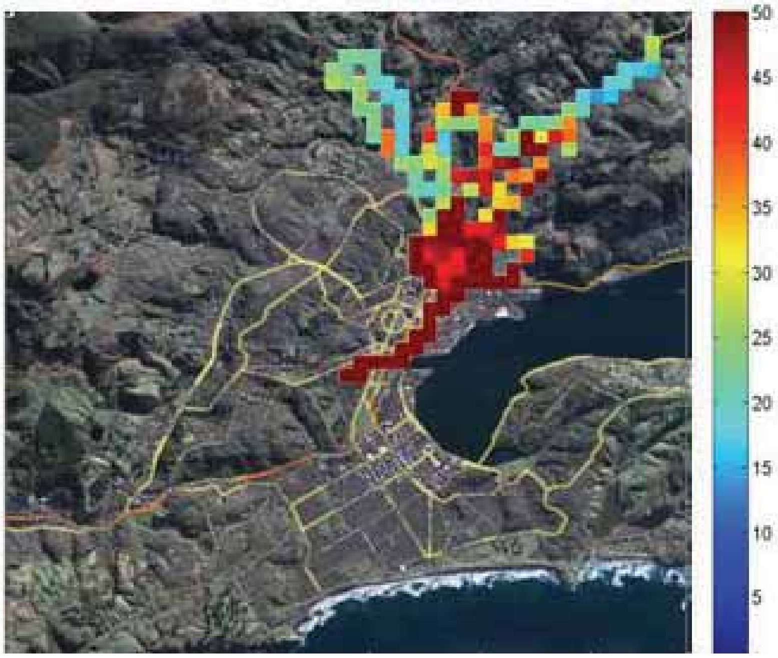


Figure 24 North and central Dunedin PM_{10} values on 27 May

Monitoring on 28 May showed fairly uniform PM_{10} values in central and South Dunedin along most of the route, except for the northern-most portion of central Dunedin, where values were lower.

Figure 25 South and central Dunedin's PM_{10} values on 28 May

4.2. Conclusions of the spatial monitoring study

Spatial measurements of PM_{10} concentrations have shown that there is considerable variation in air quality across Dunedin on winter days. The situation is complex, as there are many emission sources and a higher contribution from industrial and commercial sources than most other areas in Otago.

Over the period of a day, the central Dunedin monitor is generally representative of the central Dunedin area. However, because of the complex topography, it is only sometimes representative of other areas of the city. In addition, analysis of previous PM_{10} monitoring by ORC has shown that on a 24-hour basis, the Albany Street is positively correlated with, but is a poor predictor of, other areas of town.

The complete NIWA report is included as Appendix 1.

5. Summary

For most of the year, Dunedin experiences relatively good air quality. Nevertheless, there are times of the year when the air contains significant concentrations of PM_{10}. These are often times when the weather conditions are calm, which inhibits the quick dispersal of particles suspended in the air. These particles come from a variety of sources, including industrial and commercial emissions, as well as vehicles and domestic solid fuel appliances. They also include natural constituents such as sea salt and pollen.

PM_{10} monitoring in the greater Dunedin area over the last 12 years has provided data about the nature of air quality throughout the city. Like other large centres in New Zealand, Dunedin presents a complex PM_{10} signature due to its variety of emission sources, its hilly topography, and its proximity to the sea. Understanding the distribution of emissions and patterns of PM_{10} at various scales – both spatially and temporally – assists in the effective management of our valuable air resource in Otago.

6. Glossary

Mini-vol – A small, portable air quality monitor used to measure PM_{10}. The name refers to the fact that it draws a small volume of air across a filter to collect a sample.

Hi-vol – A large, stationary air quality monitor used to measure PM_{10}. The name refers to the fact that it draws a large volume of air across a large filter to collect a sample. The monitor must be programmed for each day's sample.

BAM1020 – Newer, automated air quality monitor used to collect hourly samples of PM_{10}. The name refers to the fact that is uses beta attenuation techniques to measure PM_{10} concentrations.

PM_1, $PM_{2.5}$, PM_{10} – Small particles suspended in the atmosphere. The number refers to the maximum size of the particulate matter. PM_{10} includes all those particles with a diameter less than 10 microns; $PM_{2.5}$ includes all those particles with a diameter less than 2.5 microns; and PM_1 includes all of those particles with a diameter less than 1 micron.

AQNES – The National Environmental Standard for Air Quality states that the limit for daily average PM_{10} is 50 micrograms per cubic metre of air, with one allowable exceedance per calendar year.

High-pollution day – A day when the average PM_{10} value is greater than 50µg/m^3 per cubic metre of air.

Temperature inversion - An atmospheric condition that occurs when colder, heavier air is near the surface, with warmer air above. This keeps the atmosphere in a 'stable' state, with little to no air movement, trapping emissions near the surface.

Appendix 1

The following is the complete NIWA report, 'Mobile Air Quality Measurements in Dunedin', which was prepared for the Otago Regional Council. The report describes and discusses the spatial monitoring project completed for Dunedin in 2009.

Mobile Air Quality Measurements in Dunedin

NIWA Client Report: AKL2009-054

July 2009

NIWAProject:ORC091

Mobile Air Quality Measurements in Dunedin

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Prepared for

Otago Regional Council

NIWA Client Report: AK2009 - 054

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NIWA Project: ORC091

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Contents

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Executive Summary

Dunedin's air quality is currently characterised by the measurements made at the Albany Street site in central Dunedin. These measurements show relatively large concentrations of pollutants during daytime. These high concentrations are contrary to the expectations in a residential combustion dominated area where night-time concentrations should dominate the diurnal cycle. Therefore, the representativeness of the Albany Street monitor needs to be assessed. In order to gather information specifically aimed to assess the representativeness of the Albany Street monitor, measurements were conducted using the NIWA car-based mobile monitoring platform $MAQS^2$ on streets in Dunedin between May 25th 2009 and June 4th 2009. The measurements were performed during daytime hours (between 9am and 5pm) in order to characterise the apparently unrepresentative high concentrations during daytime. Size resolved aerosol number concentrations were measured using a Grimm 1.107 aerosol spectrometer and black carbon absorption measured at two wavelengths (370nm and 880nm) with a Magee AE22 aethalometer®. Aerosol number counts were converted to mass equivalents using total volume as a proxy with an average particle density of 1.3 kg/l.

Measurements were made in Central Dunedin in the area around the Albany St Monitor during daytime on (09:00 to 17:00) 25th, 26th, 27th and 29th May and on the 3rd and 4th of June. Measurements were made in South Dunedin on the 28th May and in Green Island on the 2nd of June also during daytime (09:00 to 20:00). Weather during the measurement campaign divided into two periods: In general terms, the first part of the campaign was characterised by low speed northerly winds while the second part presented generally stronger and more variable winds from the NW to SW sector. There were no winds directly off the open ocean at any point during the campaign and, according to the Musselburgh EWS (45.90129S, 170.5147E) there was no significant rainfall during the campaign. Despite the Musselburgh EWS not recording any rainfall, there was enough on the afternoon of Friday 29th May to curtail monitoring.

Measured aerosol concentrations were generally higher during the early part of the campaign when dispersion conditions were poorer. Highest measured PM_1 and Black carbon concentrations were in South Dunedin on 28th May (average of 4 hours of measurements) while highest PM_{10} concentrations were found in Central and South Dunedin on the 27th and 28th May (average of 6 hours of measurements).

PM_1 was found to generally account for more than 40% of the aerosol but its contribution can drop to around 20% at times. Only about 15% of the measured particles fell in the 1 to 2.5 µm range indicating that there were mainly two size

modes, one coarse (larger than 2.5μm) and another fine (smaller than 1μm). This is consistent with both mechanical (dust and sea salt) and combustion processes (wood burning and mobile emissions) being responsible for the particles in the Dunedin atmosphere.

The BC:PM_1 ratio indicates that fossil fuel burning was dominant in Central Dunedin while a difference in absorbance at the two Aethalometer wavelengths (δC) pointed to biomass burning being more significant in the southern part of the city

A subjective assessment of results indicates that, over the period of a day, the Albany Street monitor is representative of the area immediately surrounding it but is only representative of more distant locations when the wind and topography are favourable.

Semi-variogram analysis indicated that, on the timescale of the mobile measurements (approximately 10 minutes), BC, δC, PM_{10} and $PM_{2.5}$ have spatial scales of less than 200m, making any point measurement very local in terms of its representativeness.

1. Introduction

Otago Regional Council (ORC) operates a single fixed site ambient air quality monitoring station at Albany St in central Dunedin. This site has been in operation since June 2006. Other monitoring has been carried out on an occasional or campaign basis at several other locations: North East Valley (NEV) in North Dunedin; Irmo Street in Green Island; Bayview Road and Macandrew Road in South Dunedin; (Kaikorai Bowling Club). None of these other locations have been NES compliant monitoring sites.

ORC has requested that NIWA undertake a campaign of mobile measurements in Dunedin to acquire high resolution spatial measurements of particulate pollution in order to investigate the variability of particulate pollution in the vicinity of the Albany St monitor.

Air quality monitoring data supplied by ORC suggest that the area monitored by the Albany St monitor is different from the rest of the city. The Albany St monitor displays an average daytime peak in PM_{10} measurements suggesting an industrial or perhaps a traffic source. This is different from the pattern in other South Island towns, which more usually display night-time peaks in PM_{10} pollution as a result of solid fuel burning for home heating. Monitoring of the diurnal pattern of PM_{10} was carried out in South Dunedin in June and July 2007. This showed the pattern in South Dunedin was similar to other South Island towns rather than that of Central Dunedin, with the highest values experienced in the evening indicating that solid fuel burning is likely to be a significant contributor to PM_{10} in South Dunedin.

Although diurnal measurements are not available from elsewhere in Dunedin, the 24hr PM_{10} averages from other locations in the city display winter-time peaks typical of many New Zealand towns and cities.

Because the Albany St monitor is the only NES compliant site in Dunedin, ORC would like to know how representative it is of the city. The mobile measurement campaign was carried out firstly to establish whether the site is adequately representing the area of central Dunedin and secondly how far that representation extends.

Measurements were made using the NIWA Mobile Air Quality Sampling System ($MAQS^2$), a car borne air quality measurement system developed over the past two years.

1.1 Spatial variation of particulate matter within airsheds

PM_{10} concentrations may vary within airsheds due to spatial variability of emissions (e.g. Wilton 2005, Iremonger & Graham 2007), along with topographical or meteorological influences (Aberkane 2000, Iremonger & Graham 2007). Techniques for assessing spatial variation of PM_{10} concentrations within airsheds include airshed dispersion modelling and survey monitoring. The latter approach was used by Hamilton et al. (2004) to evaluate particulate concentrations at two urban areas near Christchurch. Hamilton et al. (2004) used a handheld Dustrak (TSI Inc. St Paul Minnesota) portable laser photometer to record data related to PM_{10} concentrations at 20 sites in Rangiora and Kaiapoi. In addition, a Kestrel (Nielsen-Kellerman, Boothwyn, PA) handheld instrument was used to obtain manual observations of wind speed, air temperature and humidity. Due to the “stop and go” nature of the sampling, two hours were required to traverse the 20 sites at both towns.

From sampling over five nights, Hamilton et al. (2004) constructed contour plots based on the 10 measurements taken in each town. The survey identified that highest concentrations were recorded in residential neighbourhoods, which was attributed to burning of solid fuel on domestic heating appliances in those areas.

In another published study of spatial variability in New Zealand, Conway et al. (2007) used the same instruments and technique at ten sites in Invercargill. While highest concentrations were observed in the southern residential suburbs, a complex meteorological environment was reported. Only a limited number of observations are possible when using this technique and this may have been inadequate to identify the spatial pattern at a sufficiently high resolution to identify complex spatial patterns.

For both of these studies, numerical modelling of air pollution concentrations and meteorology was undertaken using The Air Pollution Model (TAPM), which provided useful information about the distribution of pollution under various topographical locations and meteorological scenarios. However, the model performance was compromised due to the coarse spatial resolution of the emission data.

Airshed particulate modelling has been conducted for some New Zealand urban areas, including Christchurch (Zawar-Reza et al. 2005), Hastings (Gimson 2006) and Rotorua (Fisher et al. 2007). These models demonstrate the variable nature of particulate concentrations throughout airsheds in New Zealand, depending on factors including the spatial distribution of emissions, topography and meteorological characteristics.

Mobile measurements, using instruments mounted in a vehicle, offer a complementary means of validating or reinforcing conclusions drawn from modelling, or may be used as an alternative means of assessing spatial variation in airsheds where no modelling has been undertaken. Advances in miniaturisation have made it possible for air quality instrumentation to be deployed on mobile platforms and to be operated whilst on the move. Although relatively labour intensive, this method maximises the utility of single instruments and provides information about the spatial variability of pollutant concentrations.

While the temporal variability at greater than weekly timescales is difficult to capture with these kinds of measurements, there are several advantages of mobile monitoring. Recent developments in air quality monitoring technology mean that it is now possible to build a relatively low cost mobile monitoring system that provides good quality, real time data at high spatial resolution. Such a mobile measurement system could provide data to allow the assessment of the variation of contaminant concentrations across an airshed for the purposes of identifying hot spots for monitoring sites, validating airshed dispersion models, or for input to the development or improvement of air quality management strategies.

1.2 Scope and purpose

The purpose of the monitoring campaign was to measure the spatial variation of PM_{10}, $PM_{2.5}$, PM_1 and Black Carbon absorption at two wavelengths along with high-resolution meteorological measurements around the Albany St monitor. The aim of the monitoring campaign was to characterise the area around the Albany St monitor and assess how representative the monitor is of central Dunedin.

This report summarises the results of the campaign and investigates the relationship between the spatial measurements and the fixed point monitoring at Albany St.

2. Method

The following sub-sections describe the methods and equipment used for this air quality monitoring campaign. The Mobile Air Quality Sampling System (MAQS[2]) is designed to be useable in any suitable vehicle, that is, it does not require a dedicated vehicle. The principle instruments are a Magee Scientific AE22 Aethalometer and a Grimm Aerosol Technik 107 Dust Monitor along with weather, positioning and data acquisition and storage instruments. The instruments and configuration are described below.

2.1 Instrumentation and configuration

Instruments are located both inside the vehicle and on the roof. A purpose-built conduit is used to bring cables and sample tubes through the vehicle rear passenger window, to and from the rooftop enclosure (Figure 1).

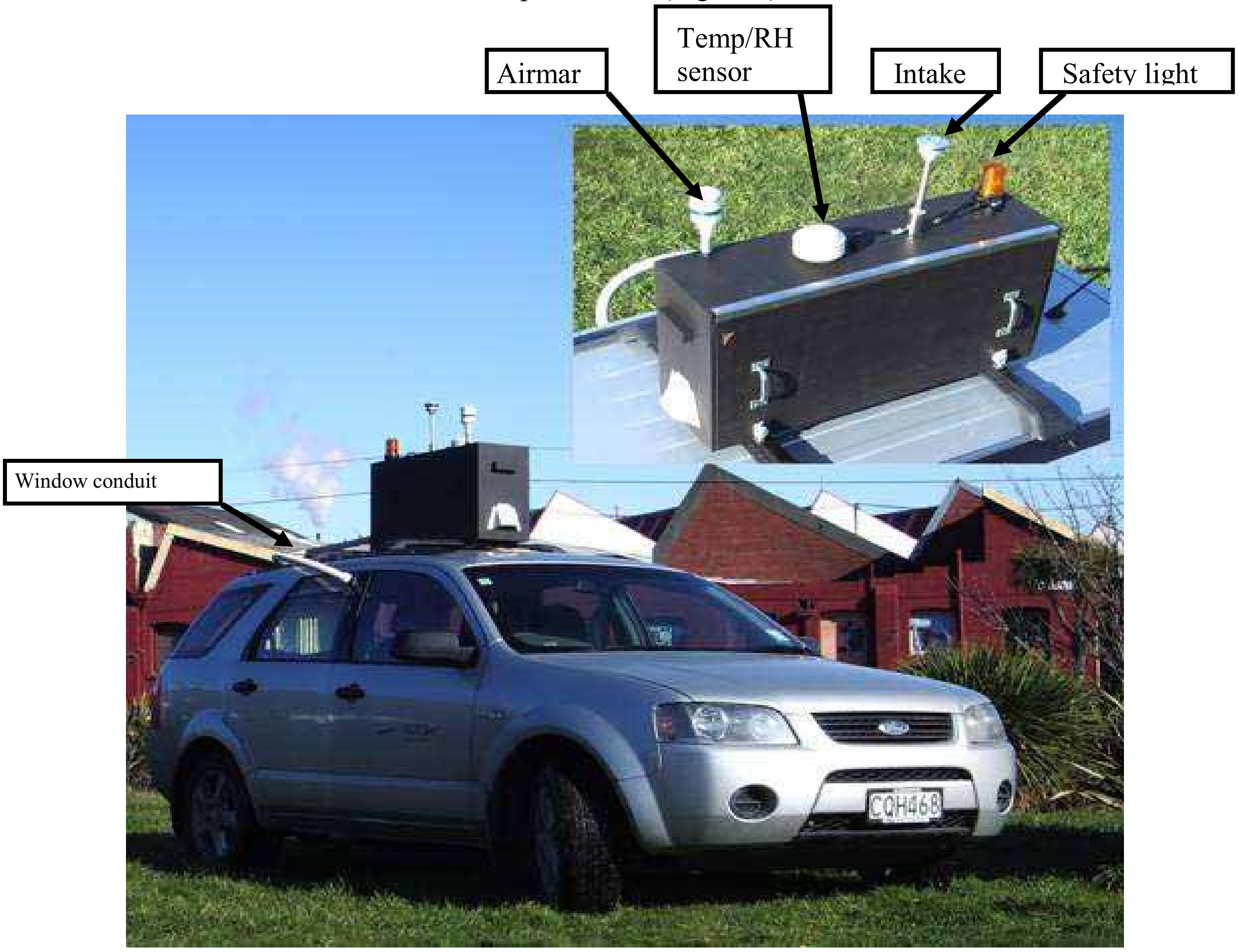


Figure 1 Mobile monitoring vehicle and (inset) rooftop enclosure. Rooftop instrumentation (including Airmar and temperature + relative humidity sensor) and air intake is shown.

2.1.1 Aethalometer

A Magee Scientific (Berkeley, California) AE22 aethalometer is housed inside the vehicle with a sample tube passing through the window conduit into the rooftop enclosure, upon which the air intake is located. The aethalometer measures the optical absorption of particles deposited on a filter. The optical absorption provides an index of mass concentration of 'Black' or Elemental Carbon (BC) particles that are generally associated with combustion sources. The AE22 uses two wavelengths: 880 nm (near-IR) to quantify BC and 370 nm (UV), which provides a qualitative measure of aromatic organic compounds. The dual wavelength measurement may be used for identification of different sources; for example, vehicle emissions vs. wood smoke from home heating or biomass combustion. Near real time measurements are possible with a time resolution from five seconds to one hour. For the present deployment of the system a time base of 5 seconds (the minimum possible) was used. It is also necessary to note that, since the Aethalometer is a filter based instrument, as part of its normal operation there is a brief pause in measurements when the filter tape gets saturated, which in the current deployment was around 2 times per hour.

2.1.1.1. Black carbon – an indicator of source type

Information about other particulate measures, particularly black carbon (BC) can provide clues about the types of emission sources present in the area. As BC is emitted at different intensities from different sources, a map of the relative abundance of BC in the particulate matter would help map different combustion sources in the area. Even though it is possible to find black carbon in the coarse fraction of PM, it is not normally associated with dust and it is used therefore as a tracer of combustion sources. Only in areas where coal is handled in open spaces it is possible to find black carbon particles of sizes large than 1μm. Therefore, the BC:PM_1 ratio could provide clues about the distribution and type of combustion sources in the area. Not all combustion sources produce the same amount of black carbon. Diesel combustion has been shown to produce about 10 times more BC per unit of fuel burnt (Imhof et al, 2005). Wood combustion aerosols tend to be less black and absorb less light than fossil fuel combustion (Olivares et al, 2008). Therefore, areas with high values of BC:PM_1 ratio would indicate areas where fossil fuels are dominant while areas with smaller ratios may be associated with wood burning activities.

The Aethalometer measures absorption at two wavelengths, 370nm (UV) and 880nm (IR). The difference in absorption between the two wavelengths (δC) is an indication of woodsmoke (Allen et al. 2004), and can hence be useful for source identification. High values of δC indicate biomass burning and lower values are associated with fossil fuels.

2.1.2 GRIMM particulate sampler

A GRIMM Model 1.107 Dust Monitor (Grimm Aerosol Technik GmbH & Co. KG, Germany) is housed in the rooftop enclosure, with power and data cabling via the window conduit. The GRIMM monitor is a low-volume sampler that uses a light scattering technique to continuously measure particle number concentration and size distribution in an air stream. The GRIMM is well suited to this mobile application due to the fast response time with near-continuous (six second time resolution), simultaneous measurements of particle number concentrations in 31 size bins from 250nm to 32,000nm. PM_{10}, $PM_{2.5}$ and PM_1 mass concentrations ($\mu g/m^3$) can then be retrieved after making some assumptions about particle density and optical properties (more details on how this was performed are given in the following section). Because particle density information is generally unavailable, it is recommended to calibrate the GRIMM by comparing results with those obtained by another measurement technique (Maletto et al. 2003). However, because the main objective of this system is to investigate relative concentrations across an airshed, a full calibration of the GRIMM is considered to be unnecessary. There is sufficient agreement between GRIMM data and TEOM FDMS results (Olivares et al. 2009) to show that the GRIMM Model 107 Dust Monitor is well suited for mobile monitoring to evaluate PM_{10} monitoring sites for NES compliance.

2.1.3 AirMar PB100 Ultrasonic weather station

A PB100 (AIRMAR Technology Corporation, Milford, New Hampshire) ultrasonic weather station is mounted on roof. The weather station provides measurements of wind speed and wind direction (both absolute and relative to the vehicle movement), air temperature, relative humidity and barometric pressure.

2.1.4 Data acquisition and accessory equipment

A USB GPS receiver (GlobalSat BU-353) is used to provide positional information (longitude, latitude and altitude) plus travel information (vehicle speed and heading) with accuracy 3m. All instruments are interfaced to a computer via either USB or serial-USB adapter (Quatech ESU2-100). A LabVIEW (National Instruments) application has been developed with functions for system control and data acquisition, such that data are updated and stored every second.

The LabVIEW application also provides an on-screen display of instantaneous data in realtime. All instruments and equipment are ultimately powered from a dedicated 12VDC lead-acid battery power supply, with a 12VDC-240VAC inverter used to power the aethalometer and DC-DC converters as required for other applications.

2.2 System configuration and operation

The intake was designed and built by NIWA with a convex top-piece (Figure 2) intended to direct air and particulate matter into the intake tube. Air is drawn through the system intake using a pump (Charles Austen Pumps – model CAPEX V2-SE) capable of 17L/min maximum flow. Sample air is then drawn from the main intake into the GRIMM and aethelometer using the dedicated pumps of these instruments.

This arrangement was developed in an effort to overcome loss of particulate that was previously observed when the system was operated at moderate vehicle speeds with the regular GRIMM intake (Olivares et al. 2008). The purpose-built intake and installation of the separate pump successfully overcame this issue, as demonstrated by Olivares et al. (2009).

Inside the vehicle, the Aethalometer enclosure along with the GPS, serial-USB interface and power converters, are positioned on the rear seat, directly behind the driver. The system is operated by two people; one person driving while the second assesses the performance of the instruments, assists with navigation and notifies the driver when it is necessary to stop for maintenance.

Figure 2 Sample tube intake, showing (inset) convex top-piece designed to direct flow into the tube.

2.3 Data analysis

This section details how the data was processed and what analysis tools were used to generate the information presented in this report.

2.3.1 Particulate Matter concentrations from number size distribution

As indicated before, the raw data obtained from the Grimm 107 Aerosol Spectrometer corresponds to particle counts for 31 size fractions between 250nm and 32000nm. This is the standard operation of this kind of optical sensors and it is always required to extract the **mass concentration** information from that **number** size distribution.

The 31 channels used by the spectrometer are indicated in Table 1. The asterisk denotes the *nominal* channel size and the data reported by the Grimm spectrometer corresponds to the "*number of particles with an optical size larger than this diameter*". The bold numbers correspond to the *representative* size for the corresponding size bin. This number was calculated as the *geometric mean* between the adjacent nominal sizes (note that for the larger size bin an upper size limit of 50000nm was arbitrarily chosen as the upper cut-off of the size distribution.

Table 1. nominal size ranges for size bins in a GRIMM 1.107 aerosol spectrometer

Dp*	*250*	*280*	*300*	*350*	*400*	*450*	*500*	*580*	*650*	*700*
Dp	**265**	**290**	**324**	**374**	**424**	**474**	**539**	**614**	**675**	**748**
Dp*	*800*	*1000*	*1300*	*1600*	*2000*	*2500*	*3000*	*3500*	*4000*	*5000*
Dp	**894**	**1140**	**1442**	**1789**	**2236**	**2739**	**3240**	**3742**	**4472**	**5701**
Dp*	*6500*	*7500*	*8500*	*10000*	*12500*	*1500*	*17500*	*20000*	*25000*	*30000*
Dp	**6982**	**7984**	**9220**	**11180**	**13693**	**16202**	**18708**	**22361**	**27386**	**30984**
Dp*	*32000*									
Dp	**40000**									

First the number concentration reported by the Spectrometer was converted from N(>Dp) to dN(Dp) in order to obtain the number of particles in each size bin. Then, and using the *representative* size, the *representative volume* of the particles was calculated. Finally, this *volume* size distribution was integrated (Equation 1) for the required size fractions and converted to mass using a standard particle density (ρ) of 1.3 kg/l.

Equation 1

$$PM_X = \rho \int_{Dp=0}^{Dp=X} dV(Dp)dDp = \rho \int_{Dp=0}^{Dp=X} \underbrace{\frac{\pi * Dp^3}{6}}_{\text{Particle Volume}} * dN(Dp)dDp$$

2.3.2 Data Smoothing and temporal and spatial scale of measurements

As indicated before, the MAQS2 records data at a temporal resolution of 1 second but its key instruments do not report at that high resolution but instead do it at 5 and 6 seconds intervals. This means that the instantaneous concentrations reported by the MAQS2 are representative of the preceding 5 or 6 seconds. Therefore, a smoothing the time base of 1 minute was chosen as it allows for at least 10 different data points from the Grimm and the Aethalometer which gives robustness to the calculated statistics.

Once the data was smoothed, it was then spatially grouped in 50x50 grids which correspond to roughly 200m horizontal resolution. This grouping, coupled to the smoothing ensures that the spatial patterns are robust and representative of the spatial variation of the ambient concentrations rather than spurious spikes in the data. For each of the daily plots, the number of datapoints behind each square ranges between 10 and 30 depending on how frequent the vehicle passed certain areas. This number rises to more than 40 for the aggregated dataset. Therefore, the plotted fields are roughly representative of 30min.

Finally, the statistics shown in this report correspond to the **median (or 50% percentile)** as opposed to the **mean**. This was done because the median is a more robust estimator of the expected concentrations than the mean for non-normal distributions such as those expected in ambient measurements.

All the analysis was performed using purpose built software routines developed in LabView® and Matlab®.

2.3.3 Variograms

Finally, one of the most powerful techniques used in this report correspond to the **variograms**. Annex 1 shows a more detailed description of the tool and more comprehensive descriptions can be found in the literature (Lightowlers et al, 2008 and references therein).

Here the technique was applied to the smoothed and spatially grouped dataset in order to obtain robust statistics. Furthermore, a finer grid (200x200 datapoints) was used in order to resolve the small scale variability of the data.

Also, a re-smoothing of the data to 10min running average was performed to test the sensitivity of the variograms to the smoothing interval and the result was that the variograms didn't change and therefore the 1min smoothing was used.

2.4 The monitoring measurement campaign

Monitoring took place between May 25th and June 4th 2009. The campaign consisted of two phases, one centred tightly on the Albany St fixed monitoring site to establish how representative the fixed monitor is and a second wider ranging one to try to establish how far its coverage extends. For the first phase, the MAQS[2] took a route around the fixed monitoring site that followed roughly a figure eight shape with the fixed monitor at its centre, one lobe to the north and one to the south. The entire route took about one hour to complete, so that the vehicle passed by the fixed monitor once every half hour. This route was driven several times each day for five of the campaign days. The route is shown in Figure 3.

The measurement times and fraction of data captured for each day is summarised in the following table (Table 2):

Table 2. Summary of the measurement times and data capture during the campaign between the 25th of May and 4th of June.

Date	*Start time*	*End time*	*Nr of records*	*% data captured*			
				PM	BC	Location	Weather
25th May	10:04	17:04	28 000	78%	94%	100%	100%
26th May	9:24	16:24	25 174	89%	91%	100%	100%
27th May	12:40	19:36	24 947	100%	99%	35%	100%
28th May	12:30	18:12	20 505	100%	100%	100%	100%
29th May	9:27	11:53	8 731	86%	87%	62%	100%
30th May				No Data			
31st May				No Data			
1st June				No Data			
2nd June	12:05	20:07	28 935	100%	98%	100%	100%
3rd June	8:28	17:08	31 213	90%	81%	97%	100%
4th June	8:27	17:10	31 416	91%	89%	14%	100%
Total			198 921	92%	92%	76%	100%

The second phase aimed to extend the measurements to try to ascertain the extent of the area covered by the Albany St monitor. The monitoring vehicle drove the phase one route and then drove to another area in Dunedin, completed a circuit there and returned to the Albany St monitor. The routes are shown in Figure 4

The *Southern Radial* (Figure 5) covered the area to the south of Dunedin on May 28th between 12:30 and 18:12. This route started at the Albany Street monitor and then headed south towards Forbury where it zigzagged east-west to cover the area before returning to the Albany Street site and following the *phase one* route. This route was repeated four times in total (4 short and 4 long routes) with a 100% data capture

The *Green Island Radial* (Figure 6) covered the area to the west of Dunedin and it was performed during June 2nd. This route started at the Albany St monitor and then took to the west until Brighton Rd before returning to the city centre and followed a *phase one* loop. The full circuit was performed seven times with a 100% data capture.

The *North Eastern Valley Radial* (Figure 7) intended to capture the variation in the ambient concentrations to the north of the city centre. This *radial* was covered during May 27th and it started from the Albany Street monitor and headed north covering Normanby, Liberton and Leith Valley. This route was followed 4 of times with another 4 *phase one* loops. Unfortunately, during this day there were technical difficulties with the instrumentation which meant that there was no information about the position of the vehicle. Every effort was made to recover the position information from the back up unit but only 35% of the data was recoverable. Despite the lack of precise position information, a simple comparative analysis of this data was possible and it is presented in Appendix 1.

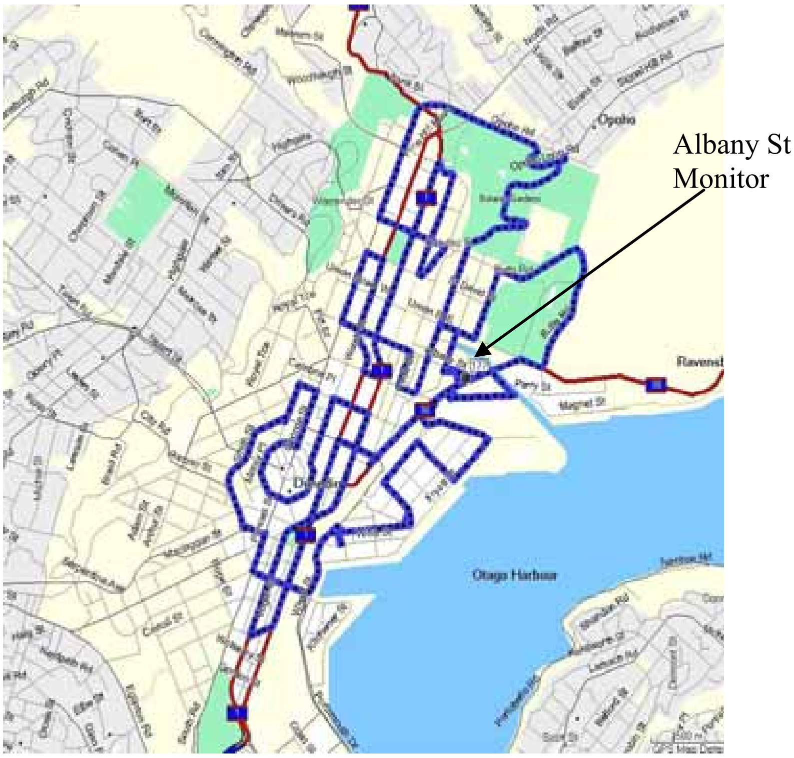


Figure 3 The route for phase one of the Dunedin mobile monitoring campaign

Figure 4 All routes travelled during the monitoring campaign

Figure 5 Southern Radial shown in yellow

Figure 6 Green Island Radial shown in yellow

Figure 7 North Eastern Valleys Radial shown in yellow

3. Results

3.1 Weather

Meteorological information, representative of the area, has been taken from the Dunedin - Musselburgh EWS (45.90129S, 170.5147E). In general terms, the first part of the campaign was characterised by low speed, northerly winds while the second part presented generally stronger and more variable winds from the NW to SW sector. There were no winds directly off the open ocean at any point during the campaign. The wind speed, direction and temperature are shown in Figure 8. There was no significant rainfall recorded at Musselburgh during the campaign.

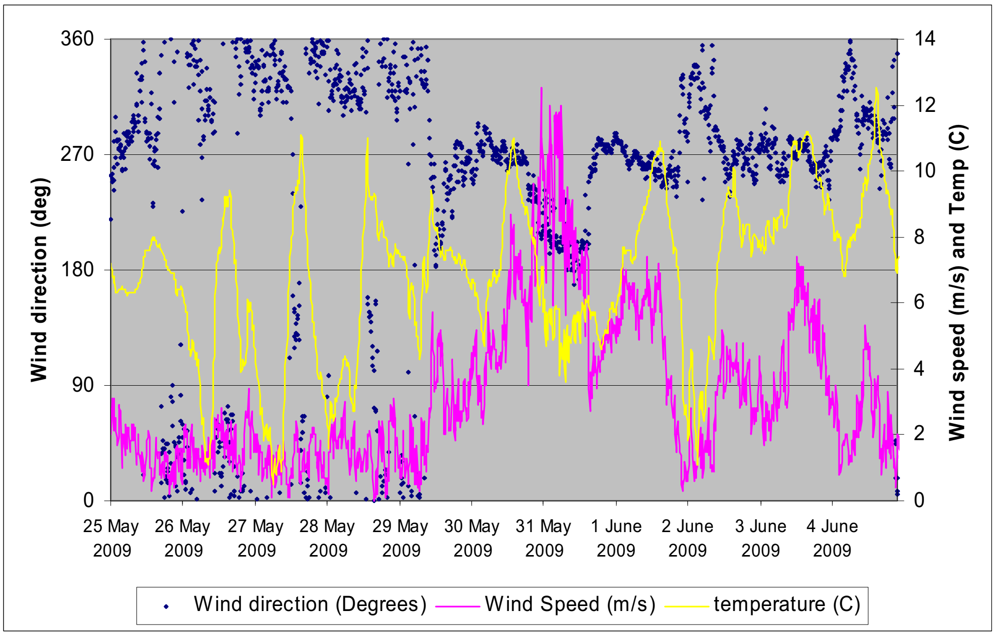


Figure 8 wind speed, direction and temperature taken from the Musselburgh EWS

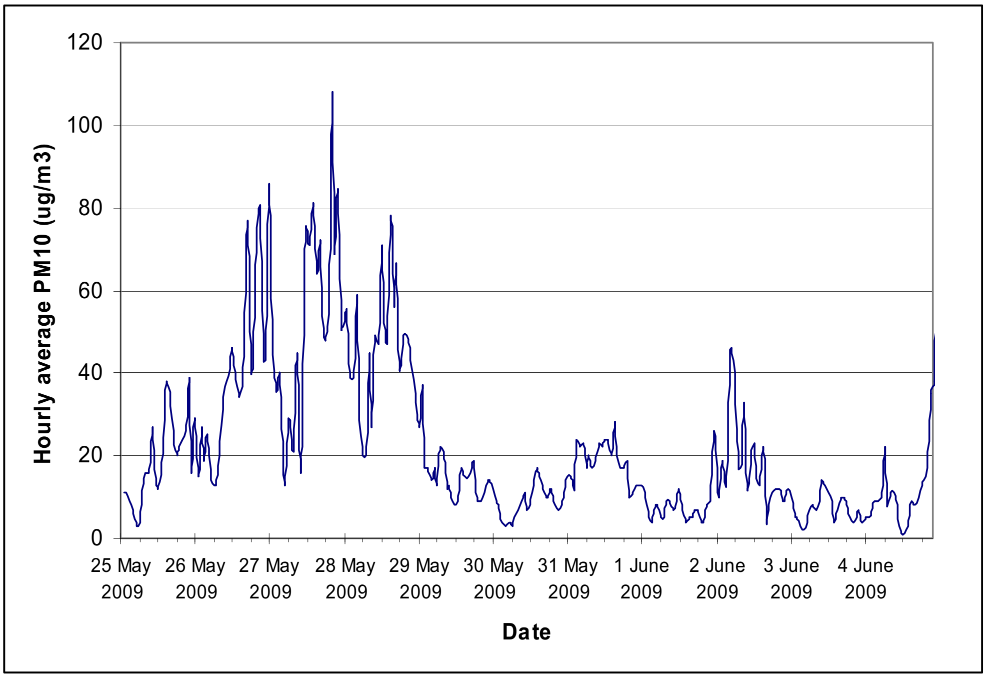


Figure 9 PM_{10} measurements at the Albany St monitor (ORC data)

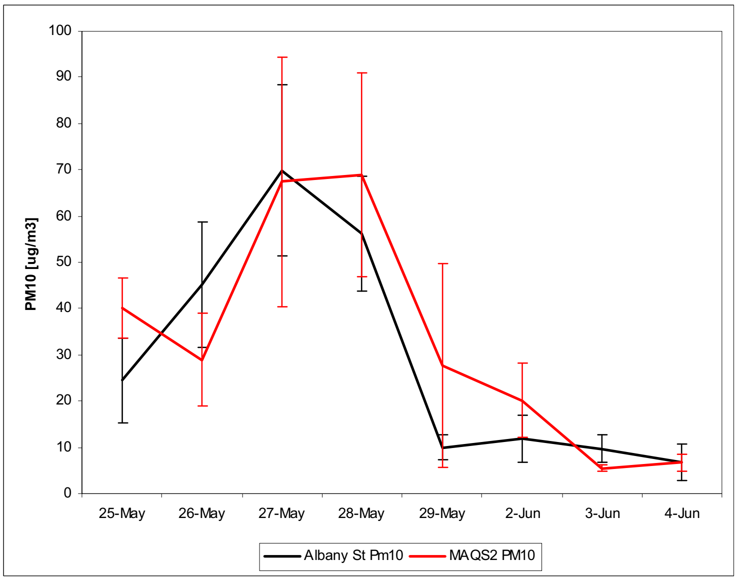
Figure 9 shows the hourly PM_{10} as measured at the ORC Albany St monitoring site during the campaign. As expected, concentrations are greatest during the periods of low wind during the early part of the campaign and more variable with the variable wind speeds during the second part of the campaign. The night time temperatures get close to freezing on several occasions and high evening peaks are recorded when this happens.

3.2 General description of results

Figure 10 shows the average concentrations measured by the $MAQS^2$ together with the corresponding average concentrations observed at Albany St. It is worth noting that the *daily averages* shown in Figure 10 correspond in fact to the mean of those hours when both the Albany St. and the $MAQS^2$ were operational (see Table 2) so <u>do not correspond to 24 hour averages</u> and are intended only to show the relative agreement between the measurements made by the $MAQS^2$ and the standard PM_{10} monitor at Albany St.

Figure 10 shows that the PM_{10} concentrations measured by the $MAQS^2$ are comparable to those measured at the Albany Street monitor, giving confidence on the absolute values measured by the system. Also, the relative agreement of the *day-by-day* variation indicates that at time scales of several days, the measurements taken at the Albany Street do capture the temporal variation of the concentrations. Because the

MAQS[2] measured across the whole city, it is possible to say that, at time scales of several days, the Albany Street monitor is representative of the daytime concentrations across Dunedin (more detailed analysis is presented later in the report). However, Figure 10 also shows that the 1-hour averages show more scatter between the MAQS[2] and the Albany St monitor indicating that at shorter timescales the monitor captures less of the variability observed throughout the city.



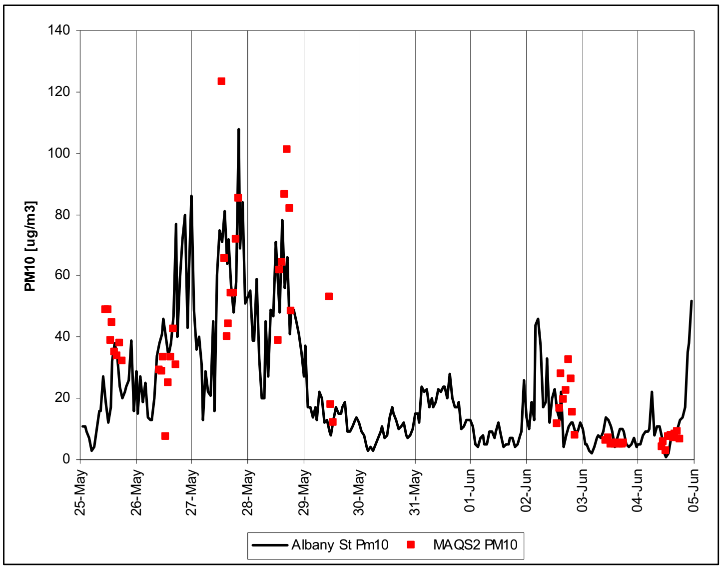


Figure 10 Time series comparison between the Albany St. PM_{10} monitor and the MAQS[2] PM10 measurements during the entire campaign. Daily (top) and hourly (bottom) concentrations averaged from the Albany St. monitor (black) and the MAQS[2] (red). In the top panel, the error bars correspond to one standard deviation of the available data. Note that these are NOT 24 hour averages (see text for details).

It is worth noting that PM_{10} is recognised as a poor indicator of combustion related pollution because it also includes wind blown dust and marine (sea salt) aerosols (Seinfeld and Pandis, 1998). Therefore to complement the measurements, PM_1 and $PM_{2.5}$ concentration were also measured, which are more directly related to combustion processes (Seinfeld and Pandis, 1998). Incorporating this information, it is possible to obtain the same time series shown in Figure 10 but indicating the relative contribution of the three measured fractions of PM (PM_1, $PM_{2.5}$ and PM_{10}). Figure 11 shows the fraction of PM_{10} that corresponds to PM_1 and $PM_{2.5}$. PM_1 generally accounts for more than 40% of the aerosol but its contribution can drop to around 20% at times. Also, only about 15% of the measured particles fall in the 1 to 2.5 µm range indicating that there are mainly two size fractions, one coarse (larger than 2.5µm) and another fine (smaller than 1µm). This is consistent with both mechanical (dust and sea salt) and combustion processes (wood burning and mobile emissions) being responsible for the particles in the Dunedin atmosphere.

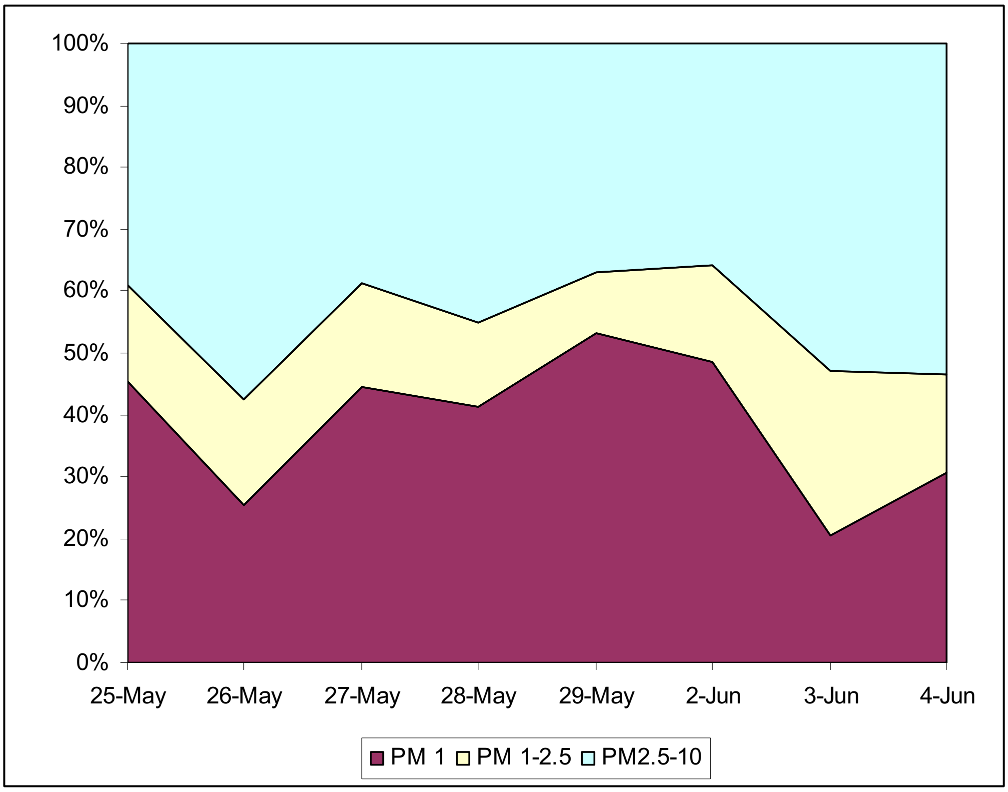


Figure 11 Relative contribution of the measured particle fractions to the total PM_{10} concentrations during the measurement campaign in Dunedin.

Data from the entire campaign were combined and plotted in Figure 12 to Figure 14. Figure 12 shows the median PM_{10} concentrations; Figure 13 shows the median $PM_{2.5}$ and Figure 14 the median PM_1 concentrations. The combined plots provide a general description of where highest concentrations were observed during the campaign, although some caution is required when interpreting these results. As indicated before, the routes covered by the measurement campaign were different for some days and therefore some locations were visited more often than others making it very difficult to draw too detailed conclusions from these plots.

Note that the plots of concentrations are overlaid on aerial photographs for indicative purposes only. Values shown are median values as these are more representative than average values. Aerosol concentrations are not normally distributed so average values can be skewed by outliers.

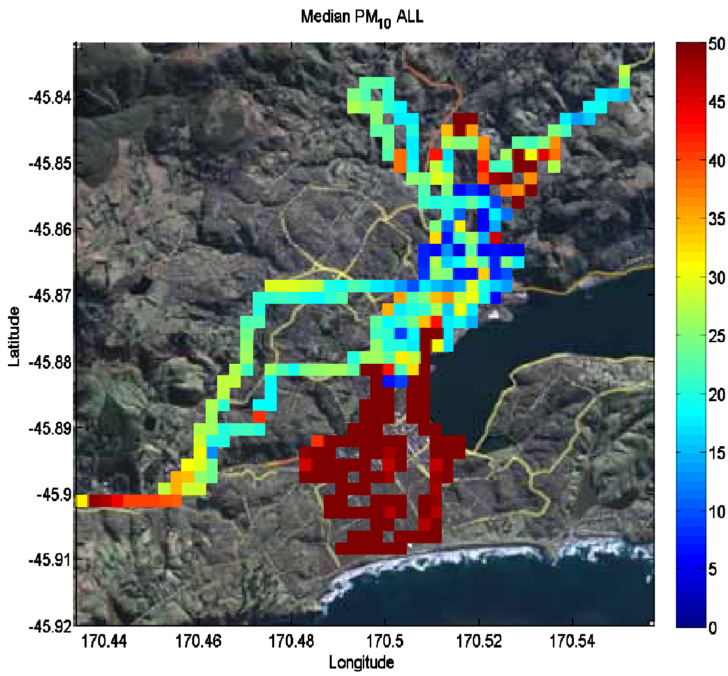


Figure 12 median PM_{10} concentrations (μg/m^3) during the entire campaign

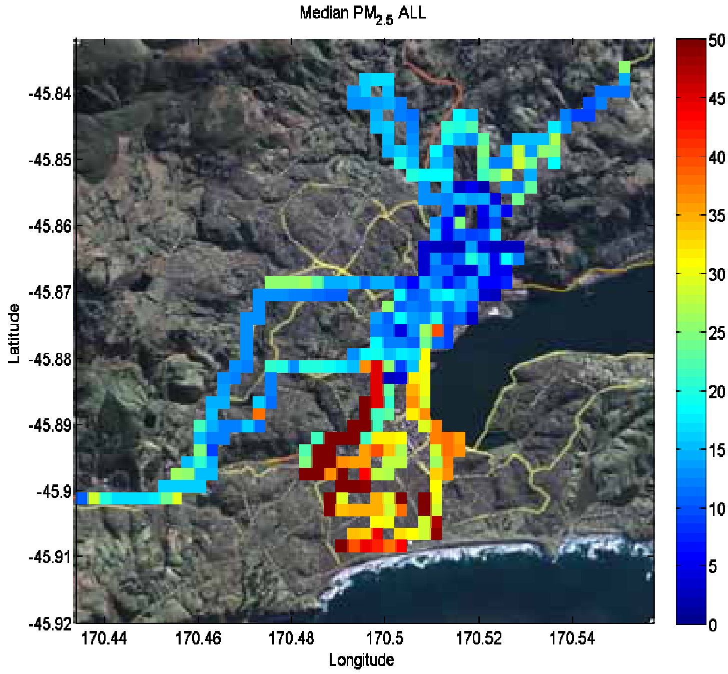


Figure 13 median $PM_{2.5}$ concentrations ($\mu g/m^3$) during the entire campaign

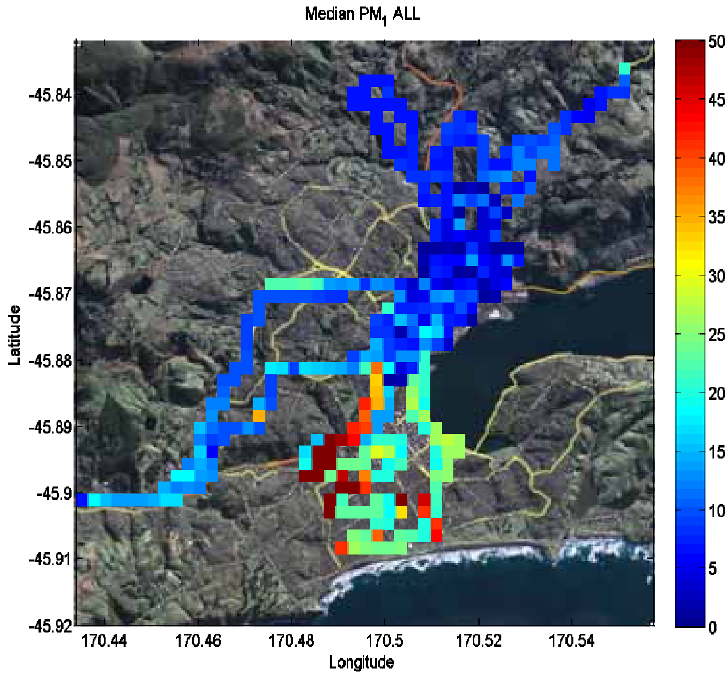


Figure 14 median PM_1 concentrations ($\mu g/m^3$) during the entire campaign

It is apparent from these plots that there are two distinct areas in the measurements, Central Dunedin and Southern Dunedin. The concentrations measured in Central Dunedin were generally lower and the differences between the three size fractions are different than in the southern part of the city. To confirm these observations, Figures 8 to 10 were recalculated for the period between the 25th and the 29th of May when weather conditions were consistent and included here as Figures 15 to 17.

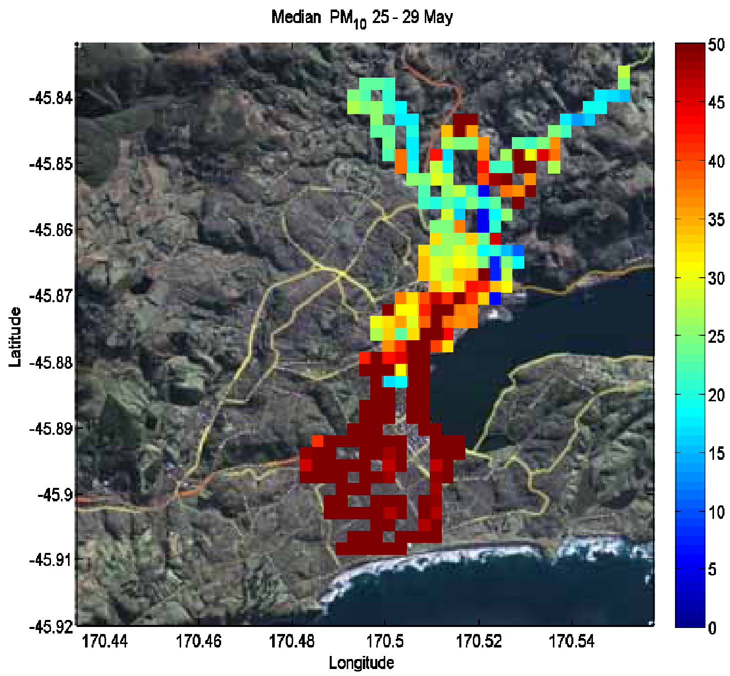


Figure 15 median PM_{10} concentrations (µg/m^3) between the 25th and 29th of May

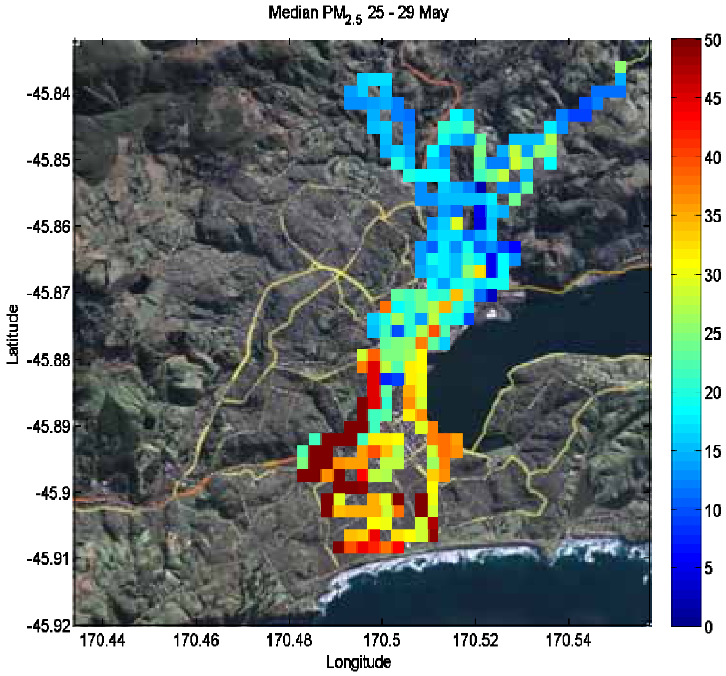


Figure 16 median $PM_{2.5}$ concentrations (μg/m^3) between the 25th and 29th of May

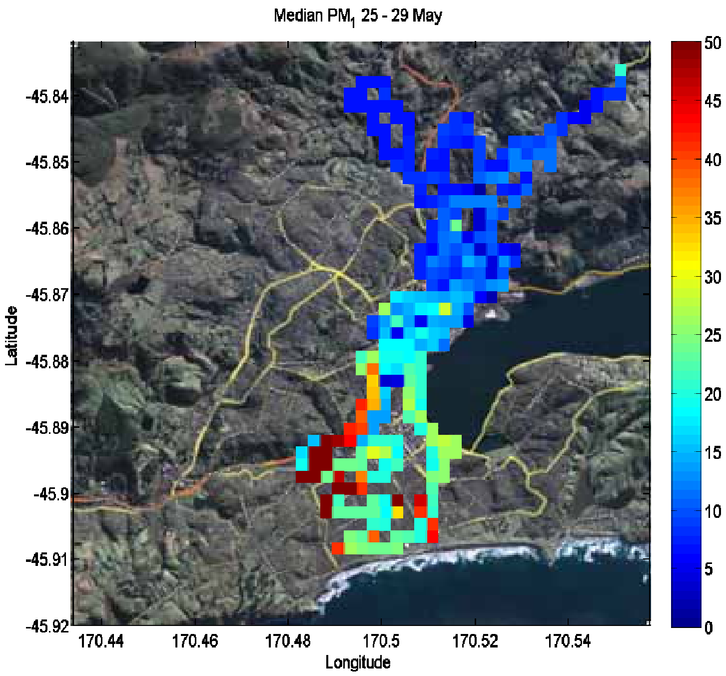
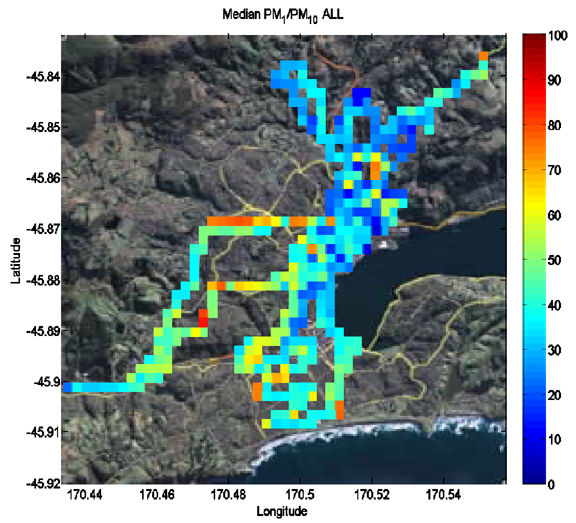


Figure 17 median PM_1 concentrations (μg/m^3) between the 25th and 29th of May

As indicated earlier, there are two distinct modes; one at <1µm and one at >2.5µm (Figure 11). The relative contribution of these modes seems to differ in central and southern Dunedin. Figure 18 shows the fraction (in %) of PM_{10} that corresponds to PM_1 and according to these plots PM_1 represents around 40% of the PM_{10} except in some areas where its contribution rises to more than 60%. Higher PM_1/PM_{10} ratios are associated to combustion processes while lower ratios indicate the impact of mechanical processes in the formation of particles, e.g., dust re-suspension and sea spray formation.



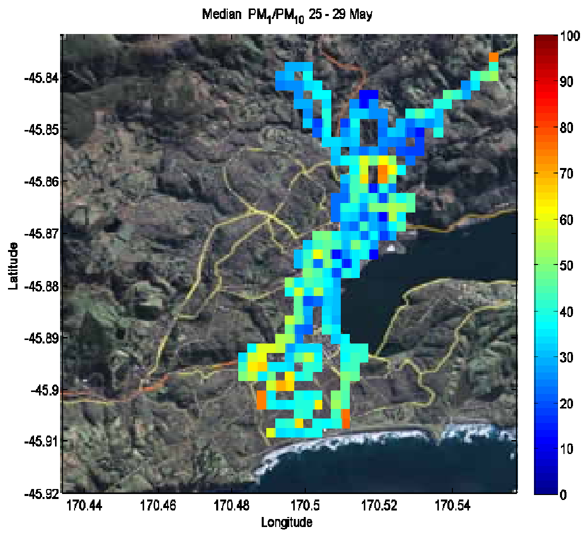


Figure 18 PM_1/PM_{10} ratio (%) for the entire campaign (top) and only between the 25th and 29th of May (bottom).

3.3 Spatial variation of PM_{10} in central Dunedin

The measurement route covered Central Dunedin on all days but with more detail on the 25th, 26th and 29th of May and the 3rd and 4th of June. As indicated before, the first days the wind was low compared to the later part of the campaign. Figure 19 shows the median PM_{10} concentrations for the 25th of May and 3rd of June. As expected, concentrations are lower on the high wind speed day.

Focusing on the high concentrations day (May 25th), it is possible to observe relatively higher concentrations around the Albany St. monitoring site and lower concentrations on the hillside to the north-west of the "Octagon". It is also worth noting that high concentrations were observed generally around SH1 and the harbour basin area. Winds measured at Musselburgh during the measuring period that day were from the North to West sector. The reason for this behaviour could be related to the amount of traffic present during that day but the impact of the westerly winds, advecting the pollutants towards the coast cannot be neglected. Annex 1 includes a day by day description of the measurements.

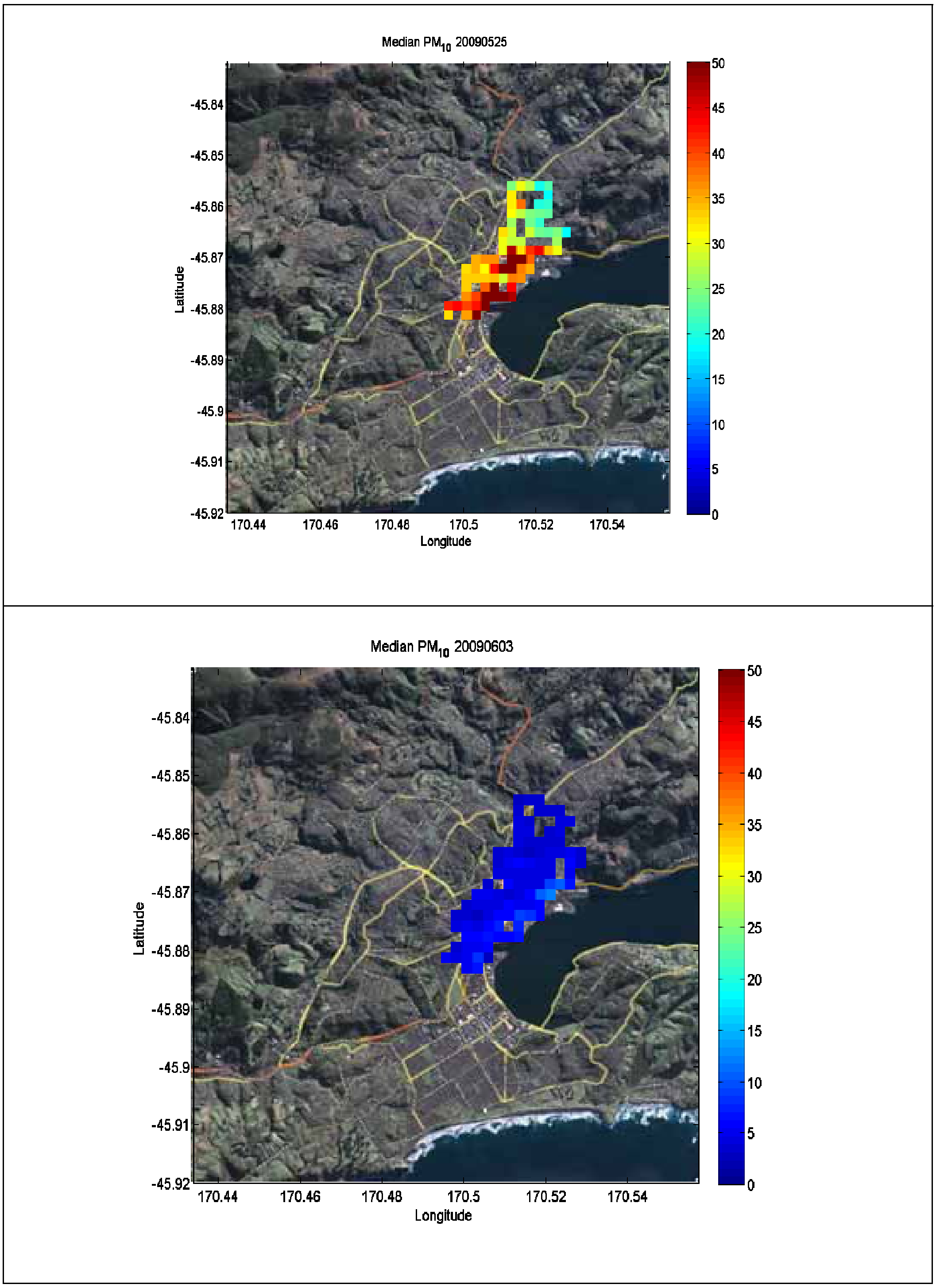


Figure 19 PM_{10} concentrations (µg/m^3) Central Dunedin PM_{10} for 25th of May (top) and the 3rd of June (bottom).

3.4 Representativeness of the Albany St monitor for central Dunedin

Two concepts are involved in the spatial representativeness of air quality measurements. First there is the spatial scale that is a property of the measured pollutant and then there is the fraction of that scale that the monitor captures.

The spatial scale of a pollutant is related to its specific sources and sinks, and it defines the absolute largest spatial scale possible to capture with any single point measurement. This spatial scale is also linked to the concept of *atmospheric lifetime*, which is species dependent (Seinfield and Pandis, 1998):

NO_x: 1 to 10 days
CO: 1 to 4 months
PM: fine ~ days
coarse ~ hours

These values would indicate that, for average wind speeds of around 2m/s, the maximum spatial scale associated to PM can be anywhere between a few kilometres to a few tens of kilometres, depending on the size distribution of the aerosol population. At longer distances, the ambient concentrations are no longer spatially correlated and therefore behave as independent variables.

Within that larger scale, the spatial scale of a monitoring station is influenced, primarily, by its specific location with respect to the emissions field. A site located deep inside an emission zone will be representative of a limited area in the immediate vicinity while a site located away from emission sources would be representative of a larger area.

Finally, the spatial scale is also dependent on the time scale that the measurements are taken. For example, annual averages can be obtained from almost anywhere in a city and be representative of the whole city but measurements of a few minutes will only be representative of a very small area.

To quantify the two terms mentioned above a *semi-variogram* analysis was performed. (Lightowlers et al. 2008) In order to achieve statistical robustness, the analysis was conducted with the complete dataset. It is, *theoretically*, possible to reproduce this analysis for every single day of measurements but the inherent noise of the measurements will obscure the analysis. Finally, care must be taken when interpreting the following results because they are biased towards the period in the day when the measurements took place and influenced by the temporal resolution of the measurements. Measurements were taken during daytime, when the traffic emissions play a more significant role increasing the variability of the concentrations and reducing the spatial scale of the ambient concentrations. Also, the high frequency of data gathered with the MAQS^2 overemphasizes the importance of fast processes (emissions and chemical reactions) further limiting the spatial scale of measurements. Considering all the above issues and because the smoothing and geographical grouping performed, the spatial scale of the measurements obtained here is related to an approximately 10min time resolution.

3.4.1 Spatial scale of pollutants (Domain semi-variogram)

In order to determine the spatial scale inherent of different pollutants, a *domain based* variogram was calculated for BC, δC, PM_{10} and $PM_{2.5}$. According to Lightowlers et al. (2008), when performing a spherical fit to the variograms it is possible to obtain an estimate for the spatial scale of the measured pollutants.

Figure 20 shows the calculated semi-variograms for BC, δC, PM_{10} and $PM_{2.5}$. From a visual exploration of the semivariograms it is possible to observe that for the measured parameters, the semivariance *levels off* before 300 m which indicates that the spatial scale of BC, δC, PM_{10} and $PM_{2.5}$ is smaller than 300 m. Table 3 shows the results of fitting the semi-variograms with spherical models as suggested by Lightowlers et al. (2008). Because a spherical model may be too restrictive in the estimate of the scale, Table 1 also shows a subjective estimate of the scale parameter, based on the visual analysis of the plots, identifying the distance at which the variance stops significantly increasing.

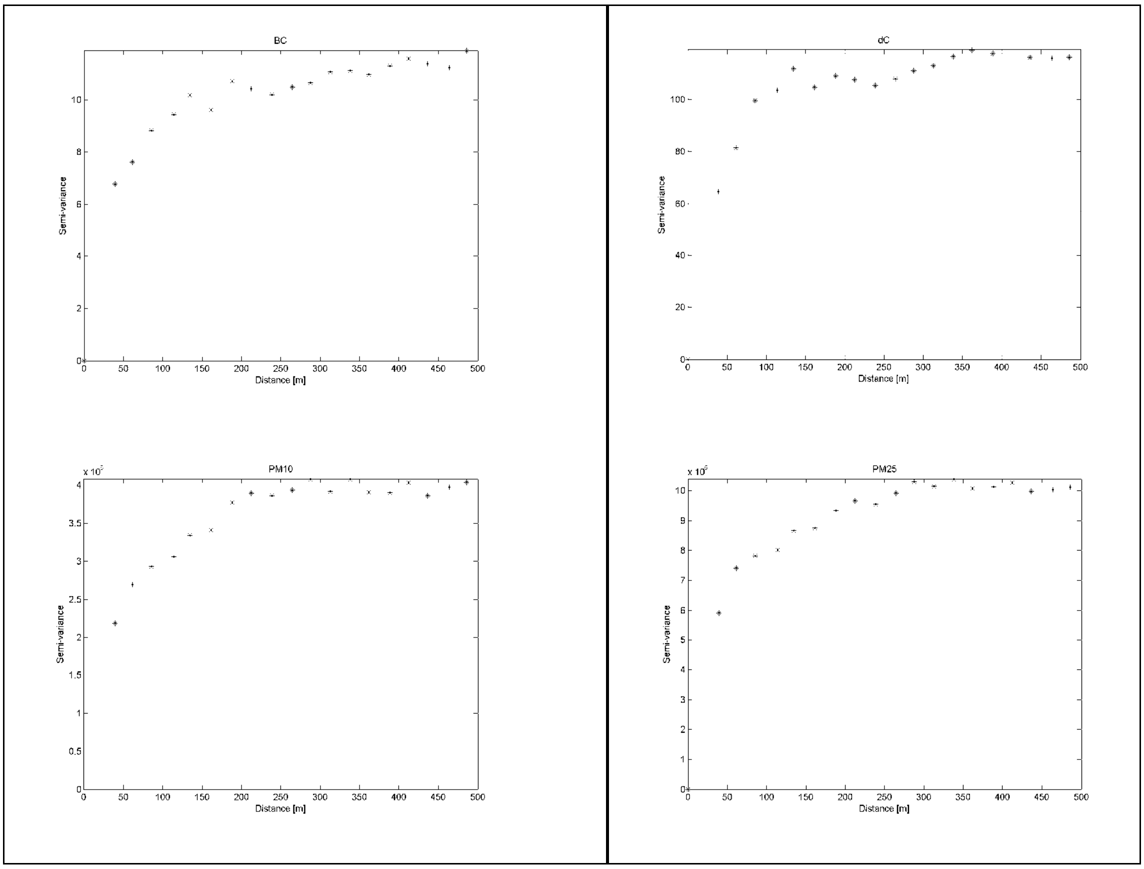


Figure 20 Empirical "Domain" semi-variograms for BC, δC, PM10 and PM2.5.

The results in Table 3 show that the spatial scale of the measured concentrations of BC, δC, PM_{10} and $PM_{2.5}$ is between 100 m and 200 m, which indicates the maximum spatial coverage that is expected to obtain with any fixed point measurement in Dunedin at ~10 minutes time resolution. As indicated above, longer time resolutions will increase the spatial scale of the measurements but given the short term nature of the mobile measurements, it is not possible to obtain these statistics for longer time resolutions.

Table 3 Spatial scale of the measurements at Albany St. (Domain variogram)

PARAMETER	BC	δC	PM_{10}	$PM_{2.5}$
Scale [m]	113	110	136	110
Scale (subjective)[m]	~200	~150	~200	~200

The same analysis presented before can be applied to a single point, in order to answer the question "how far from a location do measurements start being independent?" When the location is the monitoring site, the question translates into "how far from the monitoring site are the measurements representative?" However, by restricting the analysis to one point the statistics become less robust and, as shown in Figure 21, an adequate fit of the semi-variograms is difficult. However, by applying the general concept of the variograms, it is possible, although not with great precision or robustness, to estimate that the variance stops increasing between 150 m and 200 m but those scale values must be taken with extreme caution.

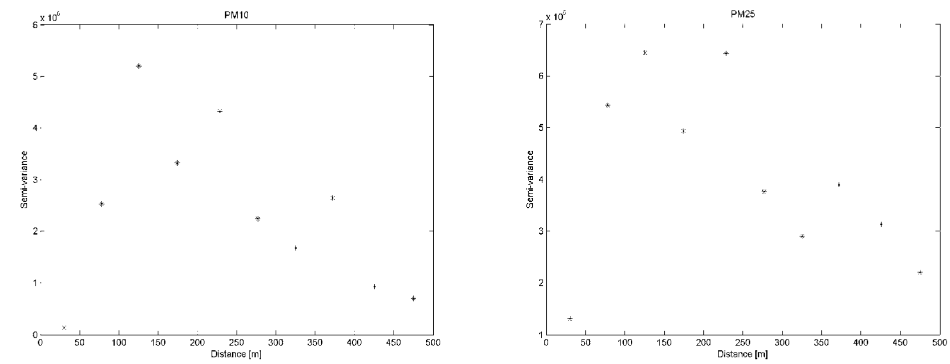


Figure 21 Empirical "Point-centred" semi-variograms for PM_{10} and $PM_{2.5}$. The centre point corresponded to the Albany St. monitoring site.

In addition to the above statistical treatment, a subjective assessment of results, comparing general values of PM_{10} measured over the course of a day with the general trend in hourly PM_{10} values measured at Albany St was conducted (Figure 10). Because the temporal scales are different (i.e. an averaging time of minutes for mobile measurements compared to hourly for the fixed point ones) such a comparison is indicative only and should be treated with caution. However, in general, mobile measurements made in central Dunedin around the Albany St monitor tend to be of a similar order to those from the fixed site whatever the conditions. This suggests that the monitor is reasonably representative of central Dunedin for relatively larger timescales (days). Measurements made on trips away from the fixed monitor tend to be different, by a factor of approximately two or more, from the fixed monitor, suggesting that the fixed monitor is not representative of those locations. This was the case in the North East Valleys and Green Island. It is possible that this difference is due not only simply to distance but also to a combination of wind direction and topography as on the NEV day the wind did blow towards the fixed monitor for part of the time but this did not show up in the record. On the day the mobile measurements were made in south Dunedin the wind was blowing from the south for a significant part of the monitoring period and, on this occasion, mobile measurements were of a similar order to the fixed ones. However, concentrations were high everywhere that day and other, larger scale, mechanisms may have been responsible. It is not possible to speculate further given the available data. This analysis indicates that, over the period of a day, the Albany Street monitor is representative of the area immediately surrounding it but is only representative of more distant locations when the wind and topography are favourable. More detail, with a day by day analysis is given in Appendix 1.

3.5 Ultraviolet and Infrared measurements of Black Carbon

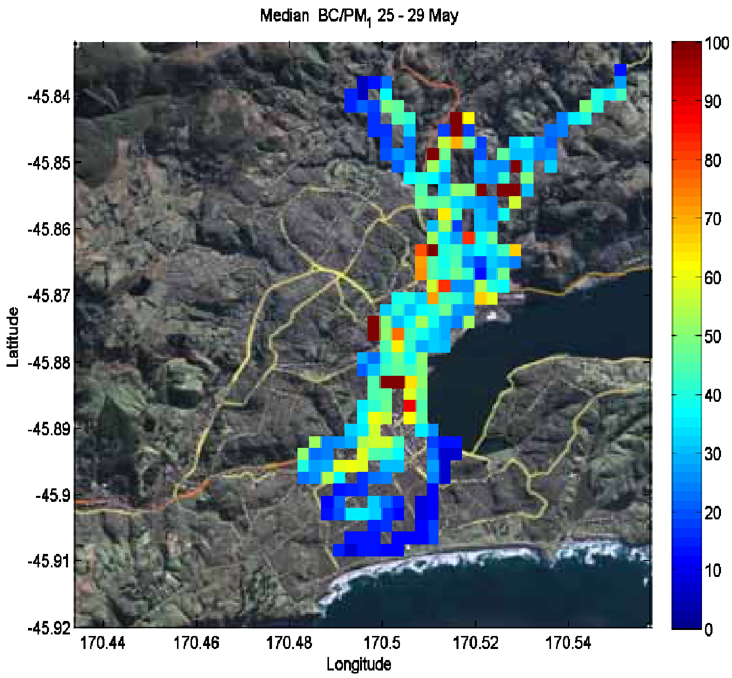


Figure 22 Median BC:PM$_1$ ratio between the 25th and 29th of May

The median BC:PM$_1$ ratio spatial distribution for all measurements is given in Figure 22. Areas with high values of BC:PM$_1$ ratio indicate areas where fossil fuels are dominant while areas with smaller ratios may be associated with wood burning activities.

The Aethalometer measures absorption at two wavelengths, 370nm (UV) and 880nm (IR). The difference in absorption between the two wavelengths (δC) is an indication of woodsmoke. Figure 23 shows the horizontal distribution of δC with values in residential areas that are more than a factor of two those observed in non non-residential areas. This indicates that biomass burning is a significant contributor to the observed black carbon in residential areas to the south of Dunedin and not so in the central-north part of the city, which is consistent with what was observed with the $BC:PM_1$ ratio (Figure 22). This strengthens the conclusion that central and south Dunedin have different emission profiles in terms of particulate matter.

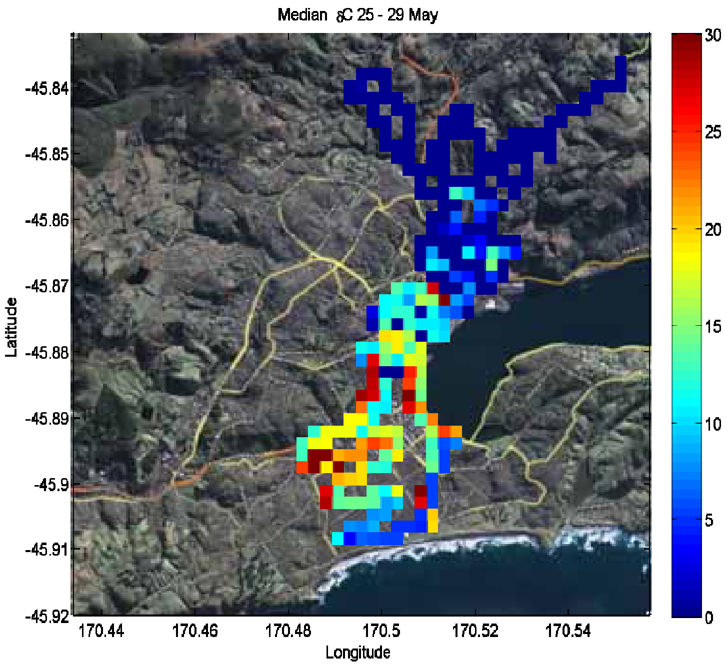


Figure 23 δC as a tracer of woodsmoke in Dunedin. Median between the 25th and 29th of May

4. Conclusions

Measurements were conducted using the NIWA mobile monitoring platform $MAQS^2$ in Dunedin between May25th and June 4th 2009. Size resolved aerosol number concentrations were measured using a Grimm 1.107 aerosol spectrometer and black carbon absorption measured at two wavelengths (370nm and 880nm) with a Magee AE22 aethalometer. Aerosol number counts were converted to mass equivalents using total volume as a proxy.

Measurements were made in Central Dunedin in the area around the Albany St Monitor on 25th, 26th, 27th and 29th May and on the 3rd and 4th of June. Measurements were made in South Dunedin on the 28th May and in Green Island on the 2nd of June. Weather during the measurement campaign divided into two periods: In general terms, the first part of the campaign was characterised by low speed northerly winds while the second part presented generally stronger and more variable winds from the NW to SW sector. There were no winds directly off the open ocean at any point during the campaign and there was no significant rainfall during the campaign.

Measured aerosol concentrations were generally highest during the early part of the campaign when dispersion conditions were poorer. Highest measured PM_1 and Black carbon concentrations were in South Dunedin on 28th May while highest PM_{10} concentrations were found in Central and South Dunedin on the 27th and 28th May.

Throughout the campaign, the aerosol appeared to have two distinct modes, one coarse (larger than 2.5mm) and another fine (smaller than 1mm). PM_1 generally accounts for more than 40% of the aerosol but its contribution can drop to around 20% at times. Also, only about 15% of the measured particles fell in the 1 to 2.5 μm range indicating that there were mainly two size fractions. This is consistent with both mechanical (dust and sea salt) and combustion processes (wood burning and mobile emissions) being responsible for the particles in the Dunedin atmosphere.

The BC:PM_1 ratio indicates that fossil fuel burning is dominant in Central Dunedin while a difference in absorbance at the two Aethalometer wavelengths (δC) pointed to biomass burning being more significant in the southern part of the city

A subjective analysis indicates that, over the period of a day, the Albany Street monitor is representative of the area immediately surrounding it but is only representative of more distant locations when the wind and topography are favourable.

The semi-variogram analysis indicates that, on the timescale of the mobile measurements (approximately 10 minutes), BC, δC, PM_{10} and $PM_{2.5}$ have spatial scales of less than 200m, making any point measurement very local in terms of its representativeness.

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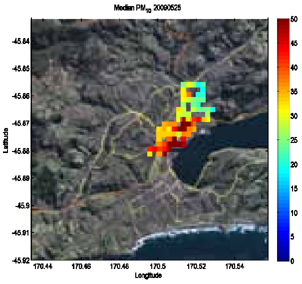
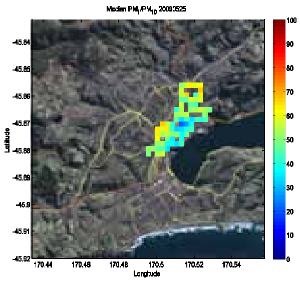
Appendix 1: Daily plots and subjective assessment of results

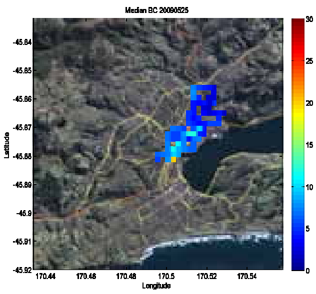
The following section contains the daily plots for PM_{10}, PM_{10}/PM_1, BC and δC along with windspeed and direction and the measurements for the Albany St Monitor. Each table contains plots for each day and a brief description of the results and the representativeness of the Albany St monitor compared to the spatial measurements.

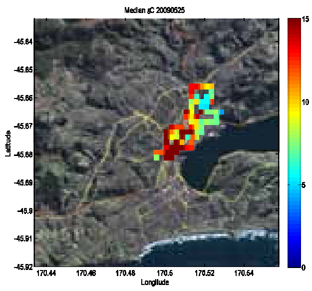
Note: this assessment is a subjective one based on comparing general values of PM_{10} measured over the course of a day with the general trend in hourly PM_{10} values measured at Albany St was conducted. Because the temporal scales are different (i.e. an averaging time of minutes for mobile measurements compared to hourly for the fixed point ones) such a comparison is indicative only and should be treated with caution. However, in general, mobile measurements made in central Dunedin around the Albany St monitor tend to be of a similar order to those from the fixed site whatever the conditions. This suggests that the monitor is reasonably representative of central Dunedin. Measurements made on trips away from the fixed monitor tend to be different, by a factor of approximately two or more, from the fixed monitor, suggesting that the fixed monitor is not representative of those locations. This was the case in the North East Valleys and Green Island. It is possible that this difference is due not only simply to distance but also to a combination of wind direction and topography as on the NEV day the wind did blow towards the fixed monitor for part of the time but this did not show up in the record. On the day the mobile measurements were made in south Dunedin the wind was blowing from the south for a significant part of the monitoring period and, on this occasion, mobile measurements were of a similar order to the fixed ones. However, concentrations were high everywhere that day and other, larger scale, mechanisms may have been responsible. It is not possible to speculate further given the available data. This analysis indicates that, over the period of a day, the Albany Street monitor is representative of the area immediately surrounding it but is only representative of more distant locations when the wind and topography are favourable.

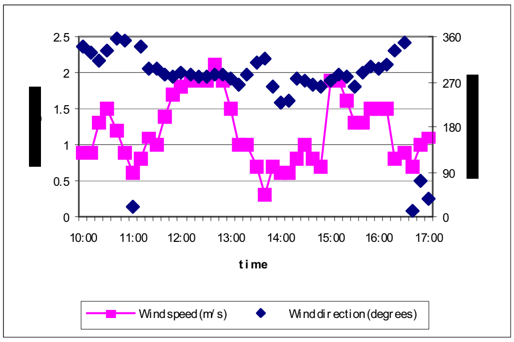
25th May PM_{10}, PM_{10}/PM_1, BC, δC, wind and Albany St monitor

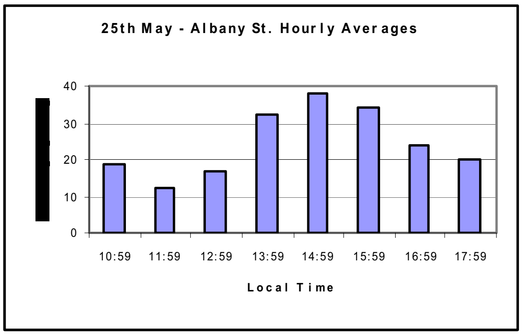










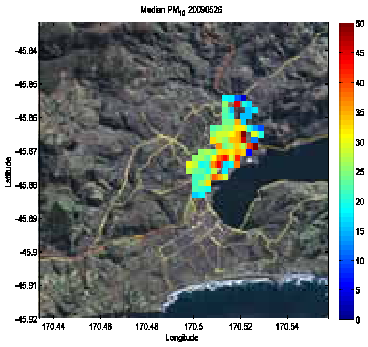


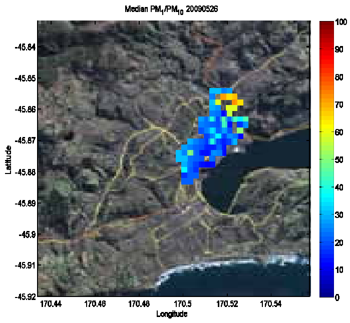
On 25th May wind speeds were 2m/s or less and came largely from the west and north. Data statistics are shown in the table below.

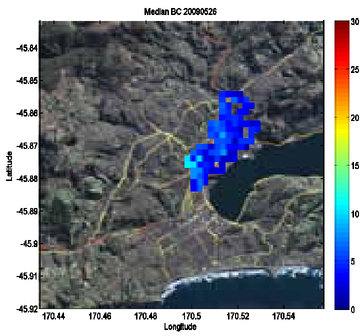
Date	*Start time*	*End time*	*Nr of records*	*% data captured*			
				PM	BC	Location	Weather
25th May	10:04	17:04	28 000	78%	94%	100%	100%

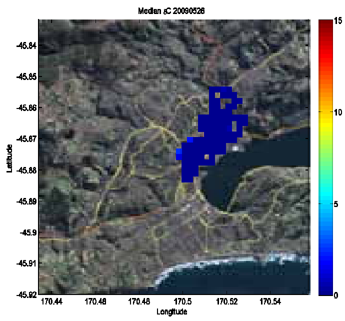
PM_{10} concentrations are relatively higher around the Albany St. monitoring site with lower concentrations on the hillside to the north-west of the Octagon. It is also worth noting that high concentrations were observed generally around SH1 and the harbour basin area. The reason for this behaviour could be related to the amount of traffic present during that day but the impact of the westerly winds, advecting the pollutants towards the coast cannot be neglected. PM_{10}/PM_1 ratios are approximately 0.5 throughout the measurement period. ΔC values are generally highest were the PM_{10} values are highest, Suggesting that the additional PM_{10} is the result of woodburning. The Albany St monitor records hourly average values of between 12μg/m^3 and 38 μg/m^3 during the monitoring period, which is of a similar order to the values measured by MAQS[2]. Therefore, on this occasion, the Albany St monitor appears to be representative of the surrounding area of Central Dunedin (Note: the averaging times for these measurements are different so comparisons are indicative and should be treated with caution).

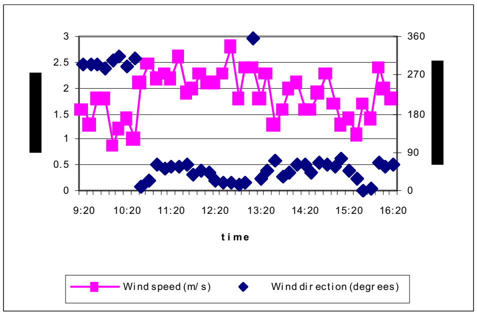
26th May PM_{10}, PM_{10}/PM_1, BC, δC, wind and Albany St monitor

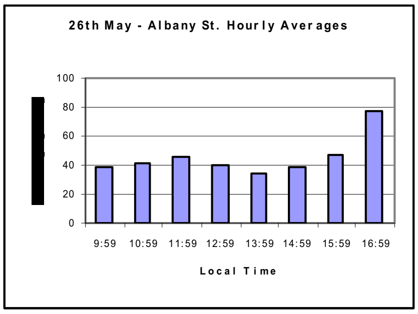










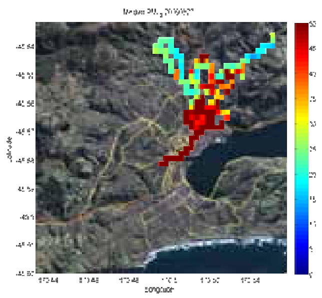


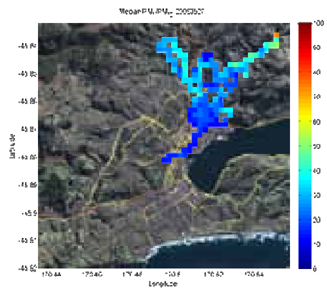
On 26th May wind speeds were between 1m/s and 3m/s and ranged from northwesterly to easterly. Data statistics are shown in the table below.

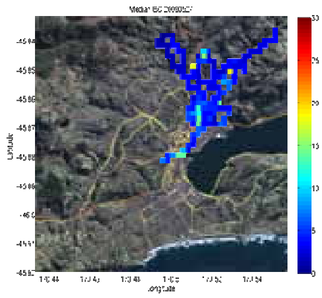
Date	*Start time*	*End time*	*Nr of records*	*% data captured*			
				PM	BC	Location	Weather
26th May	9:24	16:24	25 174	89%	91%	100%	100%

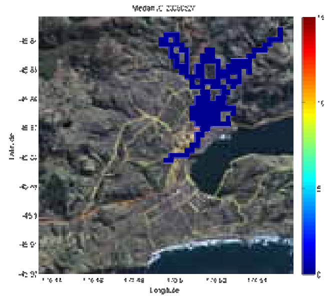
PM_{10} concentrations measured by MAQS[2] are lower than the previous day but still display highest values around the harbour basin area. PM_1 concentrations are low throughout and PM_{10}/PM_1 ratios are approximately 0.2 to 0.4 throughout the measurement period. ΔC values are all low, indicating fossil fuel combustion as a source of carbonaceous aerosol. The Albany St monitor records hourly average values of around 40μg/m^3 throughout the monitoring period except for the last hour, when concentrations rise to 77μg/m^3, which appears to be the beginning of a night-time peak where values rose to as much as 86μg/m^3. These values are slightly higher than those measured by MAQS[2] but of a similar order. Therefore, on this occasion, the Albany St monitor appears to be representative of the surrounding area of Central Dunedin (Note: the averaging times for these measurements are different so comparisons are indicative and should be treated with caution).

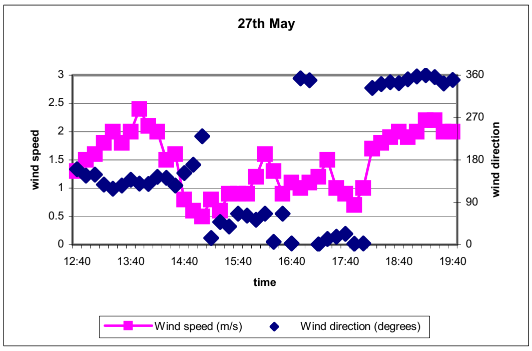
27th May PM_{10}, PM_{10}/PM_1, BC, δC, wind and Albany St monitor

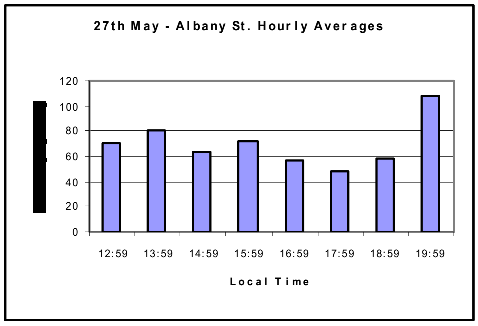












On 27th May wind speeds were between 0.5 m/s and 2.5m/s with the highest speeds at the beginning and end of the period and ranged from southerly at the beginning of the period to northerly at the end. Data statistics are shown in the table below.

Date	Start time	End time	Nr of records	% data captured			
				PM	BC	Location	Weather
27th May	12:40	19:36	24 947	100%	99%	35%	100%

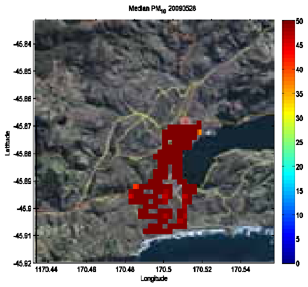
PM10 concentrations are highest in the centre of Dunedin, dropping off as the MAQS2 travelled into the North East Valleys. PM1 concentrations are low throughout and PM10/PM1 ratios are approximately 0.2 to 0.4 throughout the measurement period. ΔC values are all low, indicating fossil fuel combustion as a source of aerosol. The Albany St monitor records hourly average values of around 60µg/m3 throughout the monitoring period except for the last hour, when concentrations rise to 108µg/m3. These values are of a similar order to those measured by MAQS2 in Central Dunedin but considerably higher that those measured in the NE Valleys. Since the wind came from the South for part of the time and from the North for part of the time, this is more likely connected to topography than weather. Therefore, on this occasion, the Albany St monitor appears to be representative of the surrounding area of Central Dunedin but not further afield (Note: the averaging times for these measurements are different so comparisons are indicative and should be treated with caution).

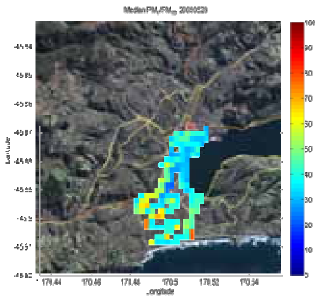
An additional analysis was performed for this day because of the problems encountered with the GPS data that resulted in only 35% of the data having reliable position information. Using the system's ability to identify individual runs, statistics for the circuits covering the northern part of the loop and the area around the Albany Street monitor were calculated separately and are presented in the table below:

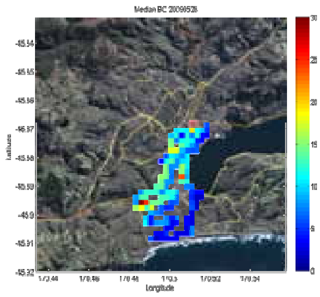
	Central Dunedin		North East Valley	
	Mean	Std Dev	Mean	Std Dev
PM10 (mg/m3)	59	39	51	63
PM1 (mg/m3)	23	20	22	24
BC (mg/m3)	9	10	7	8

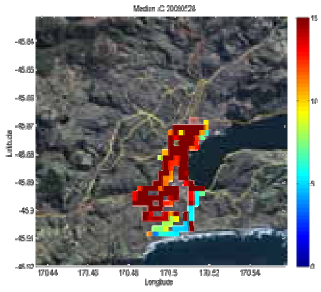
This table shows that the North East Valley data seems to have larger variability and slightly lower averages. However, the differences in mean values are not statistically significant.

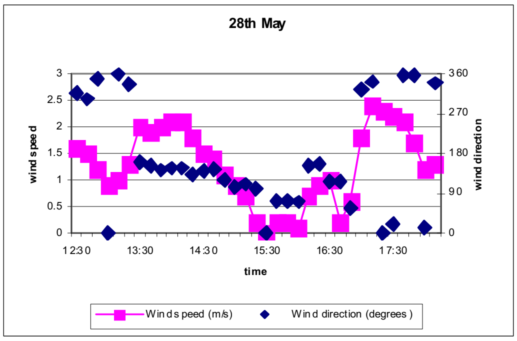
28th May PM_{10}, PM_{10}/PM_1, BC, δC, wind and Albany St monitor

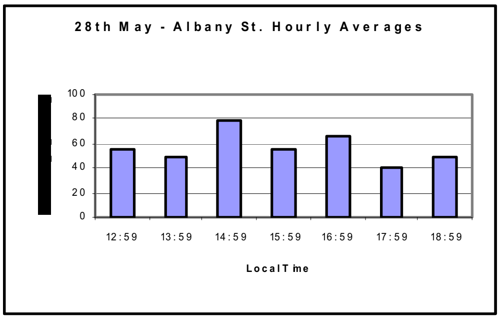










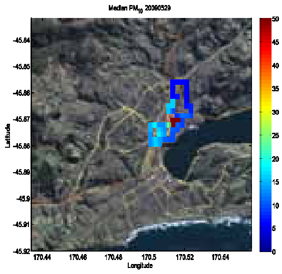


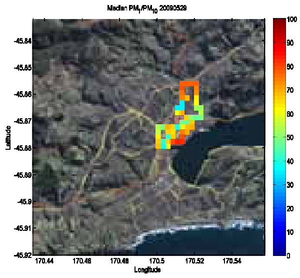
On 28th May wind speeds were up to 2.5m/s with the highest speeds at the beginning and end of the period. Wind direction ranged from northerly at the beginning and end of the period veering to southerly and then backing to northerly in-between. Data statistics are shown in the table below.

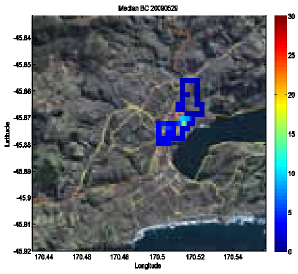
Date	*Start time*	*End time*	Nr of records	*% data captured*			
				PM	BC	Location	Weather
28th May	12:30	18:12	20 505	100%	100%	100%	100%

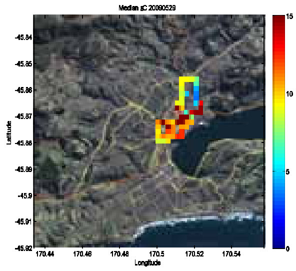
PM_{10} concentrations are high throughout the day and in all areas. PM_{10}/PM_1 ratios are lower in the central part of the city. ΔC values are variable with areas of high biomass derived aerosol around Central Dunedin and main roads such as the SH1 corridor. The Albany St monitor records hourly average values of between 40µg/m^3 and 80 µg/m^3 during the monitoring period. These values are of a similar order to those measured by MAQS[2] throughout the monitoring period. The wind was southerly during a large part of the day so pollutants from South Dunedin would have been advected towards the Albany St monitor. Therefore, on this occasion, the Albany St monitor appears to be representative of the surrounding area of Central Dunedin and further afield (Note: the averaging times for these measurements are different so comparisons are indicative and should be treated with caution).

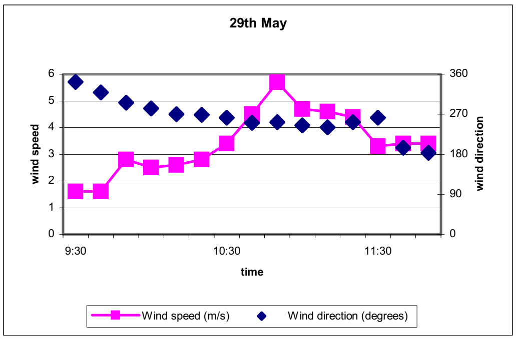
29th May PM_{10}, PM_{10}/PM_1, BC, δC, wind and Albany St monitor

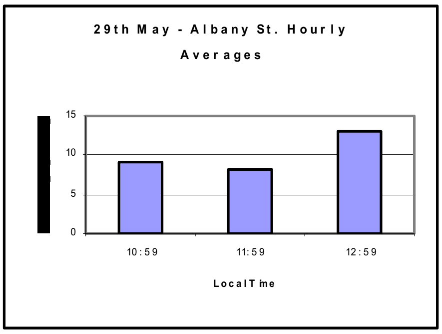










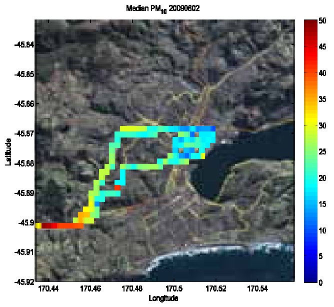


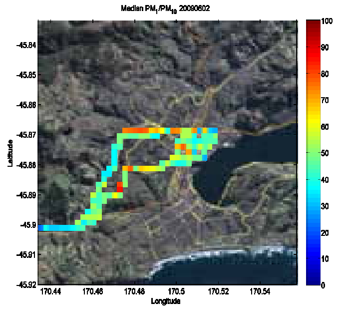
On 29th May wind speeds picked up to as much as 6m/s with the highest speeds in the middle of the period – peaking around 11.00am. Wind direction ranged from northerly at the beginning period backing steadily to southerly as the period progressed. By noon there was sufficient rainfall for monitoring to be curtailed for the day despite the Musselburgh monitor recording no rainfall. Data statistics are shown in the table below.

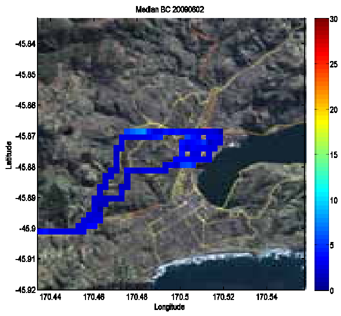
Date	*Start time*	*End time*	*Nr of records*	*% data captured*			
				PM	BC	Location	Weather
29th May	9:27	11:53	8 731	86%	87%	62%	100%

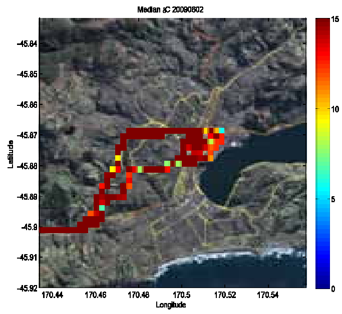
PM_{10} concentrations are low throughout the period and in all areas except for a small area NE of the Octagon, in the vicinity of the Albany St monitor. PM_{10}/PM_1 ratios are high everywhere, with PM_1 comprising between 50% to 90% of the PM_{10}. ΔC values are variable, indicating a mix of sources. The Albany St monitor records low hourly average values of less than 15μg/m^3 during the monitoring period. These values are of a similar order to those measured by MAQS[2] throughout the monitoring period. Therefore, on this occasion, the Albany St monitor appears to be representative of the surrounding area of Central Dunedin (Note: the averaging times for these measurements are different so comparisons are indicative and should be treated with caution).

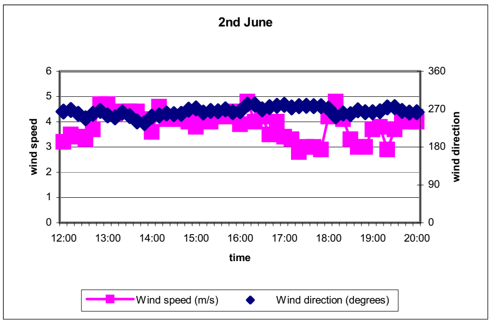
2nd June PM_{10}, PM_{10}/PM_1, BC, δC, wind and Albany St monitor

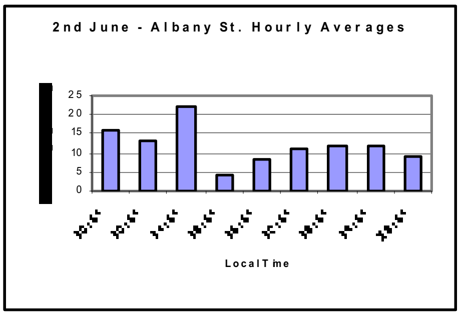










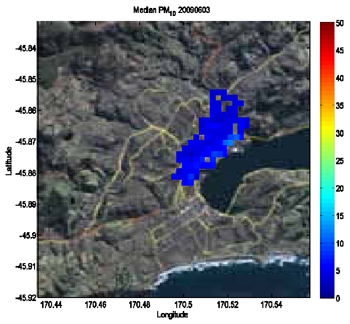


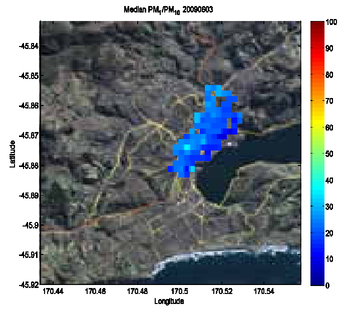
On 2nd June the wind came consistently from the west and ranged from 3m/s to 5m/s. Data statistics are shown in the table below.

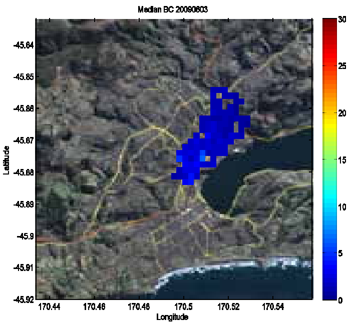
Date	*Start time*	*End time*	Nr of records	*% data captured*			
				PM	BC	Location	Weather
2nd June	12:05	20:07	28 935	100%	98%	100%	100%

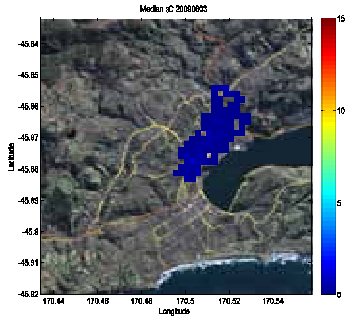
PM_{10} concentrations were relatively high around a loop to Green Island compared to central Dunedin with the highest values being in Green Island itself. PM_{10}/PM_1 ratios are variable, with PM_1 comprising between 40% to 70% of the PM_{10} but are generally lowest at Green Island and highest close to the centre of Dunedin. ΔC values are generally high, consistent with the high PM_1 concentrations being from biomass burning. The Albany St monitor records low hourly average values generally less than 15µg/m³ during the monitoring period. These values are of a similar order to those measured by MAQS[2] in central Dunedin but not in Green Island. With the wind from the west, the high values measured in Green Island will not be blown towards the Albany St monitor. Therefore, on this occasion, the Albany St monitor appears to be representative of the surrounding area of Central Dunedin but not further afield (Note: the averaging times for these measurements are different so comparisons are indicative and should be treated with caution).

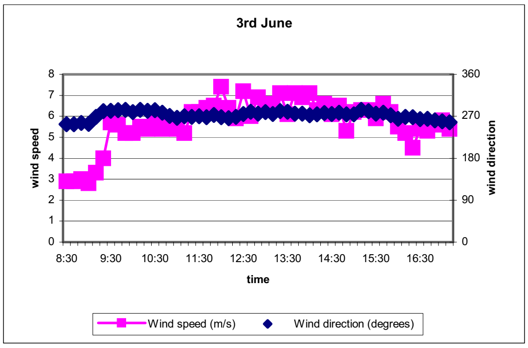
3rd June PM_{10}, PM_{10}/PM_1, BC, δC, wind and Albany St monitor

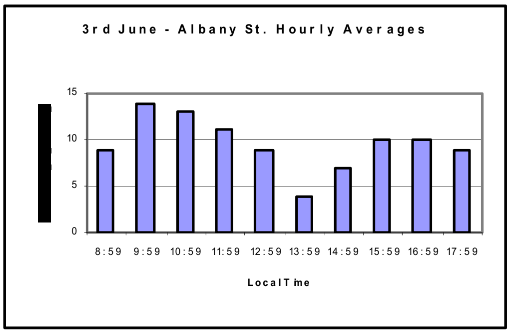










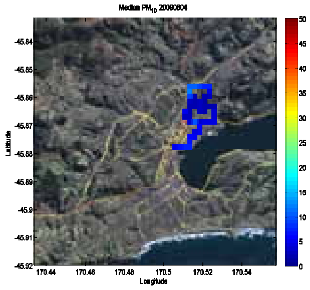


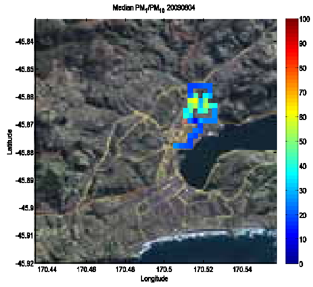
On 3rd June the wind came consistently from the west and ranged from 3m/s to over 7m/s. Data statistics are shown in the table below.

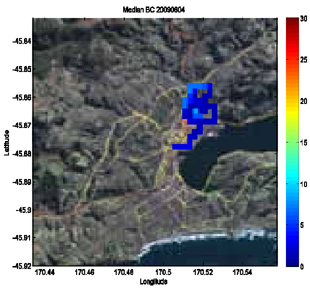
Date	*Start time*	*End time*	*Nr of records*	*% data captured*			
				PM	BC	Location	Weather
3rd June	8:28	17:08	31 213	90%	81%	97%	100%

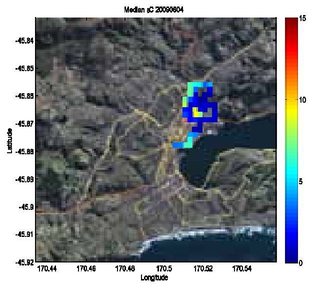
PM_{10} concentrations are very low everywhere, which would be expected in high winds. The PM_{10}/PM_1 ratios are also very low everywhere, indicating that PM_{10} consists almost entirely of course fraction. ΔC values are low, indicating that what little PM_{10} there is results from fossil fuel burning. The Albany St monitor also records low hourly average values of less than 15μg/m^3 during the monitoring period. These values are of a similar order to those measured by MAQS[2] throughout the monitoring period. Therefore, on this occasion, the Albany St monitor appears to be representative of the surrounding area of Central Dunedin (Note: the averaging times for these measurements are different so comparisons are indicative and should be treated with caution).

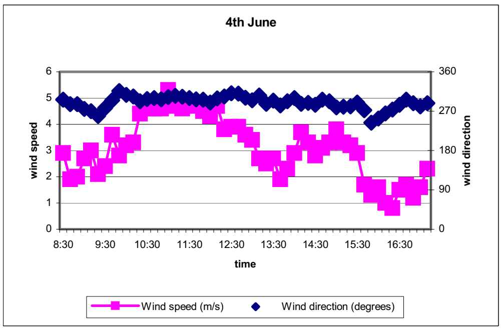
4th June PM_{10}, PM_{10}/PM_1, BC, δC, wind and Albany St monitor

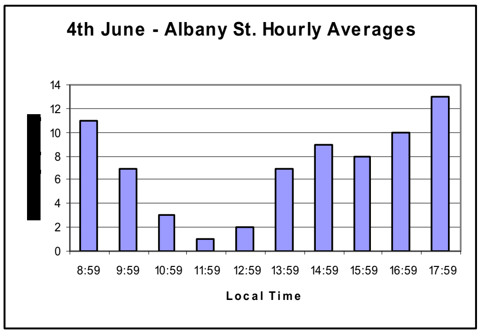












On 4th June the windspeed was variable, ranging from less than 1m/s to over 5m/s and came consistently from the west. Data statistics are shown in the table below.

Date	*Start time*	*End time*	*Nr of records*	*% data captured*			
				PM	BC	Location	Weather
4th June	8:27	17:10	31 416	91%	89%	14%	100%

PM_{10} concentrations are very low everywhere, which would be expected in high winds. The PM_{10}/PM_1 ratios are medium everywhere, indicating that PM_1 comprises around 50% of the PM_{10}. ΔC values are low, indicating that what little PM_{10} there is results from fossil fuel burning. The Albany St monitor also records low hourly average values of less than 15μg/m^3 during the monitoring period. These values are of a similar order to those measured by MAQS[2] throughout the monitoring period. Therefore, on this occasion, the Albany St monitor appears to be representative of the surrounding area of Central Dunedin (Note: the averaging times for these measurements are different so comparisons are indicative and should be treated with caution).

Appendix 2: Variograms

To translate a small set of spatially scattered point measurements into a continuous field, GIS tools require information about the scale of representativness of the individual measurements. The most used technique corresponds to *Krigging* (Chiles and Delfiner, 1999) which has its origins in mining exploration and it has proved a robust tool in environmental sciences. In this technique, the spatial representativeness of the point measurements is used as their *radius of influence* and determines the location dependent weight of the point measurements when generating a uniform field. Mobile measurements are a special case of *spatially scattered point measurements* in the sense that they cover continuous tracks and are suitable to directly generate fields or a very large number of point measurements for moderate time scales. If sufficiently high numbers of points are considered, it is possible to reverse the Krigging procedure and to obtain estimates of the *radius of influence* of the points. This is performed by characterising the relationship between the *variance* of the measurements and distance between the measurement locations calculating the *variogram* for the set of measurements (Wackernagel, 2003).

$$\gamma(h) = \frac{1}{2N}\sum_{i=1}^{N}(f_{1i} - f_{2i})^2$$

Where N is the number of points at a distance *h* of each other and *f* the values of the grid points.
Once the variogram has been calculated, the semi-variance is plotted as a function of distance. Figure 24 shows a schematic variogram indicating the main features (Janis and Robeson, 2004).

- **Range**. This is the primary parameter of a variogram and it is related to the spatial scale of the measurements. In statistical terms, at distances beyond the *range*, the variance does have no spatial structure and the measurements do not have any significant spatial correlation
- **Contribution**: Also referred to as the ***sill***, it corresponds to the *a priori* variance of the measurements. At distances beyond the **range** the contribution does not increase meaning that point measurements further apart are independent from each other.
- **Nugget**: The *uncertainty* of the expected value of the variable. Theoretically the Nugget is zero but for experimental variograms this may not be the case as it accounts for fine-scale variations not resolved by the sampling network.

In order to quantify the main features of a variogram it is necessary to fit a model to the experimental variogram. There are different models that are applicable to different situations (mining exploration, soil analyses, etc.) but the most used in environmental sciences corresponds to the *spheric* model (Wackernagel, 2003),

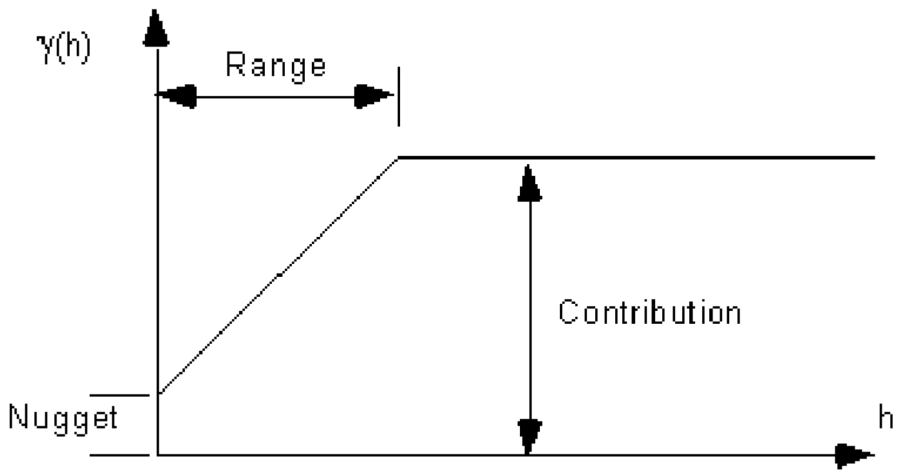


Figure 24. Schematic diagram of the main elements of a variogram.

For a full description of the statistical tool the reader is referred to Wackernagel (2003) and the references therein.

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Chiles, J.-P. and P. Delfiner (1999) Geostatistics, Modeling Spatial uncertainty, Wiley Series in Probability and statistics.

Wackernagel, H., 2003, Multivariate Geostatistics, Springer

Janis, M. and Robeson, S. 2004. Determining the spatial representativeness of air-temperature records using variogram-nugget time series. Physical Geography, **25**. 513 – 530.