SoE Report:
Air Quality 2005 - 2014

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Executive summary

Clean, ambient (outdoor) air is an important resource for supporting a healthy population and environment. Ambient air quality is a combination of the amounts and types of emissions that go into the air, along with the meteorological conditions that affect their movement. Otago Regional Council (ORC) operates a State of the Environment (SoE) air quality monitoring network throughout the region and performs other investigative studies that help define the ambient air quality in Otago. Over the past ten years, monitoring has focused mainly on PM_{10}, small particles, with a diameter of less than 10 micrometres.

This SoE report on air quality evaluates the results of the past 10 years (2005-2014) of air quality monitoring. The report assesses the current state of air quality in Otago centres and identifies the temporal and spatial trends in air quality over the reporting period. The pressures and influences on regional air quality are discussed in a section on emissions and weather.

Results of the SoE-monitoring network indicate that for most of the year, air quality in Otago is very good, with baseline PM_{10} values well within national standards and guidelines for clean air. During winter months, however, home-heating emissions increase, and the ability of the atmosphere to disperse them decreases mainly due to calm conditions coupled with strong temperature inversions. This scenario often leads to elevated PM_{10} levels, particularly in Central Otago, but in other areas as well.

Results show that Alexandra, Arrowtown, Clyde, Cromwell and Milton regularly exceed the daily standard for PM_{10} set in the National Environmental Standard for Air Quality (NESAQ), anywhere from 15 to 45 days in some winters. Other centres, such as Balclutha, Mosgiel, Lawrence and Oamaru, exceed the standard from one to ten days each winter.

Central Dunedin is currently reporting very good air quality year-round where air quality has met NESAQ standards and guidelines for PM_{10} for the past three consecutive years, a significant improvement over previous years. Improvement in Dunedin's air quality has come mainly through working with industry to lower their particulate emissions and, presumably, an increased reliance on heat pumps for domestic heating.

Recognising the challenge of improving air quality in other parts of Otago, ORC set strict emission-limit rules for domestic-heating appliances in Central Otago in the Otago Regional Plan: Air Plan (the Air Plan). To assist residents in meeting those rules, ORC operates the Clean Heat Clean Air programme, a financial- incentive package that has improved insulation and heating appliances in well over a thousand homes. Long-term trend analysis shows that air quality has improved somewhat in Alexandra, Arrowtown and Clyde; however, at current rates of change, the NESAQ is unlikely to be met, and there are still far too many days each winter with poor air quality.

Long-term trends in areas of Otago that are growing indicate that PM_{10} levels may actually be rising slowly, as is the case in Mosgiel and Cromwell.

Results from this report will be used to inform future work on air quality-management strategies and programmes in Otago.

1. Introduction

1.1 The report's purpose

Clean, ambient (outdoor) air is an important resource for supporting a healthy population and environment. Ambient air quality is a combination of the amounts and types of emissions that go into the air, along with the meteorological conditions that affect their movement. Otago Regional Council (ORC) operates a State of the Environment (SoE) air quality monitoring network throughout the region and performs other investigative studies that help to define the ambient air quality in Otago. Over the past ten years, monitoring has focused on PM_{10}, particulate matter, with an aerodynamic diameter of 10 micrometres or less.

Three previous SoE reports have evaluated air quality in Otago. Two reports described the period from 1997 through 2004; one evaluated results for PM_{10} (ORC, 2005), and the other reported on other ambient pollutants, including sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and carbon monoxide (CO) (ORC, 2005a). A third report evaluated PM_{10} results for the four-year period from 2005 through 2008 (ORC, 2009).

This report evaluates results of SoE air quality-monitoring performed over the ten-year period from 2005 to 2014. This period encompasses ORC's entire continuous-monitoring record; before 2005, monitoring was done on an intermittent basis due to the limitations of the technology in use at the time. By using the entire continuous-monitoring dataset, this report describes the current state of air quality in the Otago region and also evaluates trends in air quality.

1.2 Scope

The report relies on data measured at the continuous air quality monitors throughout the region. In addition, relevant information from other investigations, including source-apportionment studies, emissions inventories and other special studies.

1.3 Outline

The following sections are included in this report:

- Section 2 describes the current air quality-assessment framework, including guidelines, standards and local-management areas
- Section 3 describes Otago's monitoring network
- Section 4 discusses the pressures and influences on air quality
- Section 5 presents the current state of air quality. Analyses of the three most recent years' data (2012-2014) are presented for sites used in reporting on the National Environmental Standard for Air Quality (NESAQ). Results of shorter-term monitoring, used for tracking seasonal pollution or in screening campaigns, are also presented
- Section 6 provides analyses of the temporal trends in air quality from 2005-2014 and describes the spatial distribution of PM_{10} in various towns
- Section 7 discusses the results of the analyses done in sections 5 and 6 and the implications for compliance with the NESAQ.

2. Air quality assessment framework

2.1 National air quality indicators

National air quality guidelines were first established in 1994 by the Ministry for the Environment (MfE), based on international public health information (MfE, 1994). In 2002, MfE revised these health-based guidelines and set suggested limits on concentrations of various ambient air pollutants (MfE, 2002).

The NESAQ, adopted in 2004 and revised in 2011, established minimum requirements for five ambient air pollutants (MfE, 2004 and 2011). The objectives of these standards are to provide an acceptable level of protection to human health and the environment.

Table 1 provides the current New Zealand ambient air quality standard and guideline values for relevant pollutants. Guideline values are recommended; standard values are to be met by 2020.

Table 1. New Zealand guidelines and standards for ambient air pollutants

Pollutant	Status	Threshold concentration (micrograms/m^3)	Averaging period	Number of allowable exceedances
PM_{10}	Standard	50	24-hour	1 per year
	Guideline	20	Annual	n/a
Nitrogen dioxide (NO_2)	Standard	200	1-hour	9 per year
	Guideline	100	24-hour	n/a
Carbon monoxide (CO)	Standard	10	8-hour running	1 per year
	Guideline	30	1-hour	n/a
Ozone (O_3)	Standard	150	1-hour	none
	Guideline	100	8-hour running	n/a
Sulphur dioxide (SO_2)	Standard	350	1-hour	9 per year
	Standard	570	1-hour	none
	Guideline	120	24-hour	n/a

ORC's current monitoring programme focuses principally on measuring PM_{10}, the most common and significant pollutant found regionally and nationally. Earlier targeted monitoring of NO_2, SO_2, and CO indicated that these pollutants were not present in significant amounts. Ozone is considered to be a secondary pollutant formed during a photochemical reaction that occurs when oxygen (O_2) and nitrogen dioxide (NO_2) are exposed to bright light. In a study on photochemical pollution potential in New Zealand (McKendry, 1996), Dunedin was not identified as a city with atmospheric conditions conducive to the formation of ozone.

2.2 Regional goal levels

The NESAQ values are integrated into the Regional Plan: Air for Otago (the Air Plan) (ORC, 2009). In addition, the Air Plan set Otago goal levels (OGL(s)) at about 66% of NESAQ values as 'alert' levels, as advocated in the Environmental Performance Indicators Programme (MfE, 1997). The OGL for the daily mean, PM_{10}, is 35 µg/m^3.

2.3 Ambient pollutants

The emphasis over the past ten years has been on measuring PM_{10}. Earlier measurements of other pollutants (ORC, 2005a) indicated that while they are present, concentrations of NO_2, SO_2, and CO are generally expected to be below guideline and standard levels. Ozone has not been measured in Otago.

2.3.1 Particulate matter

Particulate matter (PM) refers to particles, or aerosols, that are suspended in the atmosphere. PM originates from a variety of anthropogenic mobile and stationary combustion sources, including solid-fuel burners, vehicles and industrial discharges. It also occurs naturally as agricultural dust, entrained road dust, airborne marine aerosol and pollen.

PM comprises a wide variety of physical and chemical compositions, depending on the source and size of the particles. Regardless of shape or composition, PM aerosols generally occur in one of two size categories: 'Fine fraction' for particles with an equivalent aerodynamic diameter smaller than 2.5 micrometres, and 'coarse fraction', which encompasses all particles with aerodynamic diameters between 2.5 and 10 micrometres. PM_{10} refers to the fine and coarse fractions together.

Generally, the fine fraction ($PM_{2.5}$) is emitted from anthropogenic sources and is a result of incomplete combustion. $PM_{2.5}$ includes a large number of organic and inorganic compounds, metals and black carbon (i.e. soot). These particles can remain suspended in the air for many days or weeks and can be transported hundreds of kilometres.

Coarse fraction PM ($PM_{2.5\text{-}10}$) typically originates when mechanical forces are at play, which includes wind action for natural sources such as pollen and sea salt, because abrasive and crushing actions contribute to the suspension of road dust. Particles in this fraction tend to fall out of suspension within minutes or hours and can travel anywhere from a few hundred metres to 50 kilometres.

Large-scale epidemiological public health studies (Pope and Dockery, 2006) implicate both short-term (hourly/daily) and long-term (annual) exposure to PM_{10} with adverse health effects. Due to its small size, PM_{10} is easily inhalable and the smaller the particle size, the deeper into the respiratory system it can travel. More recent research (World Health Organisation, 2013) indicates that adverse health effects are more closely related to the fine and 'ultra-fine' (less than 1.0 µm) fractions. This evidence was recently noted by the Parliamentary Commissioner for the Environment (PCE, 2015).

Adverse health effects cross a wide spectrum from irritation to respiratory systems to, at the extreme end of the spectrum, cases of premature death. The most common adverse health associations with PM are increased rates of respiratory and cardio-pulmonary events. Most affected are young children, the elderly and people with relevant pre-existing conditions.

2.3.2 Carbon monoxide

Carbon monoxide is a colourless, odourless and tasteless gas, most commonly caused by human activities. Breathing carbon monoxide affects the oxygen-carrying capacity of blood and can result in mental confusion, heart problems and a general decline in a person's wellbeing, depending on the concentrations.

Prominent sources include vehicle exhaust, and wood and coal combustion.

2.3.3 Nitrogen dioxide

Nitrogen dioxide (NO_2) is a brownish acidic gas and is highly corrosive. It forms from chemical reactions involving nitrogen oxide (NO) and other oxides, typically during combustion of fossil fuels. Inhalation is associated with aggravating respiratory diseases such as asthma and lung infections, with resulting increases in hospital admissions.

Vehicle emissions are the main source of NO_2 in urban areas.

2.3.4 Sulphur dioxide

SO_2 gas is colourless and has a characteristically pungent smell. It is produced during the combustion of sulphur-containing fossil fuels such as coal. Respiratory problems are the most common complaint with increased inhalation of SO_2. It also has links to cardiovascular disease.

Common sources in Otago include coal-burning-combustion sources such as industrial emissions and coal burners used in domestic heating.

2.3.5 Ozone

Lower-level ozone is a secondary pollutant formed from other compounds during photochemical reactions, and it results in smog. Effects of high-ozone levels include increased respiratory and cardiovascular disease. Short-term effects include irritation of the eyes, nose and throat, and headaches.

Ozone is not readily formed in Otago as it requires an abundance of sunlight.

2.4 International air quality indicators

New Zealand standards and guidelines are generally consistent with the World Health Organisation (WHO) recommendations (WHO, 2006). In the cases of PM and SO_2, however, there are some significant differences.

As regards particulate matter, international researchers accept the evidence that adverse health effects associated with $PM_{2.5}$ are greater than those associated with PM_{10} As a result, many agencies, including the WHO, the European Union and the United States have introduced $PM_{2.5}$ standards alongside their PM_{10} standards. In formulating PM guidelines and standards, the WHO assumes that the ratio of $PM_{2.5}$ to PM_{10} is 0.5, thereby setting equivalent $PM_{2.5}$ and PM_{10} daily mean guideline values of 25 µg/m^3 and 50 µg/m^3, respectively.

The WHO lowered the SO_2 24-hour guideline value from 120 µg/m^3 to 20 µg/m^3 in 2005 (Krzyanowski, 2008). The lowered value may be relevant in areas with coal-powered industrial plants and in areas where coal-burning is heavily used for domestic heating. To date, New Zealand has not revised the NESAQ SO_2 standard.

Table 2 lists relevant WHO guideline values for various ambient air pollutants where they differ significantly from the NESAQ.

Table 2. World Health Organisation guideline values for $PM_{2.5}$, nitrogen dioxide and sulphur dioxide

Pollutant	Threshold concentration (µg/m^3)	Averaging period
$PM_{2.5}$	25	24-hour
	10	annual
Nitrogen dioxide	40	annual
Sulphur dioxide	20	24-hour
	500	10-minute

National and international standards and guidelines continue to evolve over time as advances are made in health research.

2.5 Otago air-management designations

2.5.1 Airsheds

The Otago region has four designated Local Air Management Areas (LAMAs), which were gazetted as airsheds in 2005 in accordance with requirements of the NESAQ. Airsheds are used to determine whether areas are considered to be polluted by NESAQ standards.

Airshed 1 is deemed to have the most degraded air quality in winter, as it has an excessive numbers of days with unacceptable levels of pollution; Airshed 4 comprises areas where air quality could potentially be, but is not currently expected to be, degraded. Continuous, standard monitoring and reporting is required by the NESAQ for each airshed with degraded air quality.

Twenty-two towns and cities have been allocated to one of these four airsheds (Figure 1). Where monitoring data were available, those data were used to assign towns to the most appropriate airshed. In the absence of monitoring data, climate and topography data were used, in conjunction with functional boundaries, to determine the most appropriate airshed border.

Rural areas outside of town boundaries are considered to be a fifth, undesignated airshed encompassing the rest of Otago where air quality is expected to be good.

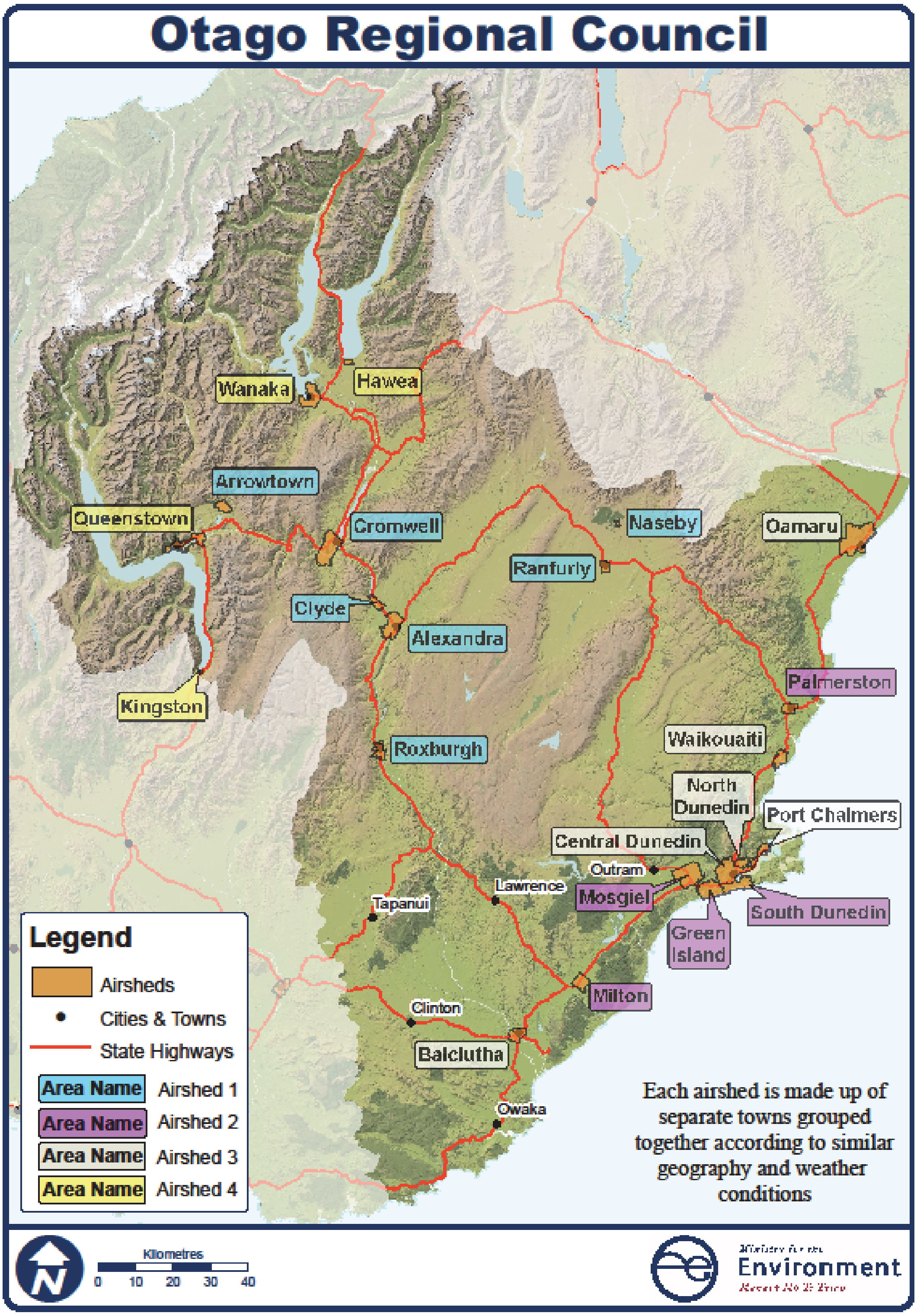

Figure 1. **Otago Regional Council gazetted airsheds**

2.5.2 Air zones

ORC placed the 22 towns and cities into one of three air zones for the purposes of air quality-management in the Air Plan. Towns were allocated based on the following criteria:

Air Zone 1 - towns expected to exceed national standards more than ten days a year

Air Zone 2 - towns expected to exceed the national standards fewer than ten days a year

Air Zone 3 - areas that are not expected to experience degraded air quality.

Air zones are used for planning purposes and provide a simplified framework for air quality-management in the community. More stringent rules regarding emissions are in effect for Air Zone 1 than for the other air zones.

Boundaries for airsheds and air zones do not always coincide because air zones normally encompass a smaller, more urban footprint than do some of the airshed boundaries.

Table 3 lists the airshed and air zone designations for Otago. Maps of airshed and air zone boundaries for centres with long-term, year-round and winter monitoring are shown in Appendix 1 Airshed and air zone boundary maps.

Table 3. Airshed and air zone designations for Otago

Designation	Gazetted Airsheds (MfE)	ORC Air Plan Zones
1	Alexandra* Arrowtown* Clyde Cromwell Naseby Ranfurly Roxburgh	Alexandra Arrowtown Clyde Cromwell
2	Palmerston Mosgiel* South Dunedin Green Island Milton	Balclutha North Dunedin Central Dunedin South Dunedin Green Island Hawea Kingston Milton Mosgiel Naseby Oamaru Palmerston Port Chalmers Queenstown Ranfurly Roxburgh Waikouaiti Wanaka
3	Balclutha North Dunedin Central Dunedin* Oamaru Port Chalmers Waikouaiti	Rest of Otago
4	Hawea Kingston Queenstown Wanaka	N/A
5	Rest of Otago	N/A

3. Air quality monitoring network

3.1 Background

ORC operates a long-term, air quality monitoring network in the region. Monitoring began in 1997, and since that time, ambient pollutants, including PM_{10}, $PM_{2.5}$, NO_2, SO_2 and CO, have been monitored in over 50 locations throughout Otago. Most of the monitoring performed over the past ten years has been in response to the requirements of the NESAQ.

A variety of monitors and monitoring techniques have been employed to define and characterise air quality, both temporally and spatially. During this ten-year reporting period (2005-2014), monitoring has focused primarily on PM_{10}.

Otago's large area, with its varying terrain and climate, make it challenging to provide a true and complete representation of ambient air quality. In accordance with the NESAQ (MfE, 2011), monitors are situated where it is considered that the most people may experience the most pollution.

3.2 Monitoring objectives

The objective of Otago's air quality monitoring programme is to provide scientifically robust data for the following purposes:

- to manage the region's air resource
- to measure the effects of ORC's air quality-management initiatives
- to fulfil the statutory requirements of the Resource Management Act 1991 (RMA)
- to measure and report on compliance with the NESAQ.

A range of monitoring activities and special investigations are needed to fulfil these objectives, and in addition to continuous site monitoring, other activities include emissions inventories, source apportionment studies and spatial studies.

Results from all monitoring programme activities help to inform on the overall, ambient air quality in Otago.

3.3 Monitoring scheme

There are four categories of air quality monitoring used in the network:

Key-indicator monitoring is performed at long-term sites that run continuously and are designed to operate year-round. Results from these sites are used to report to the MfE on compliance with the NESAQ and to track long-term trends.

These sites have different topographical and climatological features, resulting in distinct patterns of particulate pollution. They were chosen as key sites because they are considered representative of Otago's townships.

Survey monitoring is performed at permanent sites that operate continuously during winter months only. Results are used to quantify wintertime air quality and assist in tracking trends. These sites have more than five years of data.

Screening monitoring is operated as relatively short-term monitoring campaigns (fewer than three years) to identify the magnitude of particulate pollution in various centres.

Special investigations are outside of the regular network. These are short-term, targeted studies to answer specific questions regarding air quality.

Table 4 lists the sites monitored during this ten-year reporting cycle, their purpose in the monitoring network and their lengths of record. Monitoring locations are shown in Figure 2.

Table 4. Air monitoring sites and their purpose in the network

Site	Air Zone	Airshed	Purpose	Length of record
Alexandra*	1	1	Key indicator – Year-round	10 years
Mosgiel*	2	2	Key indicator – Year-round	10 years
Central Dunedin*	2	3	Key indicator – Year-round	9 years
Arrowtown*	1	1	Survey : winter focus	8 winters
Clyde	1	1	Survey : winter focus	7 winters
Cromwell*	1	1	Survey : winter focus	7 winters
Milton*	2	2	Survey : winter focus	7 winters
Balclutha*	2	3	Survey : winter focus	6 winters
Naseby	2	1	Screening	1 winter
Roxburgh	2	1	Screening	1 winter
Ranfurly	2	1	Screening	2 winters
Palmerston*	2	2	Screening	2 winters
Oamaru	2	3	Screening	2 winters
Lawrence*	3	5	Screening	2 winters

3.4 Monitoring methods

3.4.1 PM_{10}-monitoring and measurement

Two types of air quality monitors are deployed in ORC's air quality network; both are beta attenuation monitors (BAMs), manufactured by MetOne in the United States, and they measure PM_{10} continuously. Beta attenuation monitors collect hourly samples of PM_{10} and calculate an hourly mass concentration reported in micrograms per cubic metre of air (μg/m^3), using standardised airflow measurements. A daily average PM_{10} value is calculated using hourly values from midnight to midnight.

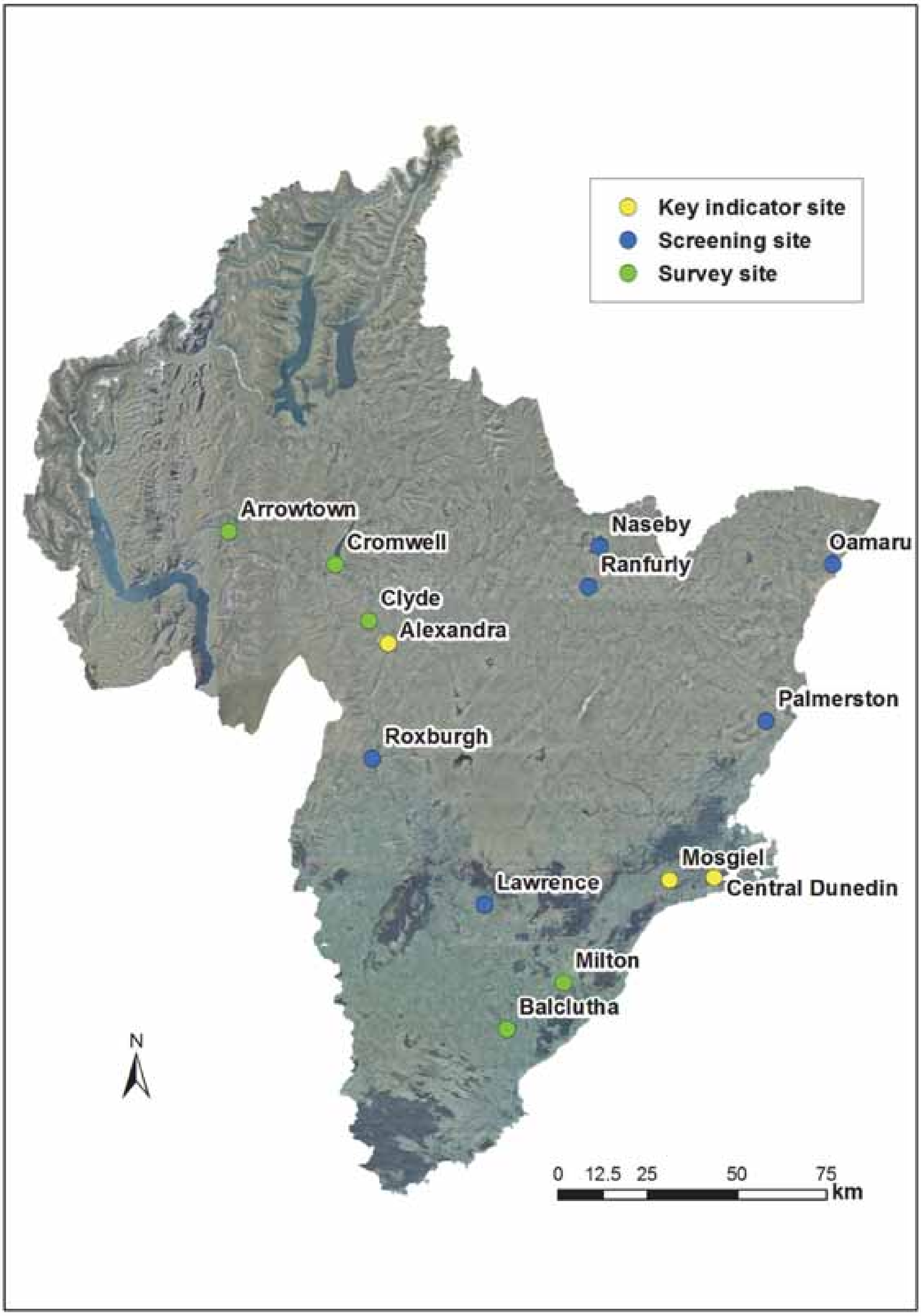

Figure 2. Otago air quality monitoring network during 2005-2014

Standard-sampling methods are required for reporting on compliance with the NESAQ. The BAM1020 is accepted by the US Environmental Protection Agency (USEPA) as an equivalent-reference standard method for measuring PM_{10} due to its automated hourly self-calibration, the data processing algorithms employed in its calculations and the pre-conditioning of the airstream being sampled. These monitoring methods are employed at Alexandra, Arrowtown, Dunedin and Mosgiel, with results reported to the MfE on an annual basis.

The Dunedin BAM1020 installation is shown in Figure 3.

Figure 3. A typical BAM1020 installation

The rest of the sites are monitored using an Environmental Beta Attenuation Monitor (EBAM). The EBAM is currently not considered to be an equivalent-reference standard method by the USEPA, but it is designed to provide average daily PM_{10} information accurate enough for tracking daily PM_{10}.

All stations are sited and operated using the appropriate standards (Standards New Zealand, 2007 and 2008) as far as is practicable.

Other monitoring technologies, such as nephelometers, which measure light-scattering properties of particulate samples, and stacked-filter unit (GENT) samplers, have been deployed in special studies, where applicable.

3.4.2 Meteorological monitoring

Air temperature, wind speed and wind direction all influence the accumulation and dispersion of pollutants. These parameters are recorded continuously at most PM_{10}-monitoring sites. Wind-sensor heights are generally located at no more than 4 metres above the ground, below the World Meteorological Organisation (WMO, 1983) standard of 10 metres. As a result, the data have limited value in terms of dispersion modelling, but can be used to describe localised meteorological effects at the sites.

The National Institute of Water and Atmospheric Research (NIWA) and the MetService have meteorological datasets that can be used to augment the meteorological data collected at PM_{10}-monitoring sites.

4. Pressures and influences on air quality

Ambient air quality at any location is the result of a complex relationship between emissions – both their type and amount – and meteorology.

Emissions come from a variety of sources, such as solid-fuel home heating, vehicle exhaust, industrial and commercial discharges, and outdoor burning. These anthropogenic sources generally emit particulates that fall within the smaller size fraction of $PM_{2.5}$ and contain a multitude of chemical contaminants, such as NO and sulphur dioxides, polycyclic aromatic hydrocarbons (PAHs) and dioxins. Particulates in the coarse fraction (between $PM_{2.5}$ and PM_{10}) generally come from naturally occurring sources such as pollen, marine aerosol, dust and crustal matter.

The daily weather and the longer-term climate of a locale help to determine how particulates are dispersed or accumulated and can have a greater influence on ambient air quality than do emission amounts. In Otago, larger-population towns with higher-mass emissions (such as Dunedin and Mosgiel) regularly have better winter air quality than do smaller, lower-emitting towns such as Alexandra and Arrowtown.

This section describes the major emission sources found in Otago and the meteorological and climatological factors that affect them.

4.1 Emissions

4.1.1 Household emissions

Two types of data provide information on the emissions profiles of Otago towns. The first is the census report on dwelling type, which includes statistics on fuel types (e.g. electricity, wood, coal, gas, etc.) used to heat homes. The second is an emissions' inventory, a tool used to compile estimated emissions for a town using information on not only burner numbers, but also on their ages and fuel usage.

4.1.2 Wood burners

The most recent census (Statistics New Zealand, 2013) provides trend information when compared to census results from 2001 and 2006. The number of wood burners being used for domestic heating, and the percentage of total households that this number represents, are shown for key towns in Table 5. The percentage of wood burners being used has dropped in each of these towns, but due to an increasing number of homes over time, the actual numbers of wood burners has gone up in some towns (e.g. Arrowtown, Clyde, Cromwell and Dunedin).

Currently, in Otago, the use of wood burners is reported in 56% of all households, well above the national average of 37%. Much higher-than-average percentages of wood use are reported in Clyde, Milton and Lawrence (63, 70 and 76%, respectively).

Table 5. Census data on wood-burner use for key Otago towns

Wood-burner use, by number and percentage						
Site	2001		2006		2013	
	# wood burners	% wood burners	# wood burners	% wood burners	# wood burners	% wood burners
Alexandra	1146	62	1098	55	1086	53
Arrowtown	483	71	549	62	558	59
Clyde	264	74	252	63	273	63
Cromwell	708	64	813	58	921	56
Balclutha	1005	61	948	57	948	59
Dunedin	14563	48	14291	45	21,918	47
Lawrence	153	77	144	73	144	76
Milton	555	73	507	67	540	70
Mosgiel	2472	55	2397	50	2397	47

The most recent emissions inventories for Otago were done ten years ago (Wilton, 2005 and 2006). Since that time, significant changes have been made to the age-related configuration of burners, effectively changing the emissions profiles for most towns; however, up-to-date information is not available at this time. This creates uncertainty when estimating current emissions and forecasting for various emission-reduction scenarios.

Results of the 2005 Air Emission Inventory for Dunedin, Mosgiel and Alexandra did estimate that discharges from domestic-heating sources accounted for at least 90% of PM_{10} emissions in Dunedin and Mosgiel, and up to 99% of all emissions in Alexandra.

For comparison purposes, assessments made in 2005 of daily winter emissions estimated the following daily emission amounts under average winter conditions:

Dunedin 2,100 kilograms PM_{10}

Mosgiel 600 kilograms PM_{10}

Alexandra 380 kilograms PM_{10}.

To compare wood-burner emissions among towns, coarse estimates of PM_{10} densities were made using general information on household-burner use, an average-emission rate, and the area of the town's air zone[1]. PM_{10} emissions from domestic chimneys are densest in Arrowtown, Alexandra and Cromwell (Table 6).

[1] Emission densities based on census area unit (CAU), wood-burner numbers (Census 2013), winter daily fuel-use assumptions (Wilton, 2005), an average emission rate of 6g/kg and airshed areas

Table 6. Estimated PM_{10} emission densities in selected Otago towns

Town	Air Zone	PM_{10} density PM_{10} (g/hectare)
Alexandra	1	207
Arrowtown	1	398
Clyde	1	125
Cromwell	1	181
Balclutha	2	102
Milton	2	124
Mosgiel	2	171

As a requirement of the NESAQ, all wood burners installed after 1 September 2005 on sections smaller than two hectares are required to have an emission rate of less than 1.5 grams of PM_{10} for every kilogram (g/kg) of dry wood burnt and to be no less than 65% efficient.

The Air Plan set stricter standards in Air Zone 1 towns, requiring all domestic-heating appliances to be fully compliant with either 0.7g/kg or 1.5g/kg emission standards (depending on the date of installation) as of 1 January 2012. It was originally estimated that replacement of all older, non-compliant solid-fuel burners with new, lower-emitting efficient wood burners would lead to the required reduction in PM_{10} emissions to achieve compliance with the NESAQ.

In Air Zone 2, it was expected that the natural rate of replacement for older heating appliances would result in the PM_{10} reductions required to achieve NESAQ compliance.

4.1.3 Coal burners

In the 2013 Census, 14% of all Otago households (11,040 dwellings) reported using coal for domestic heating, down from 24% in 2006. This is above the national average of 4%, with most of the usage reported in southern areas of Otago. Of the five Otago territorial areas, the Clutha district has the highest percentage of households (39%, 2634 dwellings) using coal for home heating (Figure 4).

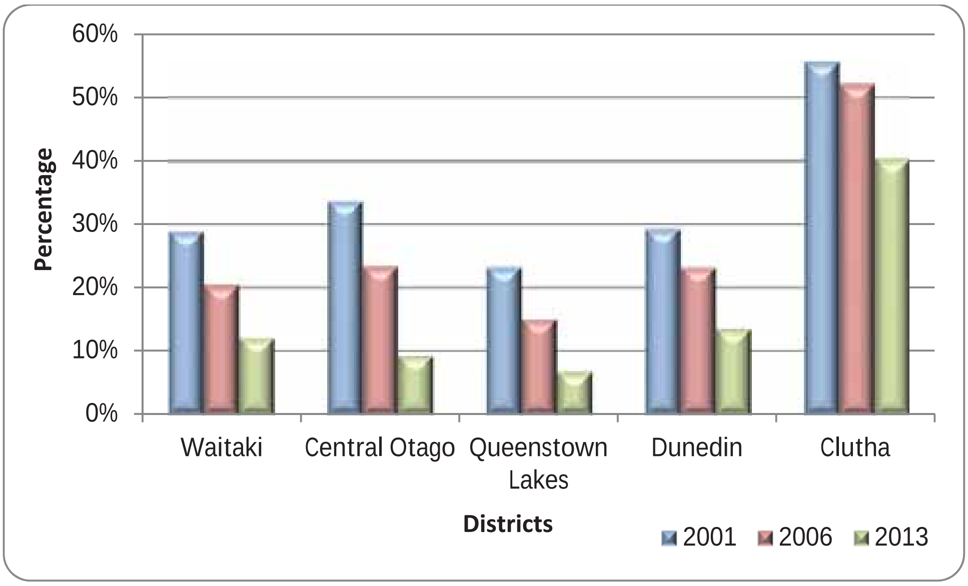

Figure 4. **Change in the percentage of households that use coal for domestic-heating purposes from 2001 to 2013**

4.1.4 Other sources of heat

In addition to solid-fuel burners (wood and coal), other sources of fuel used for heating reported in the census include electricity, mains and bottled gas, and solar power. Electricity is the most widely used fuel for heating, with anywhere from 70 to 90% of households (depending on district) reporting its use (Table 7); these percentages have not changed significantly since 2001.

Mains gas and solar power are not commonly used and bottled gas is used by anywhere from about 11% in the Clutha district to 21% in the Queenstown-Lakes district.

Table 7. **Percentage of total households using various fuels for heating**

District	Electricity	Mains gas	Bottled gas	Solar power
Waitaki	78.8%	0.5%	12.9%	1.1%
Central Otago	79.0%	0.8%	16.3%	1.5%
Queenstown Lakes	84.4%	7.6%	21.0%	1.9%
Dunedin	91.4%	0.7%	13.0%	0.8%
Clutha	69.6%	0.4%	11.3%	0.5%

4.1.5 Emissions from outdoor burning

Outdoor burning contributes PM_{10} emissions to the atmosphere; however, its impact on regional air quality has not been quantified. The Air Plan provides for most outdoor burning as a permitted activity, with rules related to nature of the material burned and distances to boundaries. The strictest rules are for residential properties in air zones 1 and 2 (Table 8).

Table 8. Key rules related to outdoor burning in Otago

	Air zones 1 & 2		Air Zone 3	
Rule	**Residential**	**Non-residential**	**Residential**	**Non-residential**
Only paper, cardboard, vegetative matter, untreated wood is to be burned	✓	✓	✓	n/a
Material must be dry	✓	✓	✓	n/a
Material must come from property where it's being burned	✓	✓	✓	n/a
Distance to boundary from fire (metres)	50	100	n/a	n/a
Smoke or odour or PM must not be offensive or objectionable at or beyond the property boundary.	✓	✓	✓	✓

In almost all instances[2], the discharge of contaminants from a variety of materials, such as tyres, treated timber, painted material, etc., is prohibited (the Air Plan, Section 16.3.3.1).

Rural-outdoor fires have, on occasion, been known to result in smoky conditions in and around nearby residential areas. Over the past four years, ORC has received, on average, approximately 600 complaints per year related to air quality. Of these, 20% relate to rural-outdoor burning.

4.1.6 Emissions from industrial sources

Industrial and commercial discharges to air are regulated through the Air Plan, with larger discharges requiring consent. Consented combustion processes (industrial and commercial) contribute about 248kg of PM_{10} per winter day to the atmosphere in Dunedin, of which about 158kg is emitted in Central Dunedin (Wilton, 2005). At that time, some of the highest emissions came from coal-fired boilers. An updated emissions inventory of consented discharges for the Otago region is not available.

In 2007, ORC signalled to all industrial and commercial dischargers in Otago with permits for coal-fired boilers that upgrades would be required when renewing their permits. As a result, about a dozen consents have been renewed, with significantly reduced emissions in Central Dunedin over the past eight years. It is estimated that about 10 tonnes of PM_{10} have been removed from the Central Dunedin airshed annually due to this initiative.

4.2 The role of weather on air quality

Long-term weather patterns (climatology) and short-term weather features (meteorology) both affect the characteristic ambient air quality of a location. Towns in Otago have a wide range of topographical and climatological features that influence daily and seasonal particulate concentrations. This section discusses the relationship between climate/weather and air quality, as illustrated in the three key indicator sites.

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[2] Except for certain activities such as incineration and Fire Services training activities

4.2.1 Alexandra

Alexandra is a small town in Central Otago, with a population of 4,800 people living in 2,100 houses. Despite its size, Alexandra has very poor air quality during winter months, which is, in no small part, due to the weather.

Alexandra has a continental climate with extreme temperatures during winter and summer. It is not unusual for overnight temperatures in winter to reach -10° C for several consecutive nights. Coupled with clear skies during periods of anti-cyclonic weather, strong temperature inversions are likely to form overnight and into the morning. During an inversion, a layer of cold, dense air is trapped at the surface below warmer and more buoyant air as a result of rapid cooling of the ground surface. These events cause PM_{10} emissions to become trapped near the ground and become more concentrated (Figure 5).

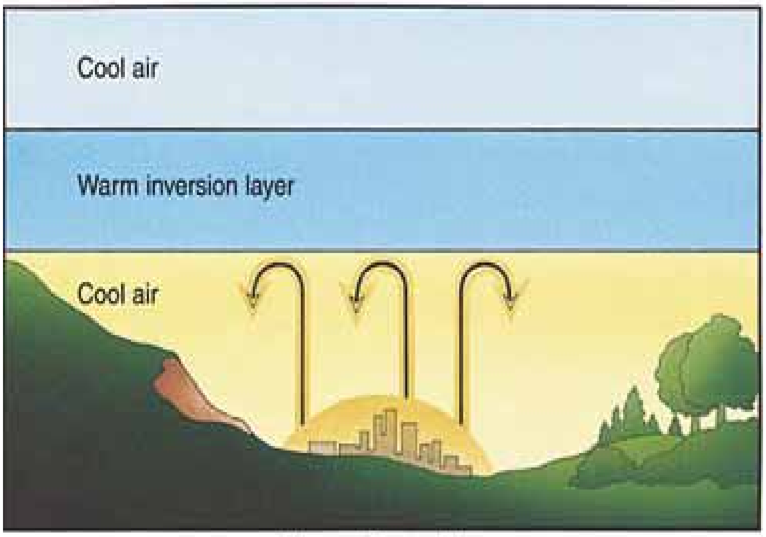

Figure 5. An inversion layer traps cool air near the surface of the Earth

In Alexandra, the relationship between daily PM_{10} and air temperature (Figure 6) indicates that the highest-daily averages of PM_{10} occur when daily temperatures drop below about 10° C. Low temperatures do not necessarily result in high-particulate concentrations; rather, atmospheric stability is a more important factor in determining whether particulates disperse or stagnate near ground level. The major weather elements affecting stability include wind speeds and air temperature in a vertical profile. Temperature inversions that trap particulates at ground level occur when conditions are cold, winds are calm, and the sky is clear (allowing radiative loss of heat from the ground surface). These conditions can occur in Central Otago up to 60-70 days during winter months, leading to elevated PM_{10} concentrations.

Due to its location in a relatively low-lying basin surrounded by high hills, Alexandra also experiences fairly benign winds all year long, but particularly during winter months

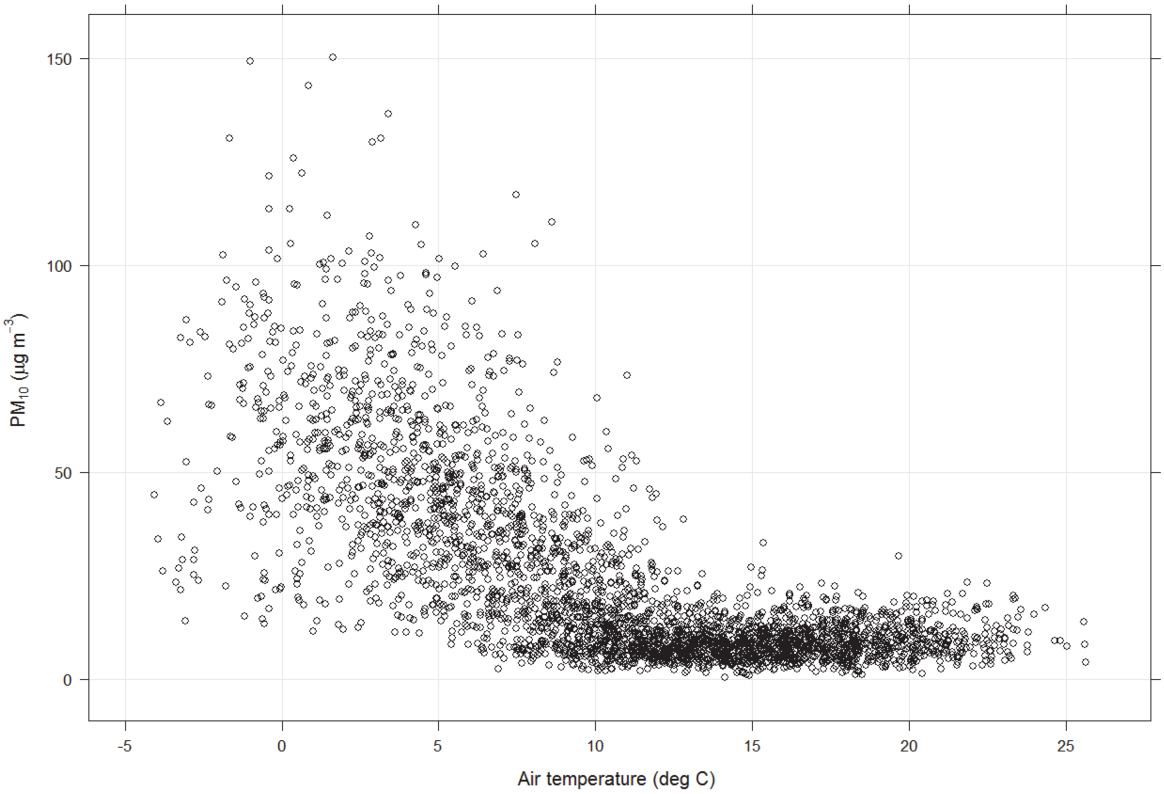

Figure 6). This exacerbates the accumulation of PM_{10} emissions, further raising particulate levels. Not only are wind speeds generally lower in winter, due to the surrounding hills, but dispersion modelling of the area (ORC, 2009) showed that cold-air drainage is a significant feature with cooler, heavier air descending the hillsides at night. Cold-air drainage tends to keep lower-level air cooler at night, which reinforces the temperature inversion.

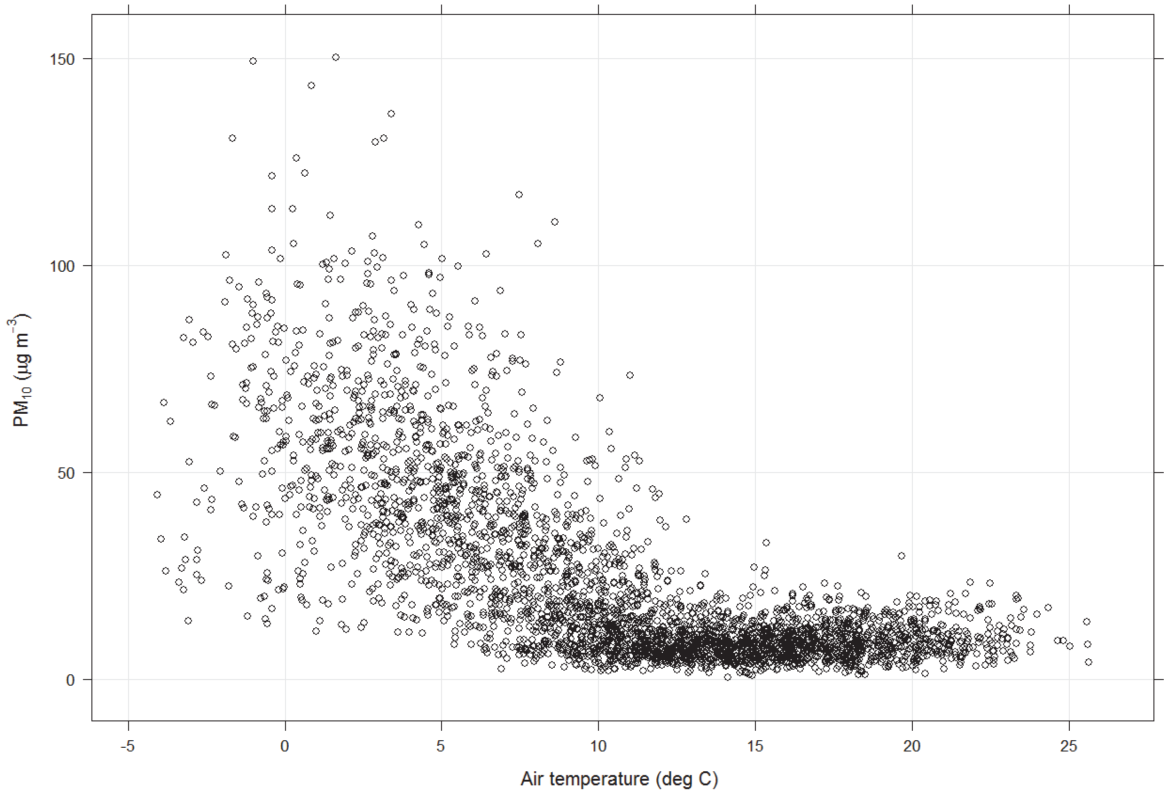

Figure 6. Relationship between daily PM_{10} and air temperature: Alexandra

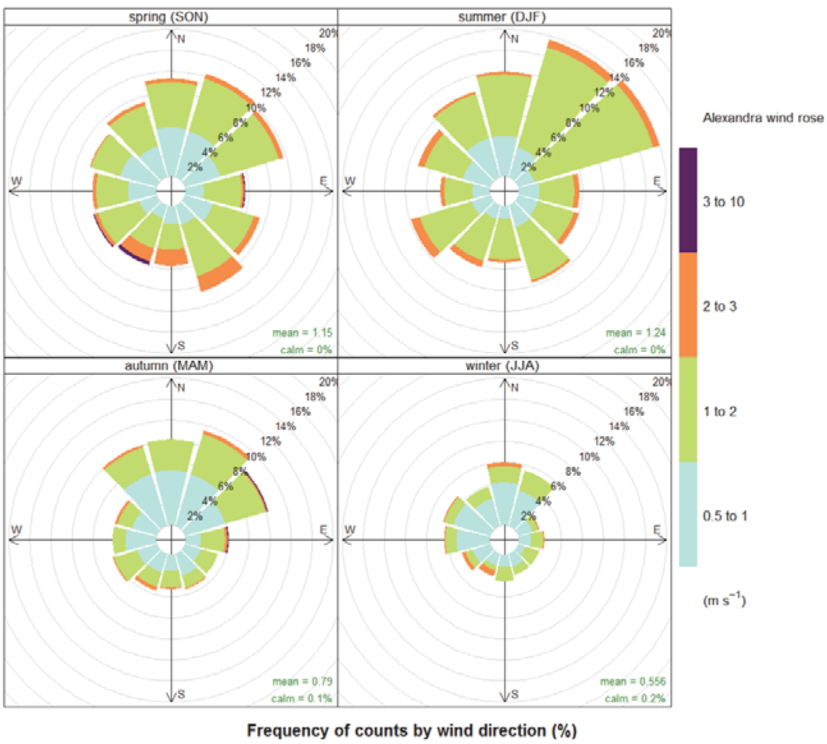

Figure 7. Seasonal wind roses: Alexandra

4.2.2 Central Dunedin

Dunedin is a mid-sized city, with a population of about 120,000, of which about 45,000 live in Central Dunedin, the area represented by the air quality monitor. Overall, Dunedin has relatively good air quality year-round, despite some valley areas where emissions can accumulate.

Key to Dunedin's good air quality is its coastal location. Compared to other more inland sites, Dunedin weather is characterised by milder temperatures and windier conditions, with more frequent winds of higher speeds throughout the year (Figure 8). A wind rose of hourly wind speeds and directions indicates that prevailing winds are from the northeast (down the harbour) and from the west and northwest. This ventilation helps disperse particulates, generally lowering the overall daily PM_{10} concentrations in the city.

The air quality monitor is located near sea level in an area of industrial, commercial and domestic-heating discharges. A study of the spatial distribution of pollutants in Dunedin (NIWA, 2009) noted that in addition to the emissions of nearby surrounding sources, cold-air drainage brings domestic-heating emissions down from the hill suburbs, from the northwest.

Unlike Alexandra, daily PM_{10} levels in Dunedin do not correlate well to air temperatures (Figure 9). High-particulate levels have occurred throughout the temperature range experienced in Dunedin.

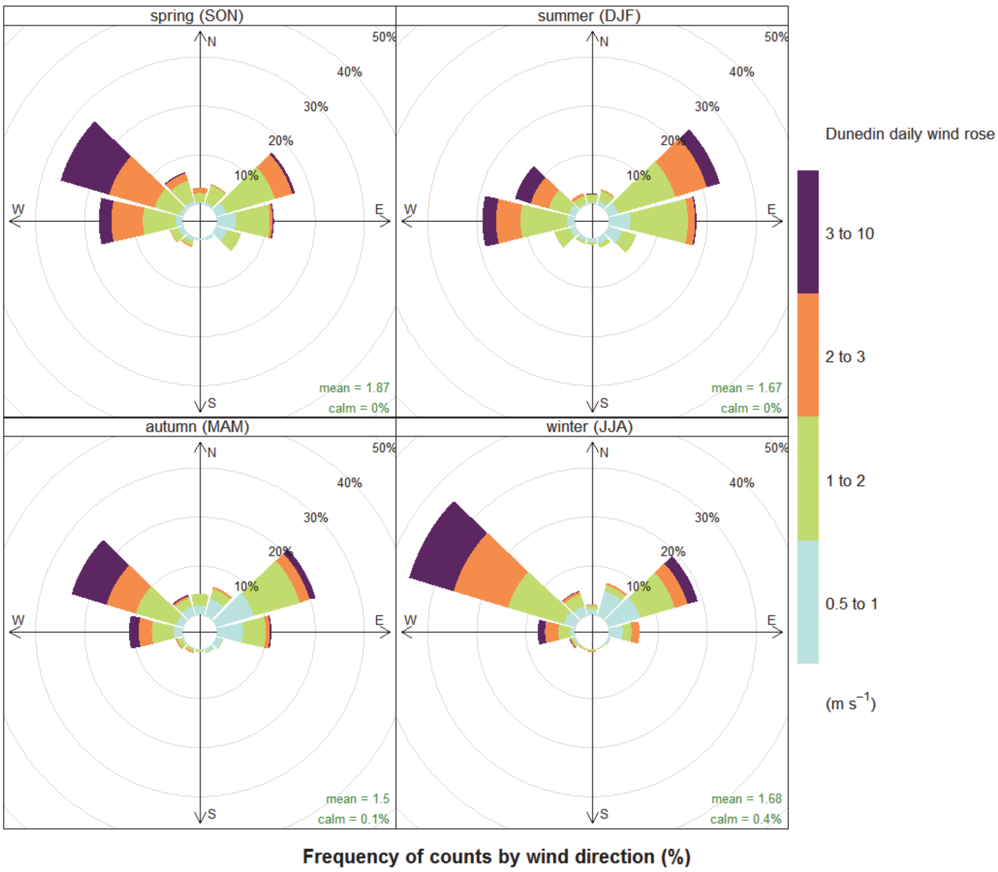

Figure 8. Seasonal wind roses: Central Dunedin

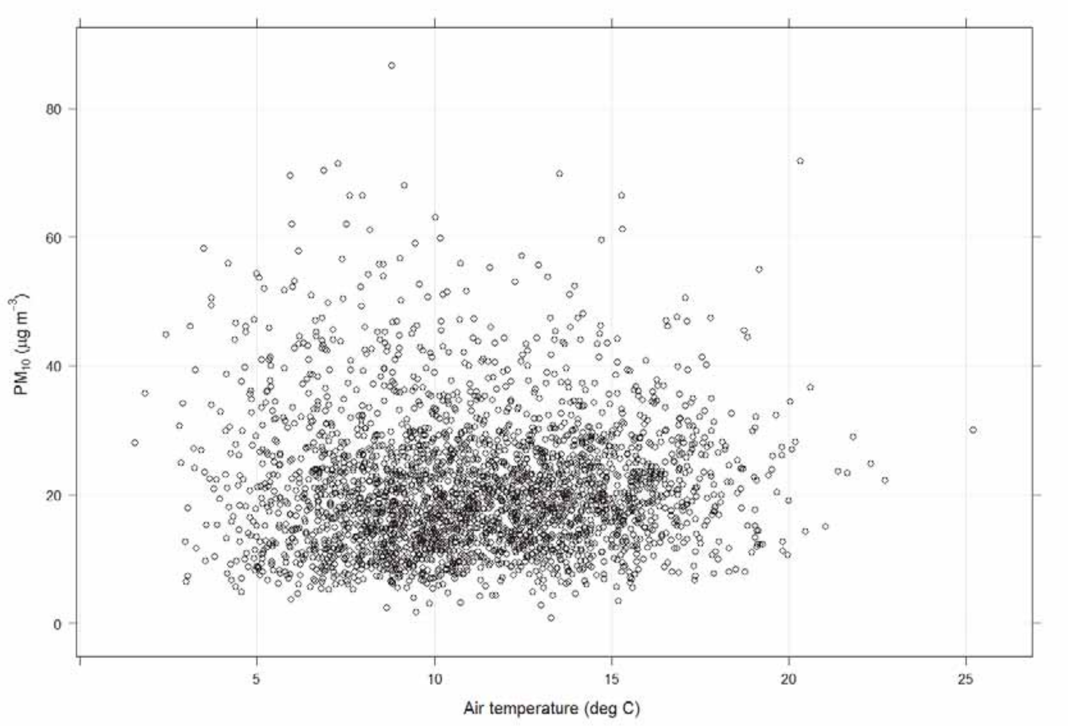

Figure 9. Relationship between daily PM_{10} and air temperature: Central Dunedin

4.2.3 Mosgiel

Mosgiel is a mid-sized town situated near the head of the Taieri Plain, slightly inland from Dunedin, with a population of about 6,600 people living in about 3,000 dwellings.

Mosgiel's weather has elements of both coastal and continental climates. Temperatures are generally colder/hotter than those recorded in Dunedin, but not as extreme as those in Alexandra. Temperature inversions often form on the Taieri Plain and a long, horizontal layer of smoke on winter mornings is sometimes visible (Figure 10).

Like Alexandra, Mosgiel's autumns and winters are less windy (Figure 11) than either summer or spring and do experience a pattern of cold-air drainage from the north.

High-PM_{10} levels are generally more correlated to colder temperatures; however, there have been days when PM_{10} has been high with higher temperatures (Figure 12), presumably influenced by outdoor-burning events.

Figure 10. Smoke trapped under the inversion layer: Mosgiel

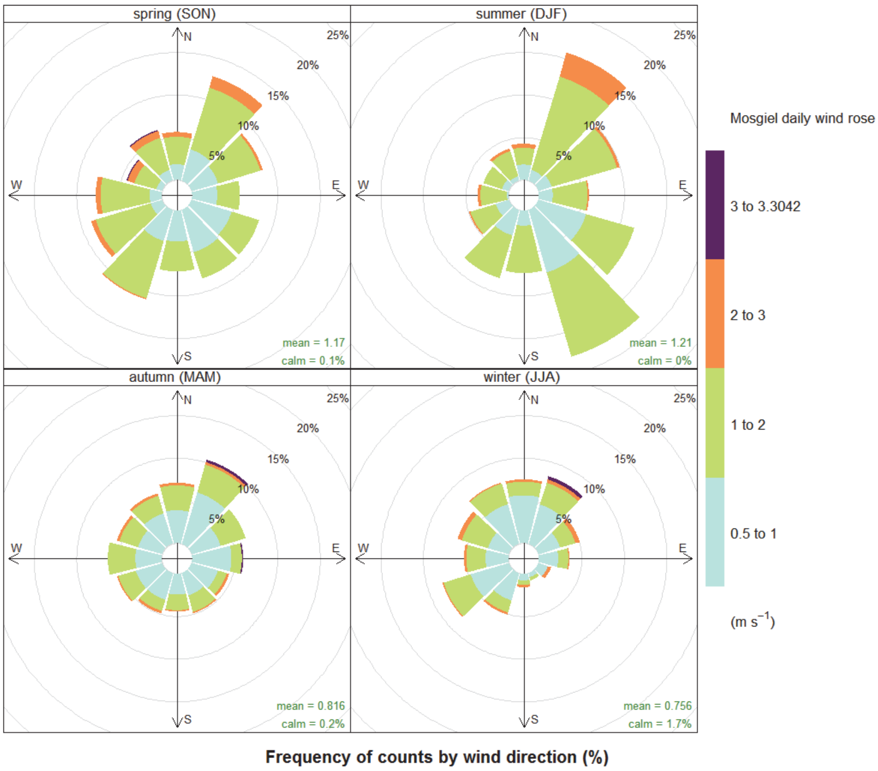

Figure 11. Seasonal wind roses: Mosgiel

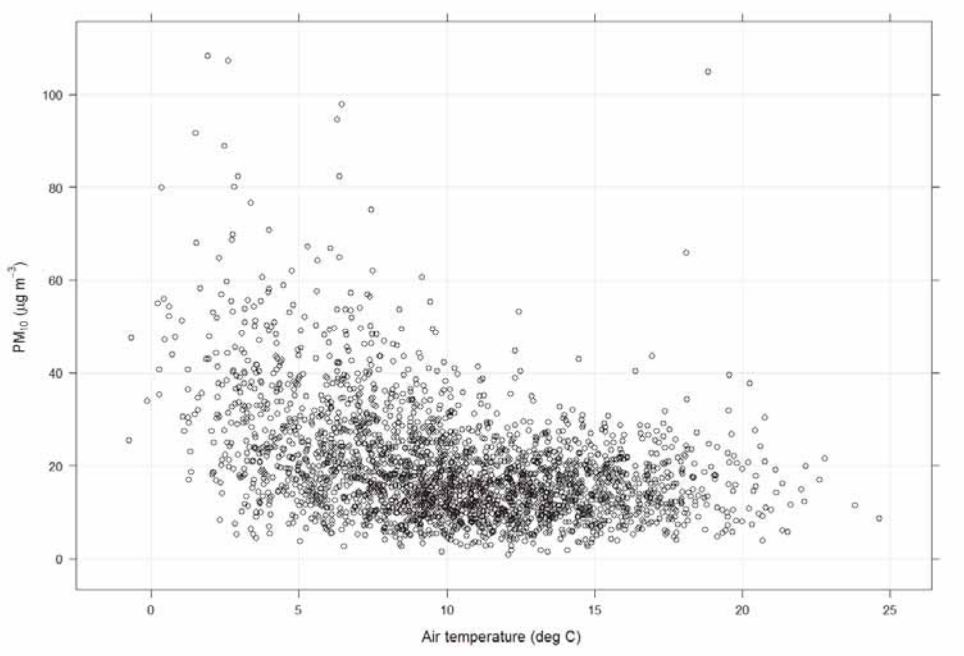

Figure 12. Relationship between daily PM_{10} concentrations and air temperature: Mosgiel

5. State of the region's air quality

This section describes the current state of Otago's air quality, based on PM_{10}-monitoring data from the last three years (2012-2014), for the eight year-round and survey-monitoring sites. A three-year period was chosen to represent the current state of air quality because it should smooth some of the variation in particulate levels due to changing weather patterns from year to year. It is also assumed that three years is too short a period to discern any significant change in air quality due to interventions designed to reduce emissions.

Results from six short-term monitoring campaigns performed for screening purposes over the past ten years are also presented. Monitoring results are compared to the limits in national standards and guidelines set for the protection of public health.

5.1 Aggregate statistics

Data from 2012-2014 were aggregated for each of the key indicator and survey sites to represent the current state of air quality at each site[3]. Annual and seasonal statistics were generated for key indicator sites; seasonal (winter-only) statistics are provided for the survey sites. For screening sites where one or two winters of PM_{10} are available, those winters are compiled into single datasets and presented as a reasonable representation of current winter air quality.

The aggregated summary statistics given in Table 9 represents the current state of air quality. Figure 13 ranks the towns in terms of average-winter PM_{10} and shows the corresponding number of days exceeding the NESAQ (exceedances). It indicates that Alexandra consistently has the highest number of exceedances each winter (46 days) and Arrowtown has the highest average winter PM_{10} (55 µg/m^3). Further detail is provided in the following sections.

[3] Mosgiel does not have a complete set of data for 2012; therefore, the SoE analysis uses 2013 and 2014 data.

Table 9. Key summary statistics aggregated over 2012-2014 provide a 'snapshot' of current ambient air quality.

Site	Average annual PM10	Average winter PM10	Number of days exceeding the NESAQ (50µg/m3)	Number of days exceeding the Otago goal level (35ug/m3)
Alexandra	24	46	46	81
Mosgiel	21	29	5	32
Central Dunedin	18	18	<1	11
Arrowtown	n/a	55	30	66
Clyde	n/a	29	14	40
Cromwell	n/a	37	37	55
Milton	n/a	42	32	74
Balclutha	n/a	30	7	48
Lawrence	n/a	22	2	13
Naseby	n/a	14	0	0
Oamaru	n/a	21	3	14
Palmerston	n/a	21	0	8
Ranfurly	n/a	22	0	16
Roxburgh	n/a	16	0	1

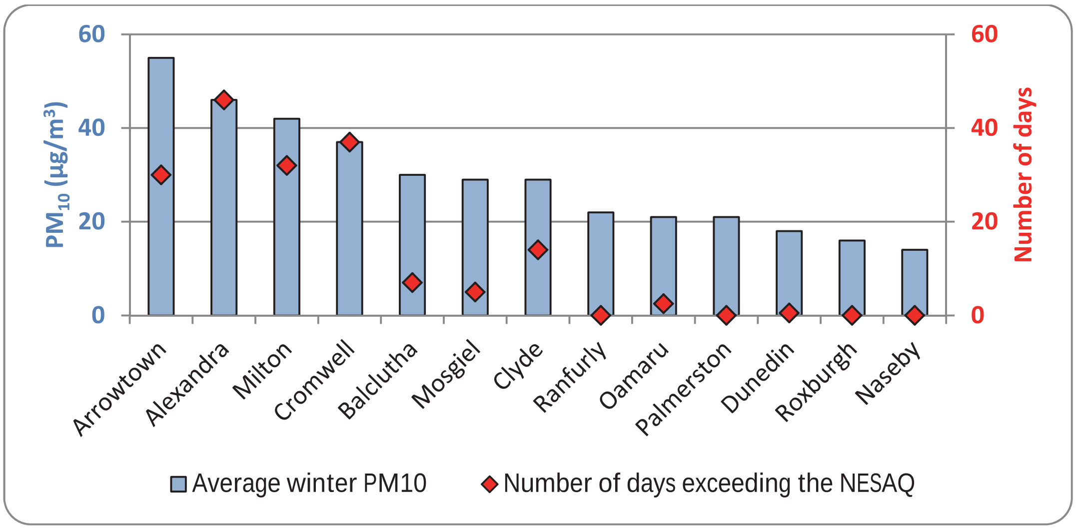

Figure 13. SoE air quality sites ranked by average winter PM_{10}

5.2 Key indicator sites

Alexandra, Dunedin and Mosgiel are key indicator sites and operate continuously year-round in each of the three airsheds in accordance with requirements in the NESAQ. Results are used to measure compliance with national standards.

5.2.1 Distribution of PM_{10} concentrations

The distribution of daily PM_{10} concentrations is depicted using box plots shown in Figure 14.

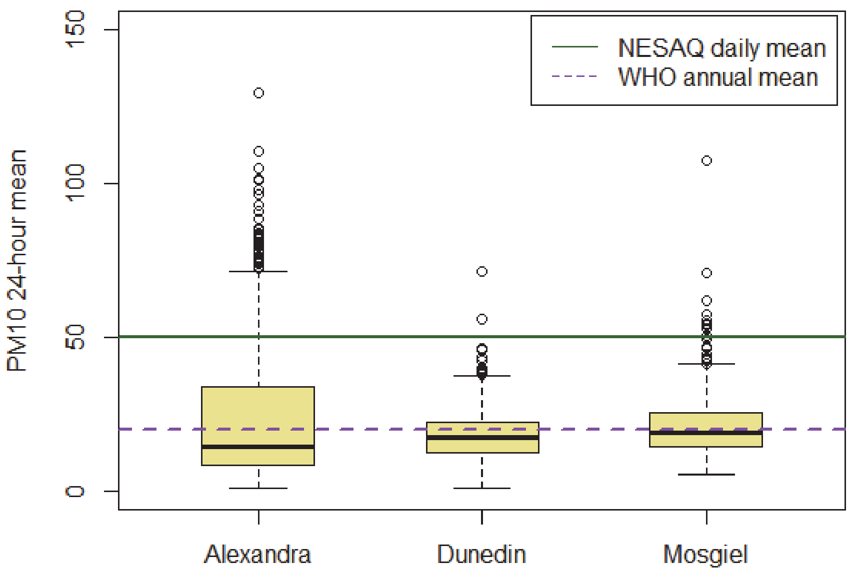

Figure 14. Distribution of PM_{10} at key indicator sites during 2012-2014

Of the three sites, Alexandra exhibits the most variability in PM_{10} concentrations and experiences a higher frequency of days that exceed the NESAQ limit. As discussed in Section 4.2.1, the combination of emissions and meteorology in Alexandra lead to high levels of PM_{10} during winter.

Dunedin exhibits the most homogeneous, and the lowest overall, PM_{10} signal throughout the year, with only a small variation during the winter months. Again, this reflects the influence of industrial emissions coupled with a climate conducive to dispersion of particulates.

Mosgiel is similar to Dunedin, but because most of the sampled particulates are domestic home-heating emissions, the winter signal is clearer here than it is in Dunedin. The area does experience more air movement than does Alexandra, resulting in lower concentrations.

Graphs of a typical year, developed as an aggregate of the 2012-2014 dataset (Figure 15), show the distinct seasonality of PM_{10} concentrations in Alexandra. The graphs are shown at the same scale for comparison between the sites.

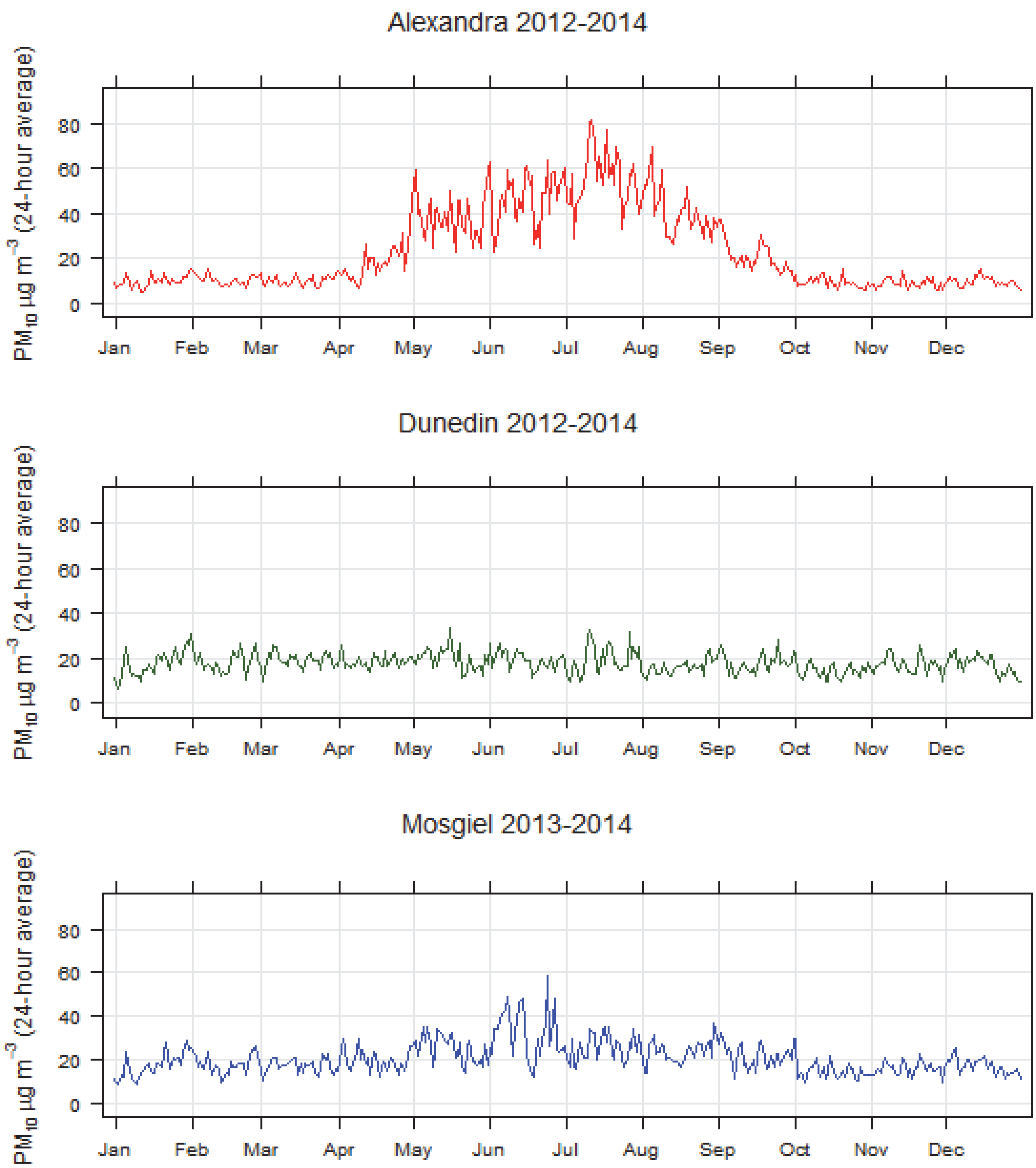

Figure 15. Typical daily PM_{10} using aggregated data from 2012-2014

5.2.2 Baseline PM_{10} levels

Baseline PM_{10} has been defined as PM_{10} levels from any source (natural or anthropogenic) that 'pre-exist the source, activity or receptor that we are interested in' (NIWA, 2008). Since we are most interested in winter air quality due to increased emissions and winter-weather conditions leading to degraded ambient air quality, baseline PM_{10} can be estimated by averaging monthly PM_{10} for the months that are not influenced by these two events.

Baseline values were calculated for the three indicator sites, using monthly averages from January, February, March, October, November and December over the three-year SoE reporting period. Table 10 lists the baseline values and, as a comparison, the winter (May through August) values.[4]

Table 10. Baseline PM_{10} and winter PM_{10} levels for three key indicator sites

Location	Baseline PM_{10} (µg/m^3)	Average winter PM_{10} (µg/m^3)
Alexandra	10	46
Central Dunedin	17	18
Mosgiel	17	29

5.2.3 Temporal variations of PM_{10} concentrations

5.2.3.1 Alexandra

Patterns in particulate levels can be seen at various timescales (i.e. hourly, daily, weekday and seasonal). The following series of figures depict those typical PM_{10} patterns during winter months at the key indicator sites. The aggregated hourly data are averaged over daily, weekly, monthly and hourly timeframes and presented in four graphs in the panel below (Figure 16).

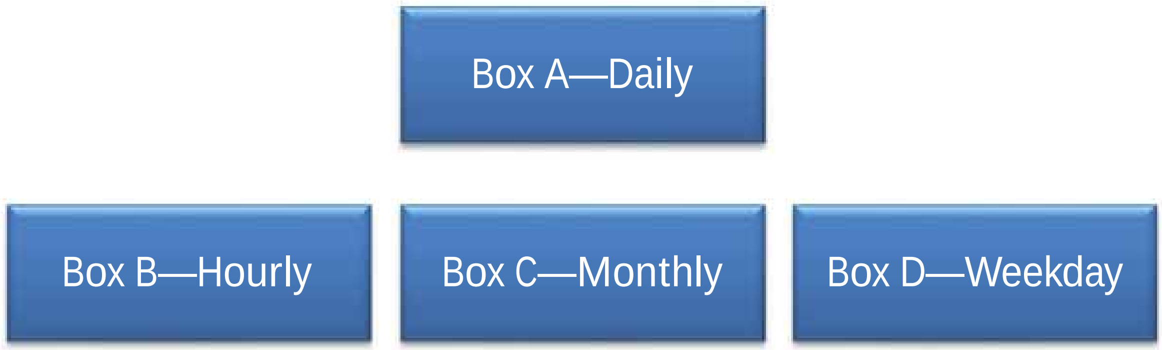

Figure 16. Graph panel template for PM_{10} at various timescales

In Alexandra (Figure 17), the hourly (Box B) graph shows the bi-modal PM_{10} peaks common to many towns with solid-fuel domestic heating as the main source of emissions. Afternoon concentrations begin to increase at about 4pm and remain high until midnight. From then, PM_{10} levels decrease through the early morning hours until they begin to rise again around 7am, leading to a morning 'peak.' This pattern is reproduced every day of the week (Panel A).

The morning 'peak' appears in most New Zealand centres. Recent research (Ancelet, 2014) in Alexandra indicates that changes in the atmosphere lead to a 'dip' in PM_{10} from midnight to around 6am. From his 4-point monitoring programme, Ancelet postulated that katabatic winds from the north during the early morning hours help to disperse pollutants built up over the evening. He also suggests that the height of the inversion layer may be increasing during the early morning hours, leading to lower concentrations.

[4] April and September are considered 'shoulder' months to the winter air-quality season and, therefore, were not used in the computation of baseline PM_{10}.

Source apportionment work performed for the Ancelet study confirmed that biomass sources (wood and coal) make up about 90% of the PM_{10} collected during the morning and evening peaks. Throughout the day, other sources include crustal matter (up to 12%) and marine aerosol (1%), which comes from the Southern Ocean during periods of high wind.

Seasonally, PM_{10} levels peak in July with a monthly mean of 56 µg/m^3 (Box C), driven by high emissions and very cold and stable weather conditions that occur during the month. On a weekly basis, Fridays and Saturdays generally have the highest average daily PM_{10} (Box D).

These patterns are similar to those found in the other monitored Central Otago towns of Arrowtown, Clyde and Cromwell and are representative of towns with a reliance on solid-fuel heating and strong-temperature inversions inhibiting dispersal of those emissions.

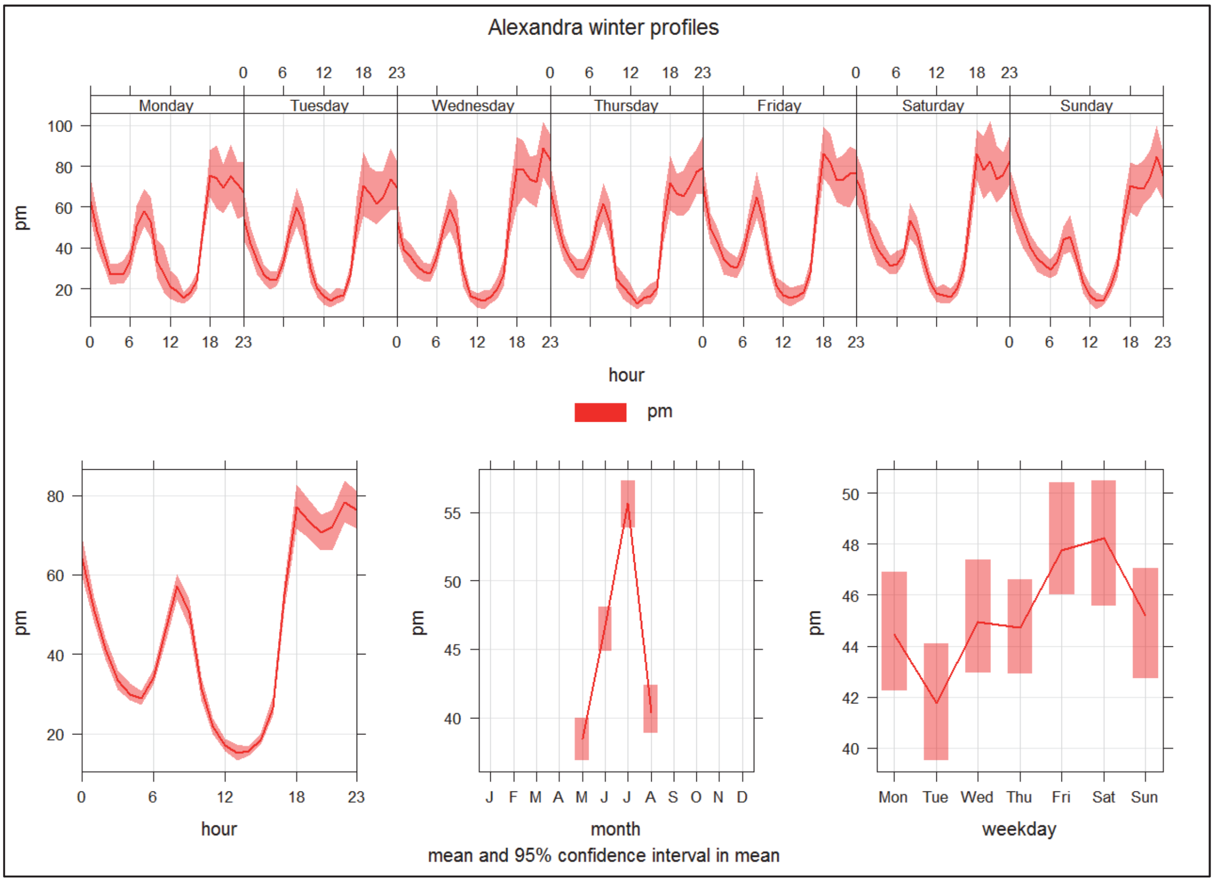

Figure 17. Temporal patterns of PM_{10} in Alexandra during winter months

5.2.3.2 Dunedin

Temporal winter PM_{10} patterns in Dunedin (Figure 18) reveal a different ambient air quality ‘signature’ than that seen in Central Otago towns. Wintertime PM_{10} concentrations do rise in the mornings (A) as they do in Alexandra but, instead of dipping down in the afternoon, they remain relatively constant throughout the day, decreasing through the evening. Additionally, the weekly graph (D) indicates that PM_{10} is significantly lower on Sundays than during the rest of the week.

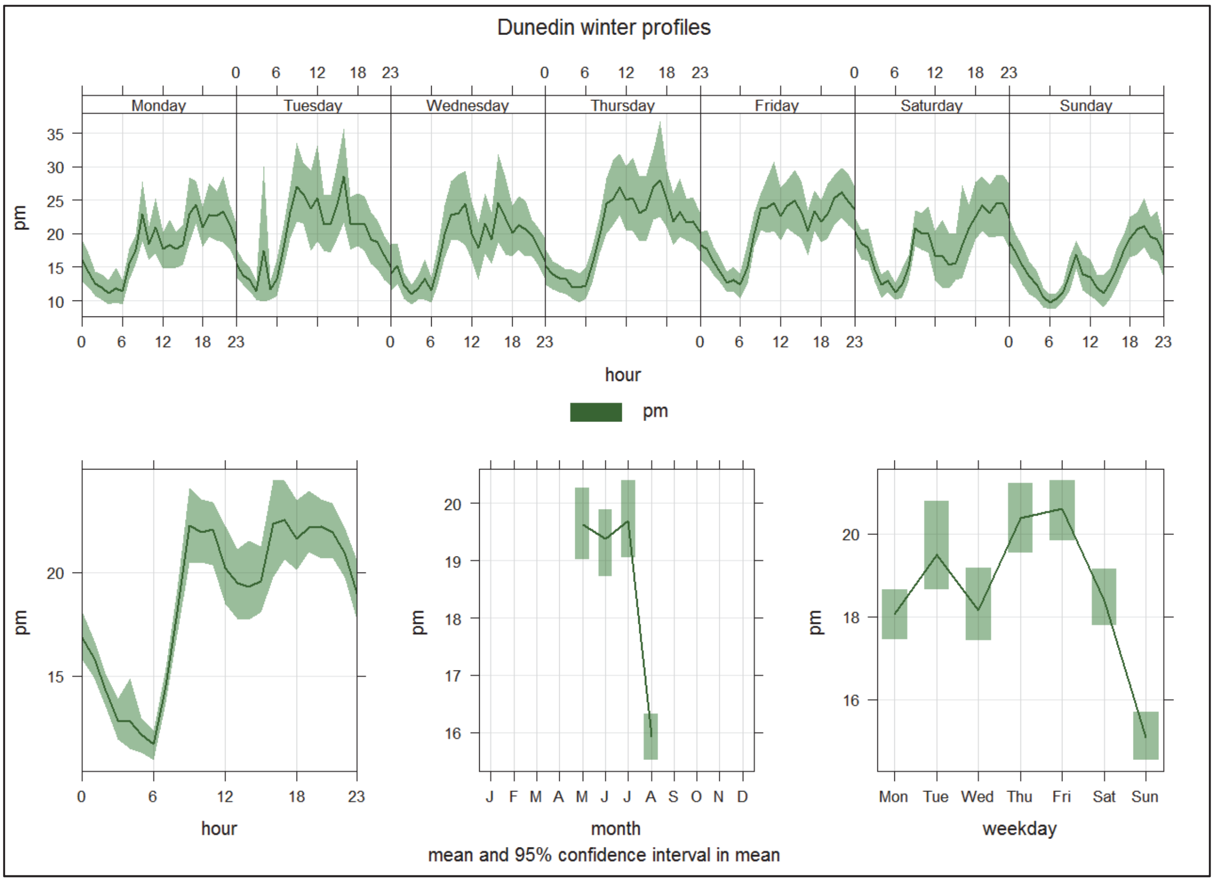

Figure 18. PM_{10} patterns in Dunedin during winter months (May-August)

The combination of these two temporal patterns is indicative of a mix of emission sources, including industrial, vehicular and commercial emissions, as well as solid-fuel heating. A source apportionment study (Davie *et al*., 2011) revealed six primary contributors to PM_{10} in Central Dunedin (Figure 19). By far the largest contributors at the time were soils and construction sources (29% and 20%, respectively). At the time of the study, particulates generated by a major construction project nearby heavily influenced these PM results.

In terms of $PM_{2.5}$, the primary contributors are:

- biomass burning 41%
- motor vehicles 29%
- sulphate 18%
- marine aerosol 12%.

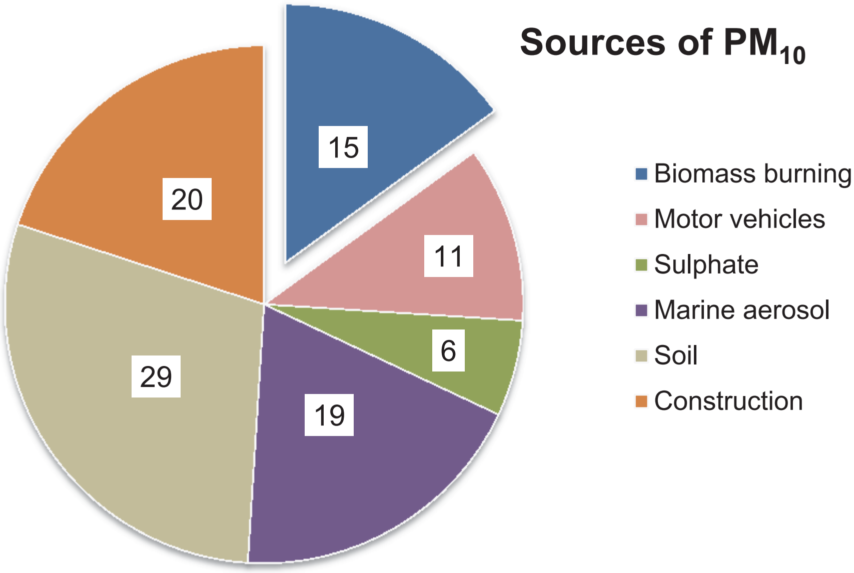

Figure 19. Percentages of the primary sources contributing to PM_{10} in Central Dunedin

Seasonally, May, June and July monthly averages are similar (19.5 µg/m^3) and only slightly higher than the August average of 16 µg/m^3 (refer to Figure 18).

5.2.3.3 Mosgiel

The temporal plots of PM_{10} in Mosgiel (Figure 20) combine elements of the Alexandra and Dunedin patterns. There is a definite bi-modal hourly pattern (B) signifying solid-fuel heating as a major source of emissions, but low PM_{10} on Sundays (D) indicate that industrial/commercial sources may be significant as well.

The monthly average PM_{10} is highest in June (32 µg/m^3) and significantly lower in other winter months.

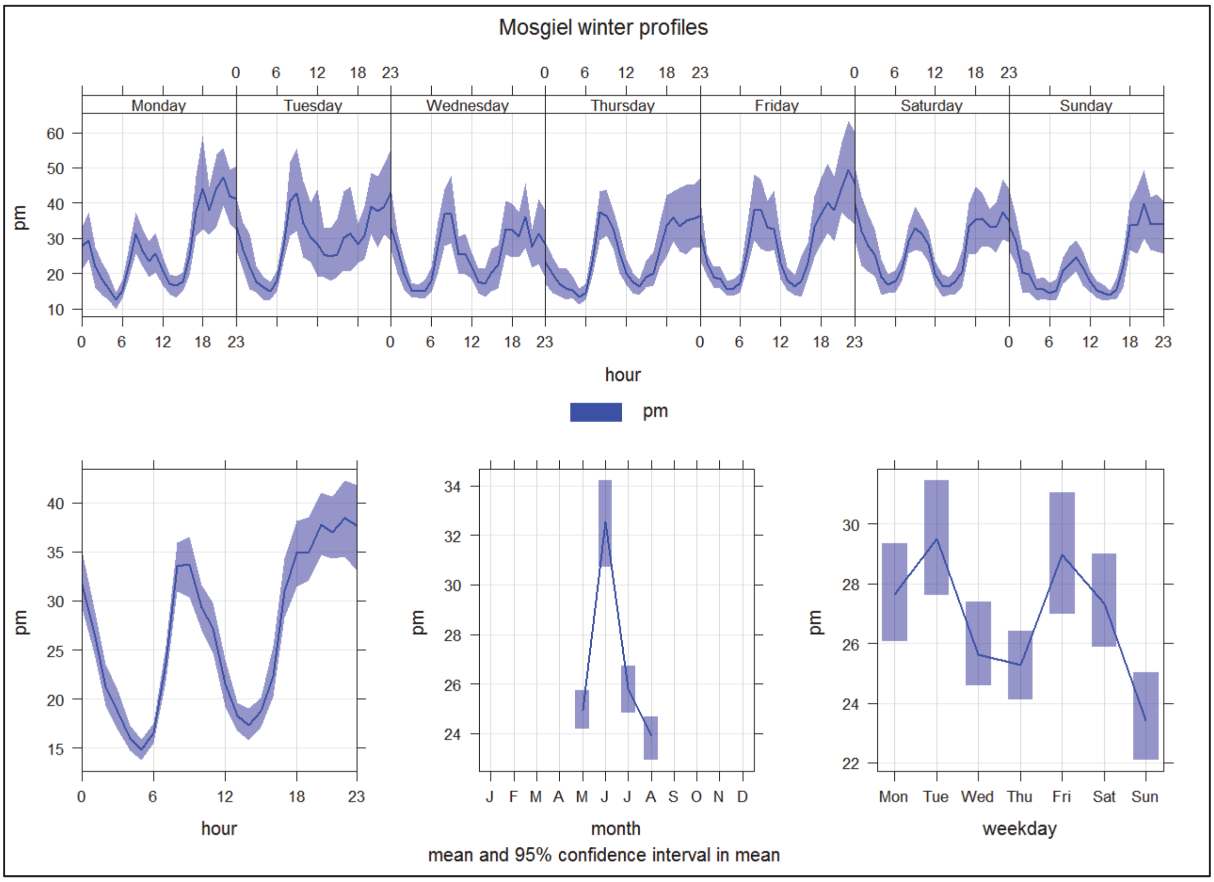

Figure 20. **PM_{10} patterns in Mosgiel during winter months (May-August)**

5.2.4 Relationship to NESAQ standards and WHO guidelines

Average annual PM_{10} concentrations and the average annual number of NESAQ exceedances are shown in Table 11. Dunedin and Mosgiel both meet the WHO annual average PM_{10} guideline of 20 µg/m^3. Alexandra, due to its high winter PM_{10} values, does not meet the WHO annual guideline.

Table 11. **Average number of days that exceed the NESAQ in gazetted airsheds (2012-2014)**

Site	MfE airshed designation	Average number of exceedances per year
Alexandra	1	46
Mosgiel	2	6
Dunedin	3	<1

These three gazetted airsheds are currently designated as ‘polluted’ by the MfE, a determination made in 2011 based on each airshed’s average number of exceedances from 2006-2011.

Two NESAQ compliance target dates (2016 and 2020) with allowable number of exceedances for each year were set, depending on which exceedance category was applicable to the five-year average. Table 12 indicates the current compliance date for each of the three airsheds.

Table 12. Airsheds and their NESAQ compliance targets

Location	Airshed	Average # of exceedances (2006-2011)	Exceedance category	Compliance targets (allowable exceedances per year)
Alexandra	1	48	10 or more	3 by 2016; 1 by 2010
Dunedin	3	11	10 or more	3 by 2016; 1 by 2020
Mosgiel	2	9	2 to 10	1 by 2016

Once designated as polluted, five consecutive years of compliance with the NESAQ (no more than one exceedance per year) are required to attain a classification of 'non-polluted'. Dunedin has now met this criterion for three consecutive years.

5.3 Survey sites

Five survey sites focus on seasonal air quality and capture PM_{10} data during winter months (May-August) only. The survey sites include: Arrowtown, Clyde, Cromwell, Balclutha and Milton, with periods of record ranging from six to eight winters.

The distribution of PM_{10} measured over three winters (2012-2014) is shown in Figure 21.

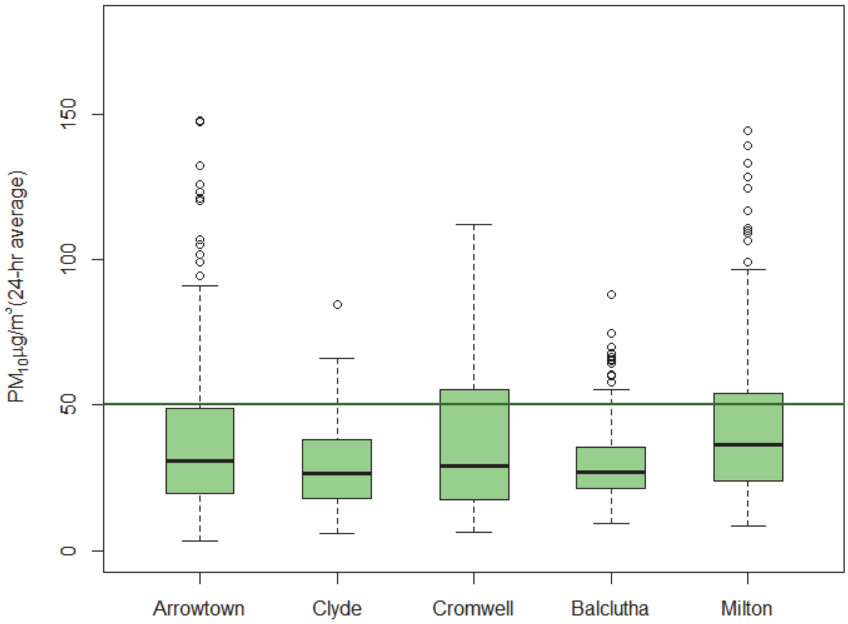

Figure 21. Distribution of winter PM_{10} concentrations at survey sites (2012-2014)

All survey sites experience multiple days when average daily PM_{10} concentrations are higher than the threshold concentration set in the NESAQ. Arrowtown, Cromwell and Milton have the highest frequency of days breaching the limit.

Arrowtown and Milton also typically record the highest-daily values with maximums of 148 μg/m^3 and 144 μg/m^3, respectively. Winter averages range from 29 μg/m^3 in Clyde to 55 μg/m^3 in Arrowtown. Milton is currently in Air Zone 2, a category set in 2007 based on limited monitoring at the time.

The three-year aggregate dataset for Arrowtown includes data from two different sites due to the monitor being re-located for the 2014 season. The new, current site indicated higher PM_{10} readings than those measured at the previous site.

5.4 Screening sites

PM_{10} monitors have operated in numerous other centres around Otago for short-term monitoring campaigns in order to understand the magnitude of PM_{10} concentrations. These monitors have been deployed for one-to-two winters at each site at some point during the last ten years. Screening sites include Lawrence, Oamaru, Palmerston, Naseby, Ranfurly and Roxburgh.

The distribution of winter PM_{10} concentrations (Figure 22) shows that, in all instances, PM_{10} levels are significantly lower in the screening sites than in the key indicator or survey sites. Of the six sites, only Lawrence and Oamaru breached the NESAQ standards for PM_{10} during the monitored winters; the other sites did not.

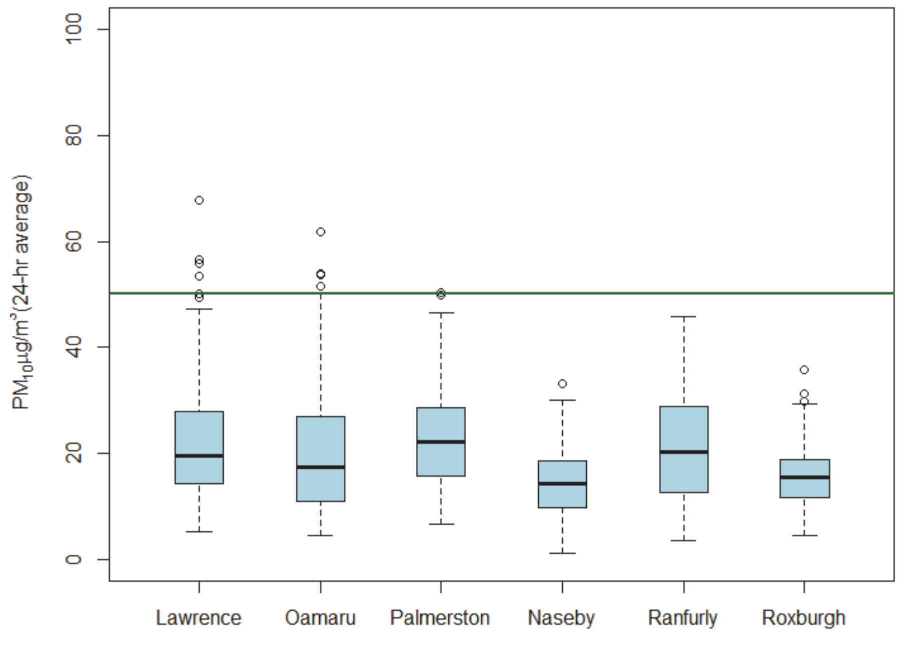

Figure 22. Winter distribution of PM_{10} concentrations at screening sites throughout Otago

With the exception of Oamaru, these are all relatively small communities with emissions of less than about 50 kg PM_{10} per winter day. Even though air quality is generally considered good in these towns, there are times during winter days – both morning and evening – when PM_{10} becomes elevated (Table 13).

Table 13. Maximum one-hour PM_{10} recorded at screening sites

Town	Maximum 1-hour PM_{10} concentration ($\mu g/m^3$)	Time of day
Lawrence	420	10 am
Oamaru	189	7 pm
Palmerston	141	10 am
Naseby	84	5 pm
Ranfurly	150	5 pm
Roxburgh	90	11 pm

6. Temporal and spatial trends in ambient air quality

Changes in a town's air quality can result from a number of factors, including:

- regulatory requirements for home-heating options
- change in way solid-fuel burners are used
- fuel choices
- addition or removal of particular point sources of emissions
- natural year-to-year variability in weather patterns, particularly as they affect atmospheric stability.

Statistical testing of consistent, long-term, ambient air quality data can be used to ascertain the effectiveness of policies on emissions. Statistical hypothesis testing provides a '*p*-value' that represents the probability that random chance could explain a change in ambient air quality levels. A *p*-value of 0.10 suggests that we are 90% confident that the changes observed in PM_{10} are not due to chance alone.

For this report, trend analyses were performed at sites having at least five years of record. These sites include the three year-round, key indicator sites (Alexandra, Dunedin and Mosgiel) and the five winter-survey sites (Arrowtown, Clyde, Cromwell, Balclutha and Milton).

6.1 Trend-analysis techniques

Trends were evaluated using a variety of statistical techniques. A TheilSen approach, customised for analysing air quality data (Carslaw & Ropkins, 2012), was performed to determine statistical significant of any changes in PM_{10}. TheilSen analyses work best when applied to monotonic trends (i.e. straight-line trends upwards or downwards) and have a more limited value when applied to highly seasonal data. To minimise that limitation, monthly means were de-seasonalised where necessary. Where results are statistically significant, they are discussed in the following sections.

A smoothed-trend technique, using monthly mean values of the 50^{th} and 95^{th} percentile values, was also applied. The smoothed trend analysis fits a smooth line to the dataset using monthly mean concentrations and shows the 95% confidence interval around the line. The line is fit to show important features and real variation in the data without including excessive 'noise' found in the dataset (Carslaw *et al*., 2014).

Annual box plots of daily PM_{10} during winter months show the change of PM10 distribution from year to year. A full set of plots is shown in Appendix 2 (Annual box plots of wintertime PM_{10} distribution).

6.2 Key indicator site trend results

These sites have the longest, continuous datasets in the Otago air quality monitoring network. For each site, a TheilSen analysis was performed over the entire year-round data, as well as on the winter (June – August) data only. In Alexandra, where numerous breaches of the NESAQ occur each winter, a trend analysis was also applied to the PM_{10} values on only those days exceeding the standard.

Results of the TheilSen analyses showing percent change in PM_{10} per year are given in Table 14, along with the statistical significance of the result.

Table 14. TheilSen analysis results of PM_{10} means at key indicator sites

Site	Period of record	PM_{10} value evaluated	Percent change per year	Statistical significance
Alexandra	2005-2014	Year-round	+1.1	Not significant
		Winter	-0.5	Not significant
		Exceedance values	-0.7	*p<0.1*
Dunedin	2006-2014	Year-round	-1.9	Not significant
		Winter	-2.5	$p<0.1$
Mosgiel	2005-2014	Year-round	+3.4	$p<0.01$
		Winter	+3.0	$p<0.1$

6.2.1 Alexandra

There has been a statistically significant decrease in PM_{10} values in Alexandra on those days that exceed the NESAQ. On average, the monthly means of the exceedance values have decreased about 0.7% each year. Over nine years, the decrease is just over 6%. Despite this lowering of the highest PM_{10} values, neither the year-round nor the wintertime trend in PM_{10} is statistically significant over the period of record.

The smoothed trend analysis (Figure 23) on the year-round data shows the variability in PM_{10} over time, particularly for values in the 95th percentile range. From the graph, it is apparent that 2008 was prominent in terms of PM_{10} levels.

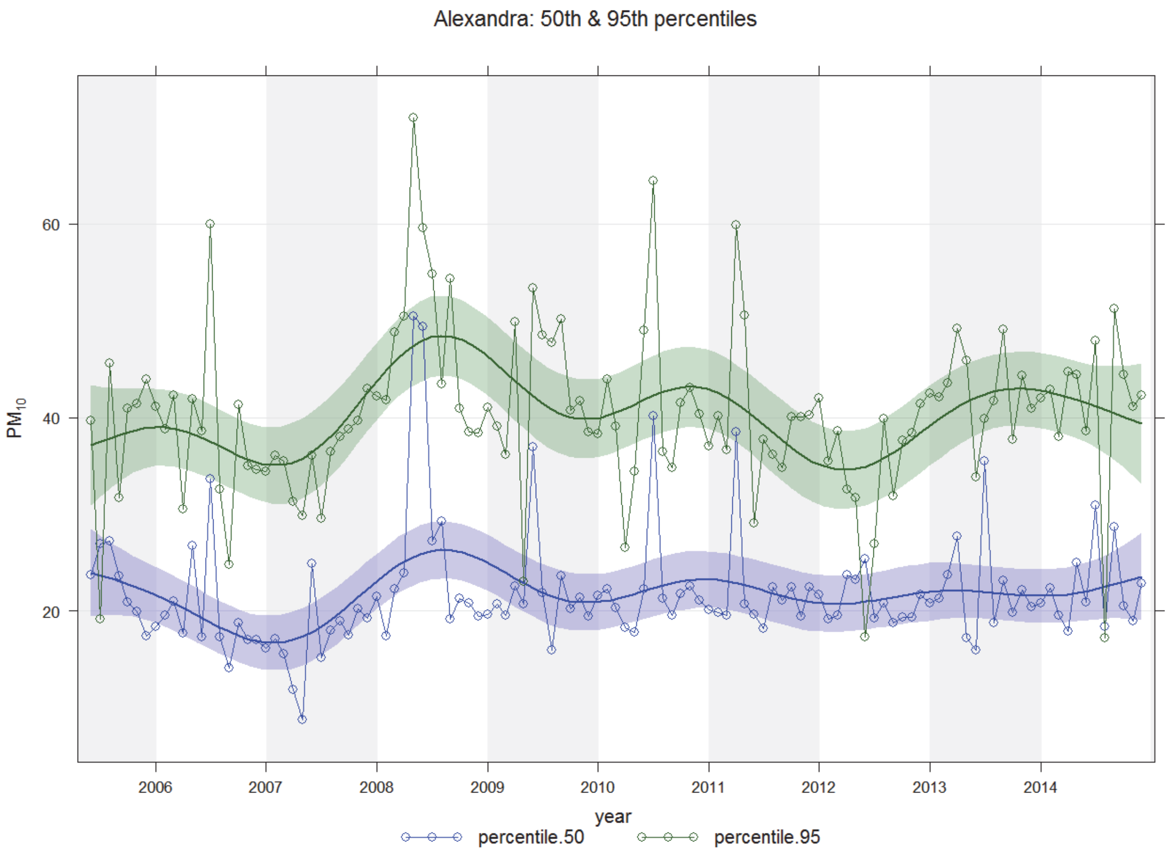

Figure 23. Smoothed trend analysis for Alexandra's PM_{10} concentrations

Daily weather and seasonal climate patterns are strong determinants for ambient air quality, particularly in Alexandra. A trend analysis has been developed to examine PM_{10} levels, giving consideration to the influence of winter weather.

For this analysis, common weather elements were identified for days that exceeded the NESAQ standard for PM_{10}[5]. The weather on those days was calm, with clear skies, and cold overnight temperatures. A typical synoptic condition that produces such conditions is shown in Figure 24.

[5] This work was done using 2006 data before any significant reductions in emissions, due to ORC's air-quality strategy of burner replacement, were anticipated.

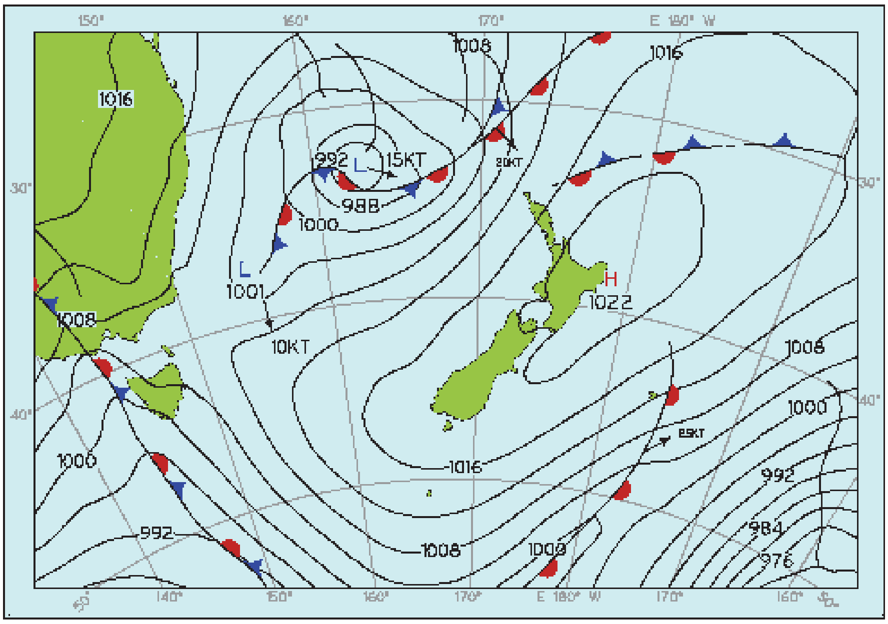

Figure 24. Winter synoptic weather events that result in clear, calm and cold conditions

Conditions during these periods lead to overnight temperature inversions and minimal dispersion, resulting in what can be termed 'high-pollution-potential' (HPP) days. HPP days can be simulated using a few key meteorological variables (Table 15), making this model more physically based than other purely statistical relationships.

Table 15. Meteorological conditions necessary for a HPP day

Parameter	Condition
Minimum daily temperature	< 0.0 degrees
Temperature range	> 7.0 degrees
Average wind speed	< 1.0 metre/second
Maximum hourly wind speed	< 2.0m/s

Tracking the numbers of HPP days and their PM_{10} characteristics from one year to the next may give an indication of whether or not air quality is improving due to changes in emissions. Indications of improving air quality are:

- reduction in the number of *measured* exceedances versus the *predicted* number of exceedances (HPP days)
- reduction in the PM_{10} average of the HPP day subset
- lowering of the upper range of PM_{10} values of the HPP day subset.

Table 16 shows the number of days when exceedances of the NESAQ are predicted versus the number of days when exceedances were measured. It appears that there was some improvement in air quality, given the weather, between 2009 and 2012; however, that trend was broken in 2013 when more high-pollution days were measured than expected. This analysis corroborates the ThielSen trend results, in that a significant trend is not yet apparent in the data. It also illustrates the inter-annual variability that occurs in both PM_{10} and the weather.

Table 16. Number of predicted versus actual days exceeding the NESAQ in Alexandra

Year	Number of predicted exceedances	Number of actual exceedances
2006	50	45
2007	37	33
2008	63	70
2009	44	37
2010	61	51
2011	51	39
2012	64	40
2013	40	47
2014	60	48

An annual summary of PM_{10} characteristics for the subset of HPP days (Figure 25) indicates a slight downward trend in average PM_{10} on those days from 2008-2012. There was a concurrent decrease in the average of the highest ten days each year during those years. After 2012, PM_{10} averages appear to have plateaued.

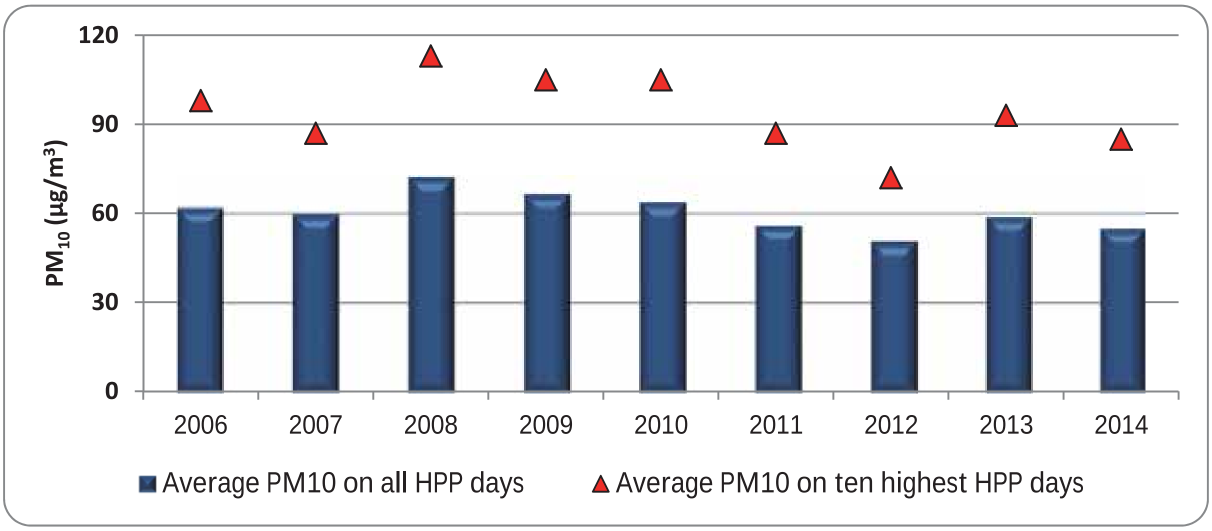

Figure 25. PM_{10} characteristics on HPP days

6.2.2 Dunedin

According to the TheilSen results, there has been a statistically significant decrease in particulate levels in Dunedin over the last ten years. On average, PM_{10} levels have declined 2.5% per year, from 26.3 µg/m^3 in 2006 to 17.3 µg/m^3 in 2014. This trend has probably had the indirect effect of reducing the number of annual exceedances of the NESAQ to zero in the last two years.

The smoothed trend of the 95th percentile (Figure 26) shows a fairly sharp decrease from 2011 to 2013 and a corresponding but smoother decrease in the 50th percentile values. According to the 2011 source apportionment study, PM_{10} was dominated by particulates in the coarse fraction (i.e. crustal matter, construction-related materials and marine aerosols). The highest values occurred during calm conditions and were probably caused by the entrainment of road dust generated by vehicle movements near to the monitoring site. Major construction activity near the monitoring site throughout most of 2011 was the source of increased truck and vehicle movements and the presence of crustal material.

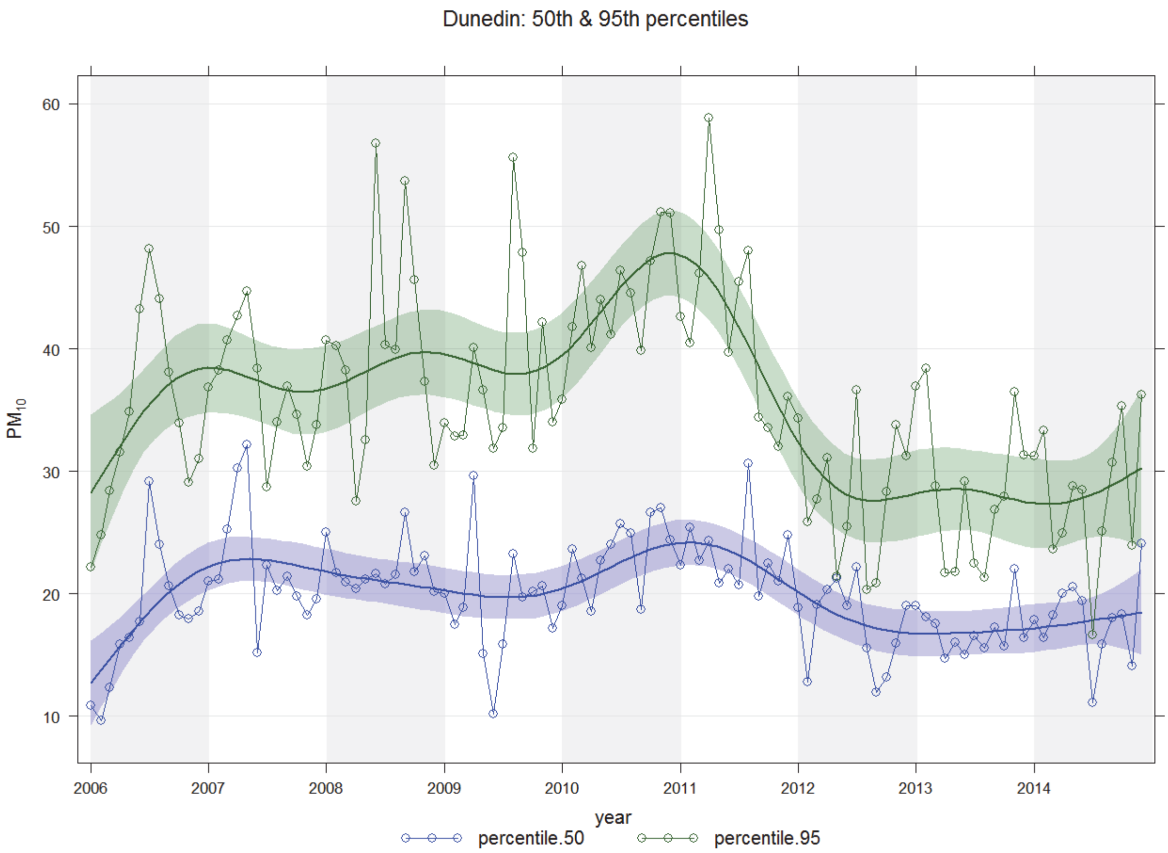

Figure 26. Smoothed trend analysis of PM_{10} concentrations: Central Dunedin

6.2.3 Mosgiel

Mosgiel has the strongest statistical trend of the three sites, an *increase* in PM_{10} levels of 3.4% per annum. This equates to an increase of just over 0.5 μg/m^3 each year, and brings this past year's annual PM_{10} average to 20 μg/m^3.

Though some of the increase is driven by a 3% increase per annum in wintertime values, a seasonal TheilSen analysis reveals strong upward trends exist in spring (+6.4% per year, p<0.001) and summer months (+9.2% per year, p<0.05). The implication of this result is that sources of PM_{10} other than solid-fuel burners are becoming more significant in the airshed.

The smoothed trend (Figure 27) shows relatively little variability in the 50th percentile values. The dip seen in the trend line during 2012 may be artificial due to the interpolation of data by the smoothed trend function to account for the missing data during the year.

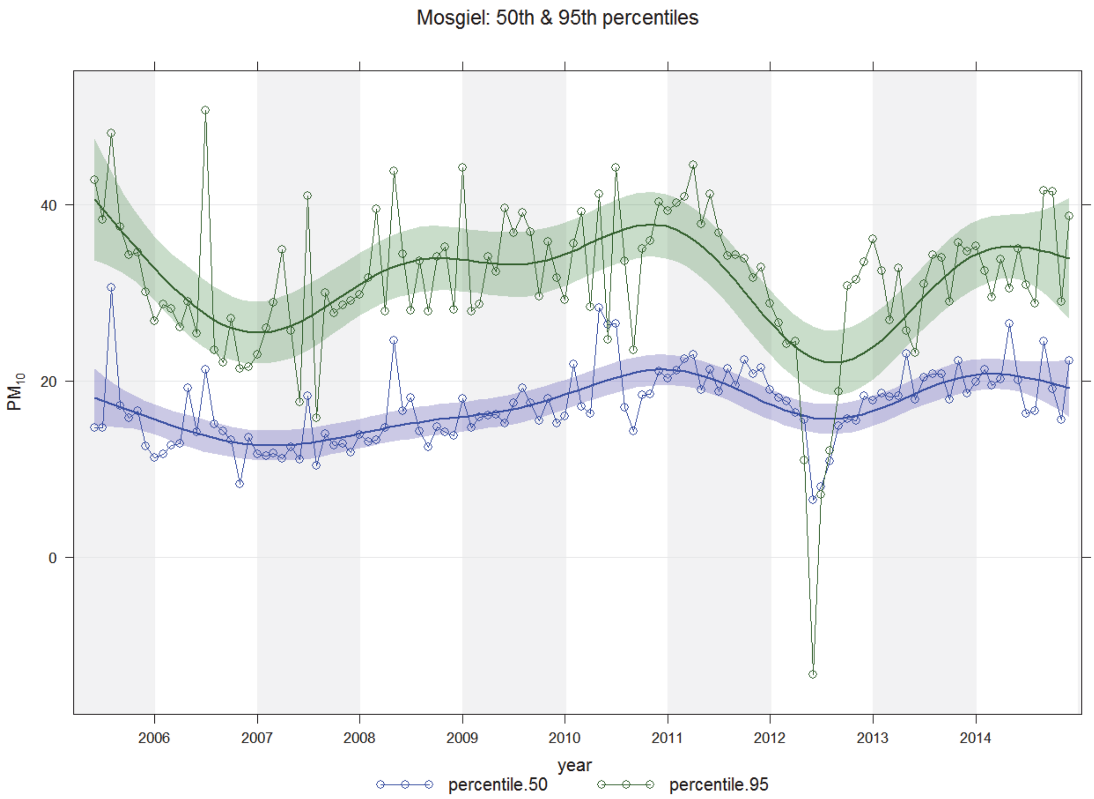

Figure 27. Smoothed trend analysis of PM_{10} concentrations: Mosgiel

6.3 Survey site results

Statistically significant downward trends have been reported for wintertime PM_{10} levels in Dunedin, Clyde and Arrowtown, with varying degrees of certainty. Table 17 gives the annual percent change in PM_{10} means and the statistical significance for each result.

Table 17. TheilSen trend analysis results of PM_{10} means at survey sites

Site	Period of record	PM_{10} values evaluated	Percent change per year	Statistical significance
Arrowtown (all years)	2006-2014	Winter	-2.5	*p*<0.01
		Exceedance values	+1.1	Not significant
Arrowtown (original site)	2006-2013	Winter	-4.0	*p*<0.001
		Exceedance values	-1.5	Not significant
Clyde	2008-2014	Winter	-3.1	*p*<0.1
		Exceedance values	-3.0	*p*<0.001
Cromwell	2008-2014	Winter	+3.1	*p*<0.1
		Exceedance values	-0.5	Not significant
Balclutha	2009-2014	Winter	+5.0	Not significant
Milton	2008-2014	Winter	-1.2	Not significant
		Exceedance values	-0.2	Not significant

6.3.1 Arrowtown

Two datasets were developed for Arrowtown; the first contains data collected at the original site at Cotter Avenue (2006-2013), and the second (2006-2014) includes the 2014 data with the monitor at its new location at the Queenstown-Lakes District pump station, about 400 metres east of its original position. Due to time constraints, no co-location study linking the two sites was possible.

A downward winter trend of -2.5% per annum ($p<0.01$) is reported over the entire dataset. Before the monitor's re-location for the 2014 season, a statistically significant downward trend of -4.0% ($p<0.001$) is found in the data. Any change in exceedance values is not statistically significant.

The smoothed trend (Figure 28) in the 95th percentile range evaluated over the entire dataset does show a downward sloping trend from 2007-2013; however, the 2014 results from the monitor's new location were much higher than those reported in previous years, serving to pull the trend upwards.

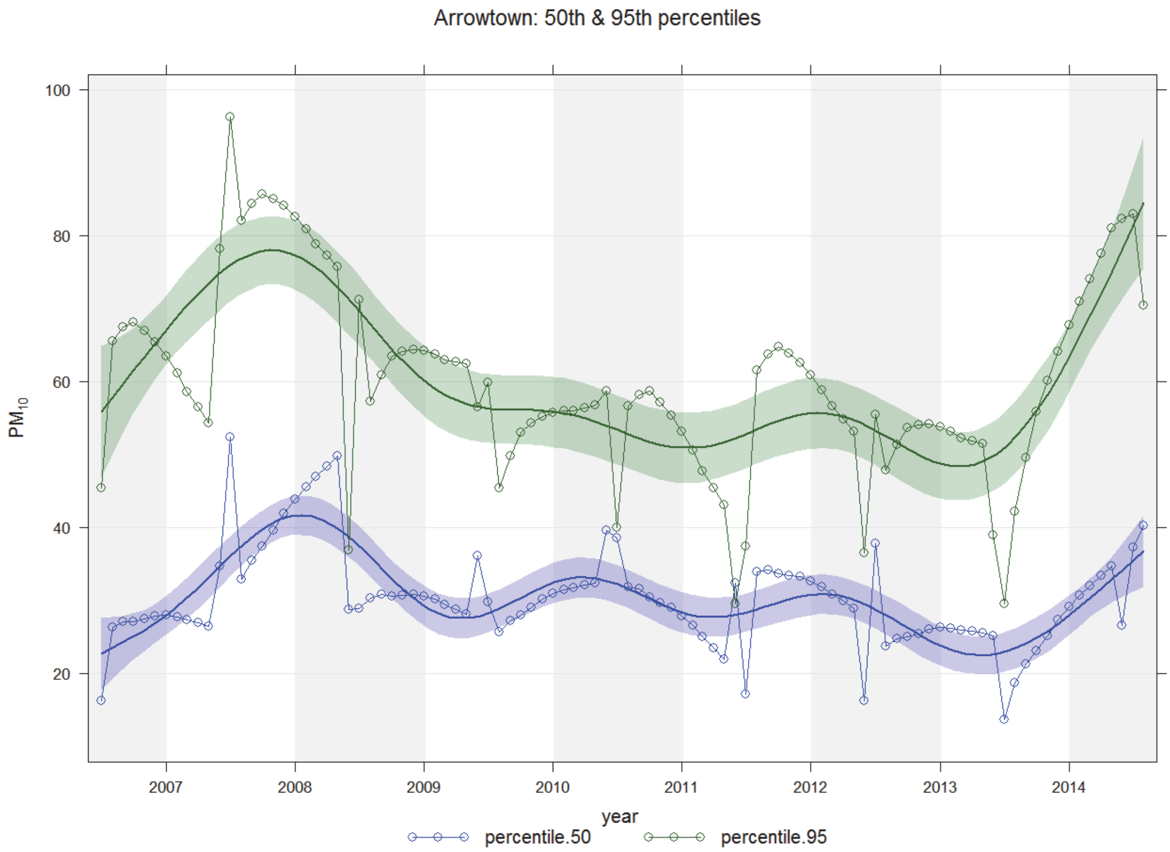

Figure 28. Smoothed trend analysis of PM_{10} concentrations: Arrowtown

6.3.2 Clyde and Cromwell

Clyde and Cromwell have shown very different PM_{10} trends since 2008, with concentrations decreasing in Clyde and increasing in Cromwell.

In Clyde, a downward annual trend of -3.1% in wintertime PM_{10} has resulted in winter means decreasing to about 34 µg/m^3. Exceedance values have also decreased over the monitoring timeframe by about -3% each year.

Results of the smoothed trend analysis (Figure 29) show a marked decrease in the upper 95th percentile monthly means, which has probably led to the reduction in the number of days exceeding the NESAQ.

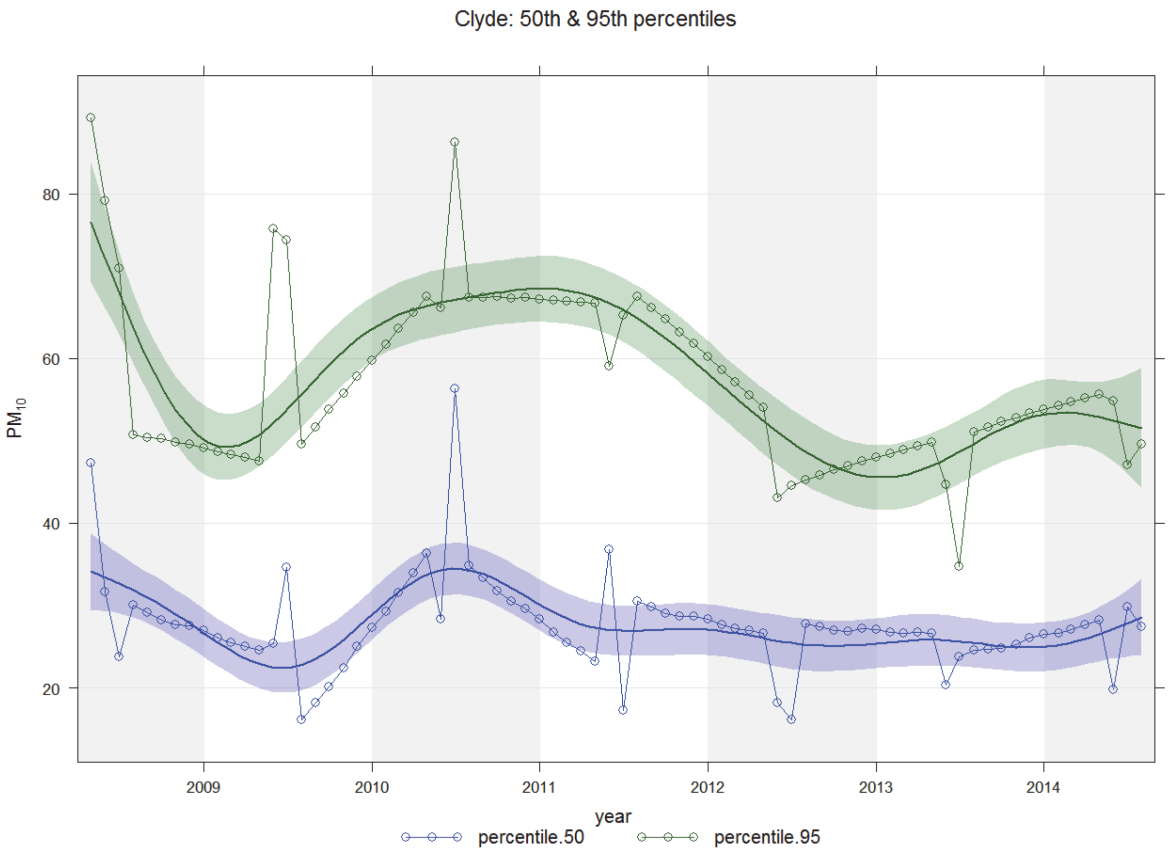

Figure 29. Smoothed trend analysis of PM_{10} concentrations: Clyde

Cromwell's winter PM_{10} levels (Figure 30) show an overall upward trend, increasing about +3% each year from 2008 to 2014. The smoothed trend reveals increases in both the 50th and 95th percentile during 2010 and 2014.

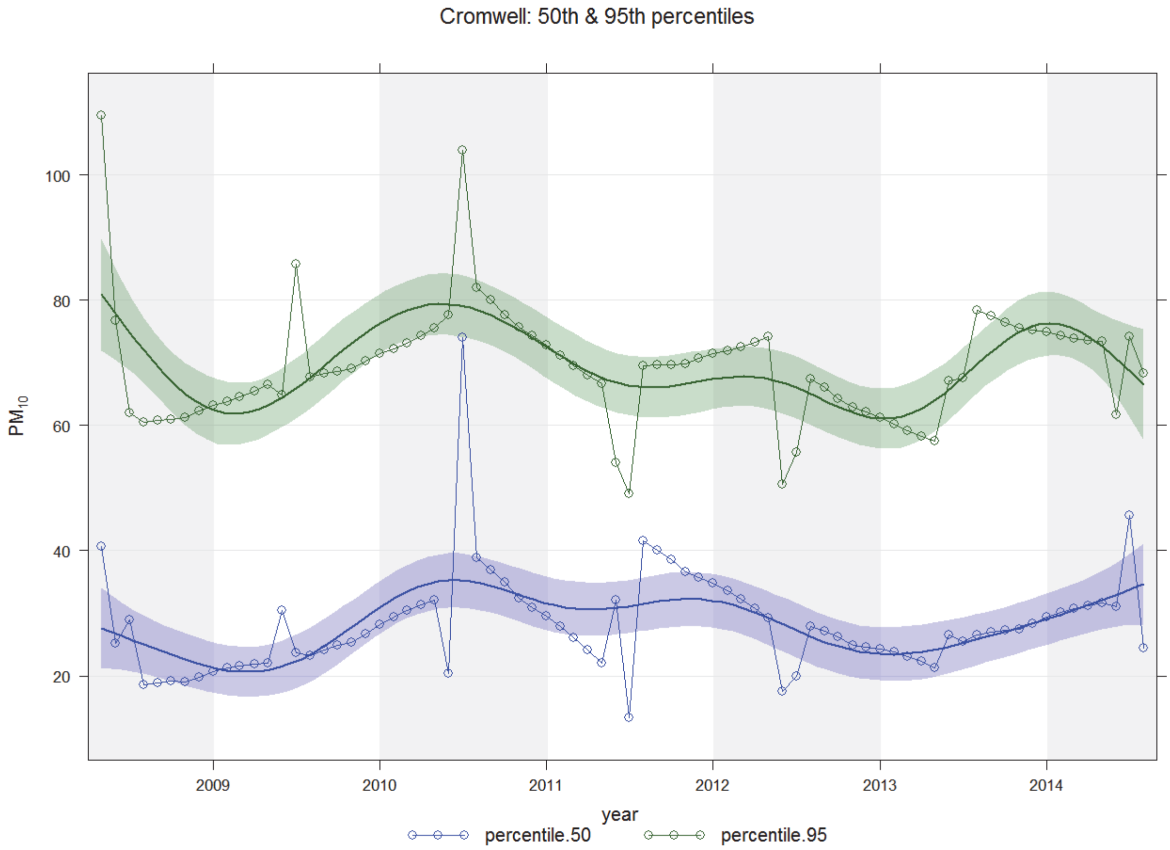

Figure 30. Smoothed trend analysis of PM_{10} concentrations: Cromwell

6.3.3 Balclutha and Milton

No statistically significant trends have been noted in either Balclutha or Milton.

The smoothed trend for Milton (Figure 31) does indicate a recent downward trend in winter monthly means; however, additional monitoring is required to evaluate whether that change is statistically significant or not.

In Balclutha's smoothed trend (Figure 32), 2012 appears as a prominent year; however, no real trend is apparent.

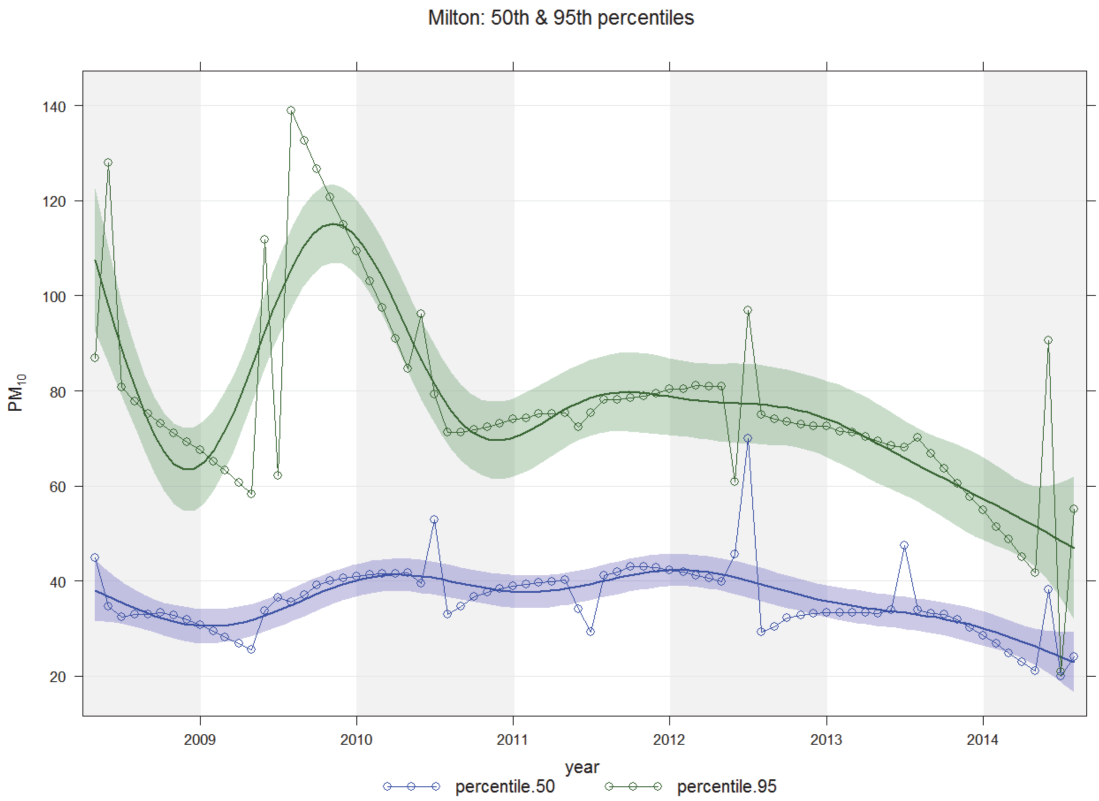

Figure 31. Smoothed trend analysis of PM_{10} concentrations: Milton

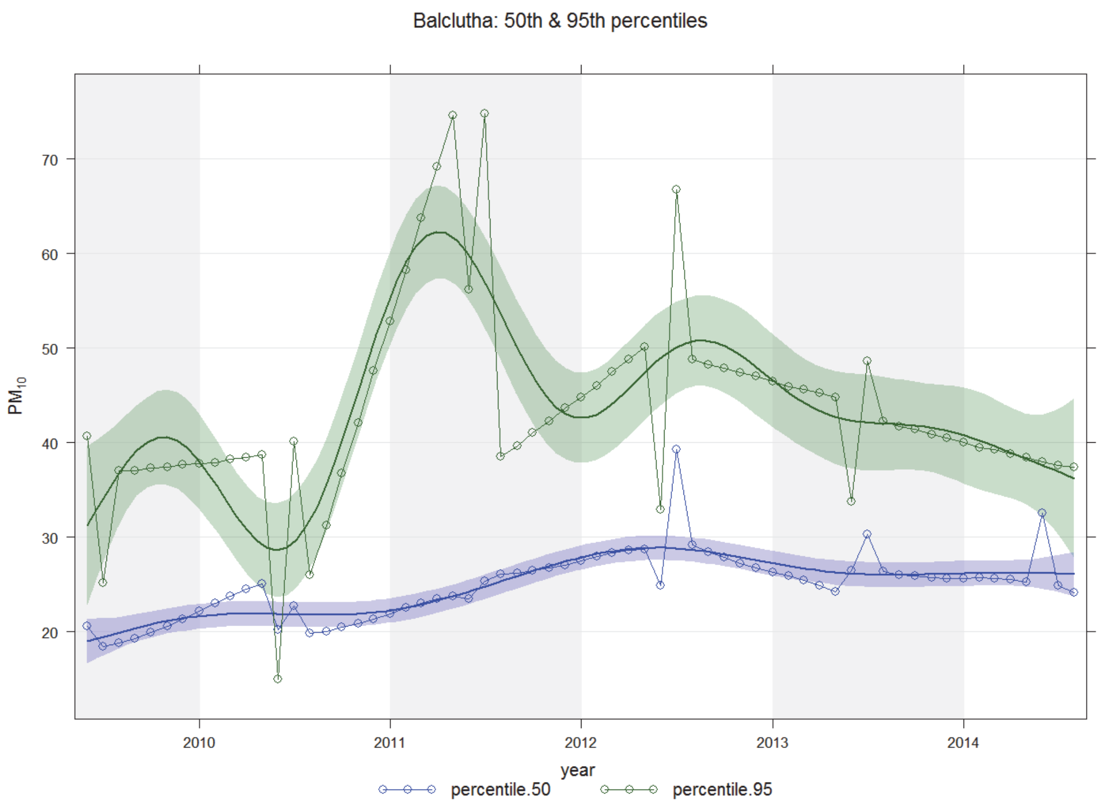

Figure 32. Smoothed trend analysis of PM_{10} concentrations: Balclutha

6.4 Spatial distribution of PM_{10}

Stationary monitors in the air quality network provide long-term PM_{10} readings at a single point in each town. Depending on the size of the town and the complexity of its terrain, results from a single monitor point may not be representative of the entire area. The NESAQ addresses this issue by requiring monitoring in what is considered to be the 'worst' part of the airshed. This is the area that has either the highest-PM_{10} levels or high-PM_{10} levels that affect the greatest number of people.

Mobile monitoring across a town using a portable air sampler offers a spatial 'snapshot' of ambient air quality. During the period 2004 to 2015, ORC has performed 11 spatial studies[6] to either 1) provide context to existing monitoring, or 2) assess relative PM_{10} levels in towns without monitors. Studies are typically performed over three to four winter days during a period when concentrations are expected to be relatively high. In each study, numerous monitoring runs of about 20-25 sampling points are performed during both morning and evening periods.

Some general conclusions can be drawn based on the studies, even though each town has its own ambient air quality 'signature.'

Ambient air quality can, at times, vary significantly from one street to the next, depending on emissions and wind conditions.

Topography can have a significant influence on particulate movement, as exhibited in Palmerston where a corridor of low-lying land through the middle of town enables particulates to move from south to north towards the lower-lying Shag River.

Particulates are often elevated where older housing is the densest. This was observed in Cromwell, with the older, central section of town generally having the highest PM_{10} levels.

Particulate movement is often influenced by nocturnal drainage winds with PM_{10} accumulating in a 'downwind' area of an airshed. This was observed in Milton, where PM_{10} is, on average, highest at the southern end of town partly the result of gentle nocturnal winds moving southwards.

1. In Balclutha, the same effect of winds on particulate transport was noticed, but with a different result. Drainage winds following the Clutha-Mata Au River help flush PM_{10} levels on the flat, central portion of Balclutha, keeping PM_{10} levels relatively low compared to the hill suburbs to the northeast and southwest of the town centre.

2. In Alexandra, the unique basin topography and meteorology combine to create a large area of nocturnal wind convergence in town, resulting in little ventilation and relatively high PM_{10} through the central part of town.

A study (NIWA, 2009) was performed in Dunedin over two weeks in winter 2009. The results of this larger scale study showed several of the elements noted above, with Dunedin's complex topography creating multiple paths of nocturnal drainage of winds. Results of the

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[6] Alexandra (2015), Arrowtown (2014), Balclutha (2011), Cromwell (2015), Dunedin (2009), Lawrence (2013), Milton (2011), Mosgiel (2009), Palmerston (2011), Queenstown (2013) and Wanaka (2014)

analysis indicated that while there is a considerable variation in air quality across Dunedin during winter days, the ORC monitor is representative of the Central Dunedin area.

These studies have added an additional dimension to the understanding of winter air quality in Otago towns by offering a ‘snapshot’ view of ambient air quality across wider spatial areas.

7. Discussion and conclusion

Air quality monitoring results over the past ten years indicate a wide range of ambient air quality throughout the region, particularly during winter months when conditions are calm and cold. Emissions from solid-fuel burners used for domestic heating are the major contributor of PM_{10} in most areas of Otago, with industry playing a role in Central Dunedin and Mosgiel.

During winter, emissions from all sources are often trapped near the ground under an inversion layer, causing PM_{10} concentrations to rise to high levels. This is particularly true in Central Otago towns and Milton, where high PM_{10} leads to numerous exceedances of the NESAQ each winter. The number of days each year that average daily PM_{10} levels have exceeded the NESAQ threshold concentration (50 $\mu g/m^3$) is listed in Table 18. A more comprehensive listing of parameters can be found in Appendix 3: Hourly air quality summaries by sites.

Table 18. Number of days when average daily PM_{10} exceeds the NESAQ

Site	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Alexandra	42	45	33	74	40	51	40	40	47	51
Mosgiel	11	8	4	9	7	8	8	n/a	5	7
Dunedin	1	6	1	9	6	12	14	1	0	0
Arrowtown		18	39	38	31	39	27	24	17	48
Clyde				37	23	40	23	9	10	22
Cromwell				31	30	43	20	30	33	49
Milton				46	33	46	20	38	42	14
Balclutha					2	2	4	13	4	3
Naseby			0							
Roxburgh			0							
Ranfurly			0	0						
Palmerston									0	0
Oamaru				3	2					
Lawrence							2	2		

Programmes to improve insulation and upgrade wood burners in these towns have resulted in over 1,000 new (MfE-compliant) appliances being installed. While this undoubtedly has led to reductions in emissions, a corresponding reduction in concentrations is not apparent in most towns. Trend analyses do show some slight reductions in PM_{10} in Clyde, Arrowtown and Alexandra, but not to the extent that was originally predicted in work done for Otago's original air quality-management strategy (ORC, 2007). To achieve compliance with the NESAQ, a more extreme reduction in emissions will be required in these areas.

In Air Zone 2 towns, such as Balclutha and Mosgiel, PM_{10} levels are still exceeding the limits deemed acceptable for human health set in the NESAQ, and there is no sign of any downward trend. Relying on the natural rate of burner replacements to improve air quality over time and achieve compliance with the NESAQ has not proven to be successful.

Central Dunedin has shown the most significant improvement in air quality over the last ten years. This is probably due to the reduction in industrial emissions that have occurred due to the pro-active approach to upgrades of coal boilers in the city. The Central Dunedin airshed has complied with the NESAQ for the past three years.

Projected emissions reductions from domestic-burner upgrades have not yielded the expected reductions in PM_{10} concentrations. Key to successful planning for future work will be to understand why that is.

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Appendix 1 Airshed and air zone boundary maps

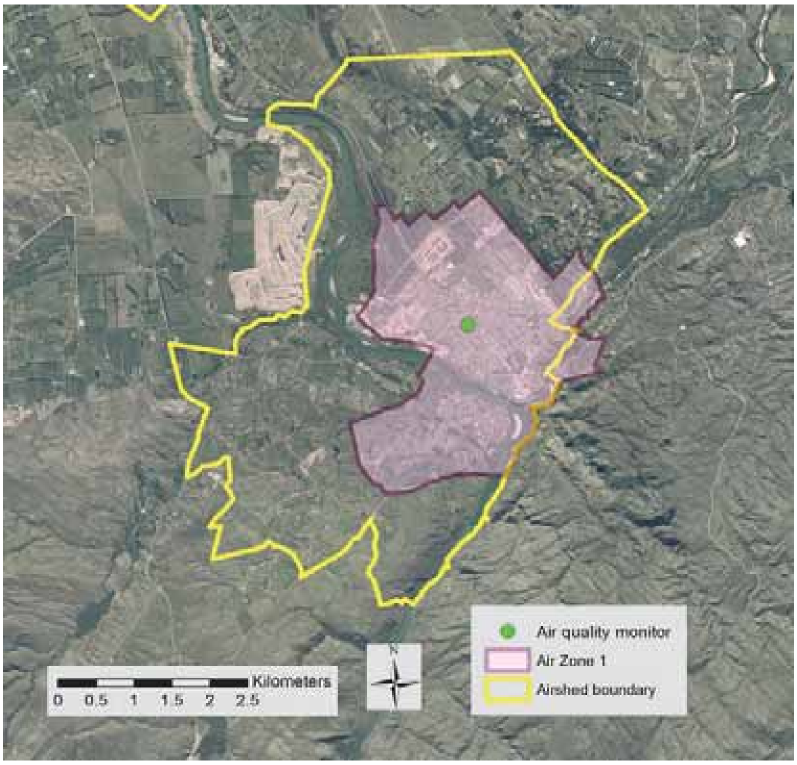


Figure 33. Alexandra airshed and air zone boundaries

Figure 34. Central Dunedin airshed and air zone boundaries

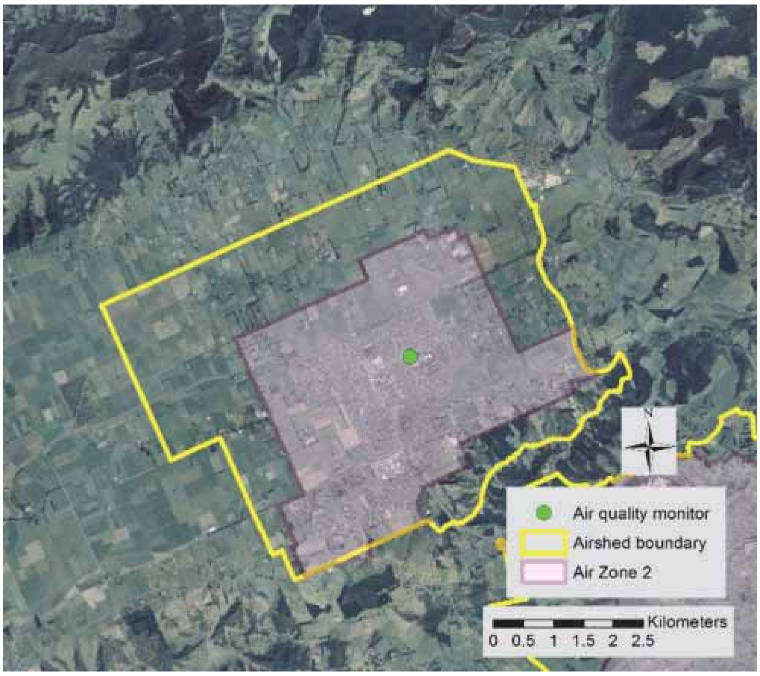


Figure 35. Mosgiel airshed and air zone boundaries

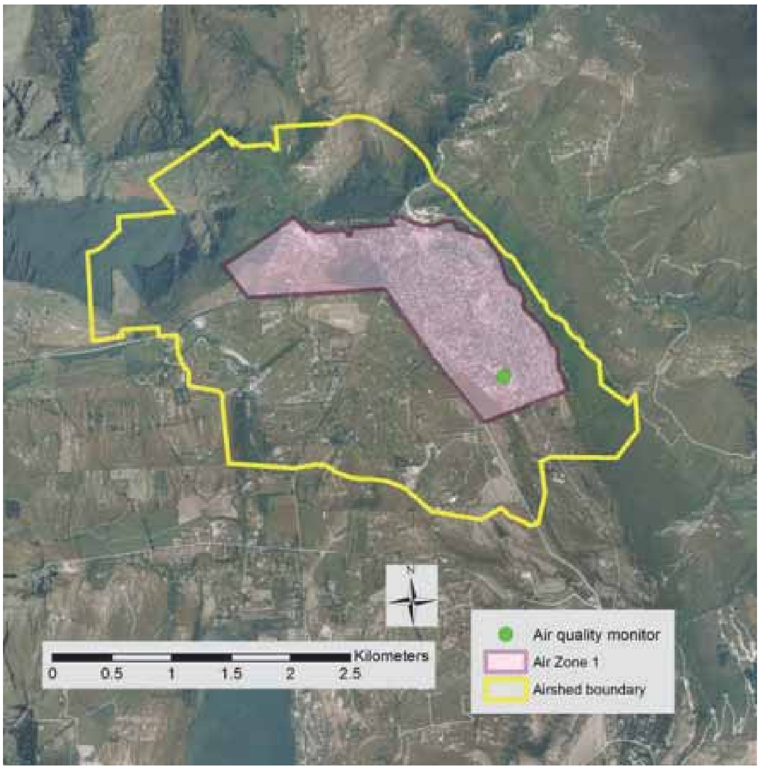


Figure 36. Arrowtown airshed and air zone boundaries

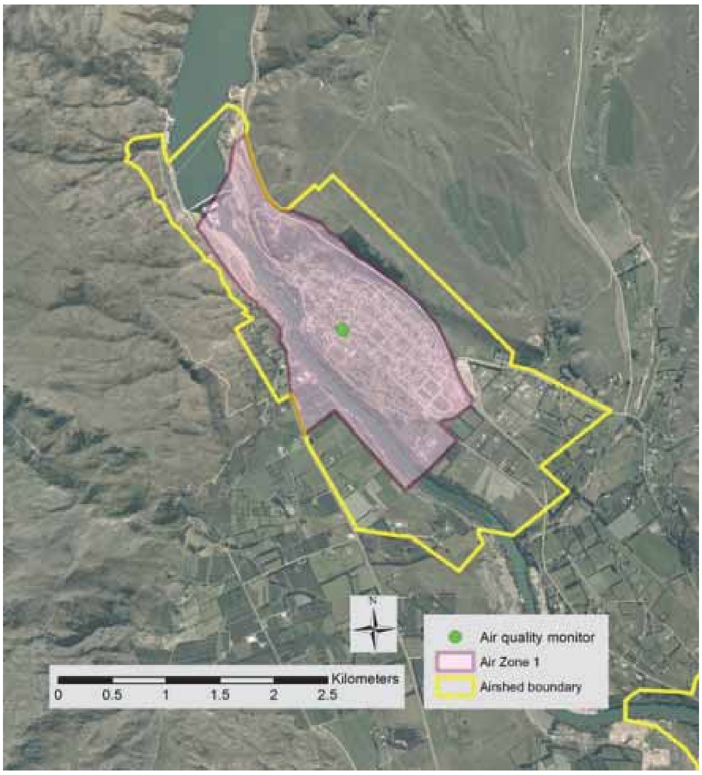


Figure 37. Clyde airshed and air zone boundaries

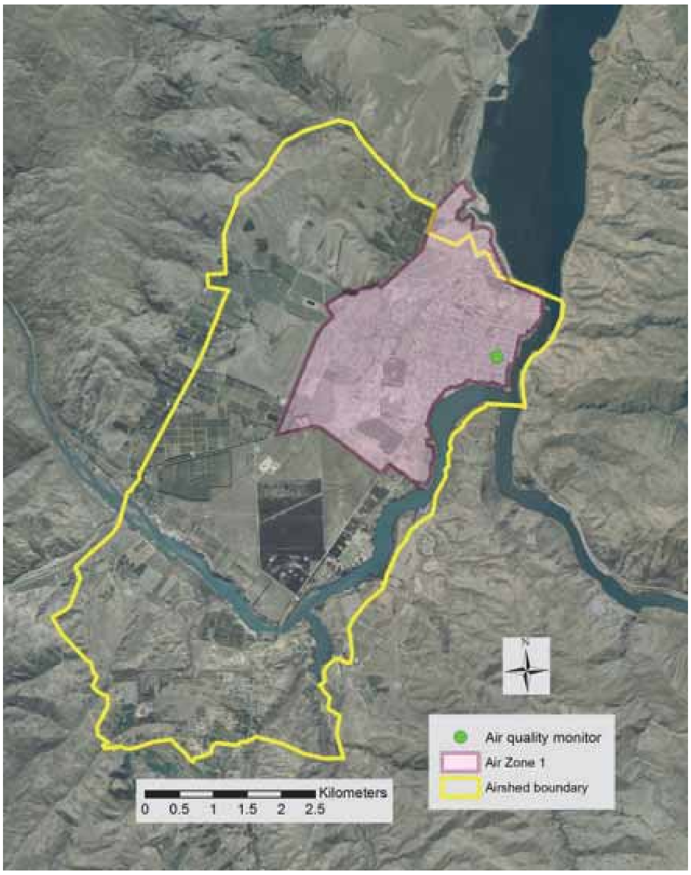


Figure 38. Cromwell airshed and air zone boundaries

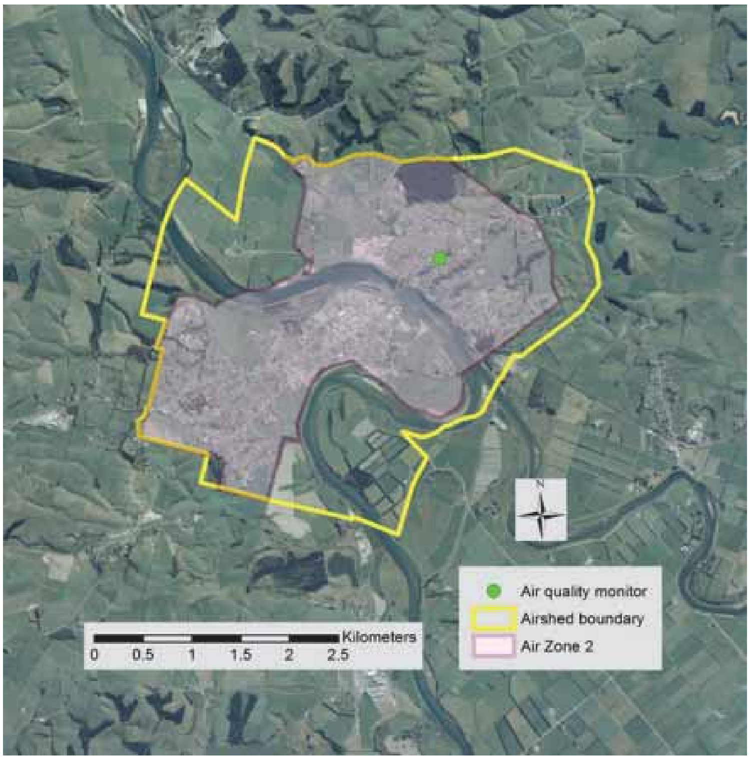


Figure 39. Balclutha airshed and air zone boundaries

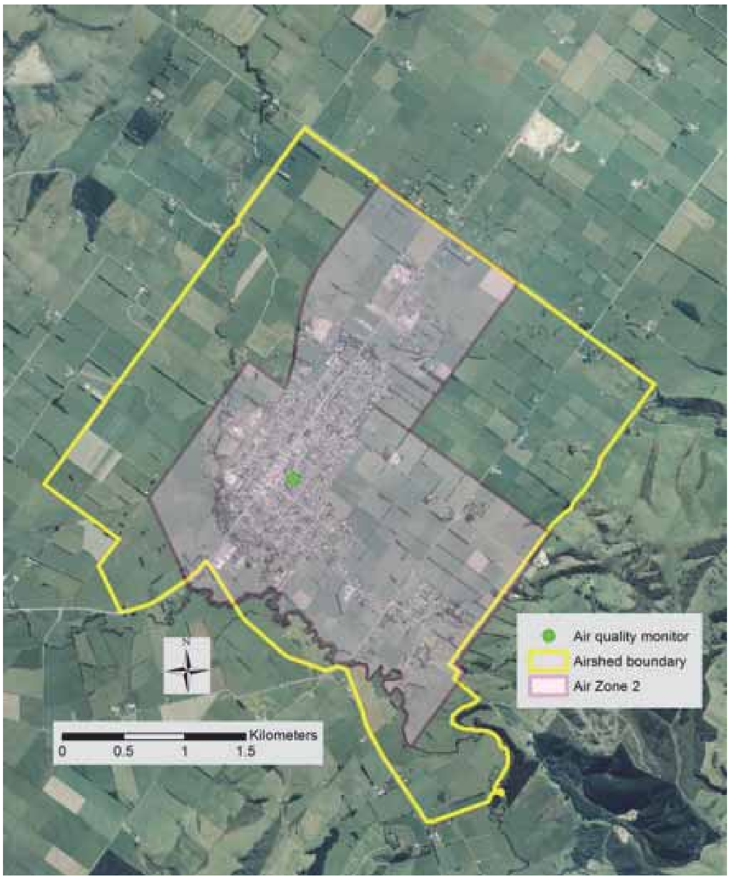
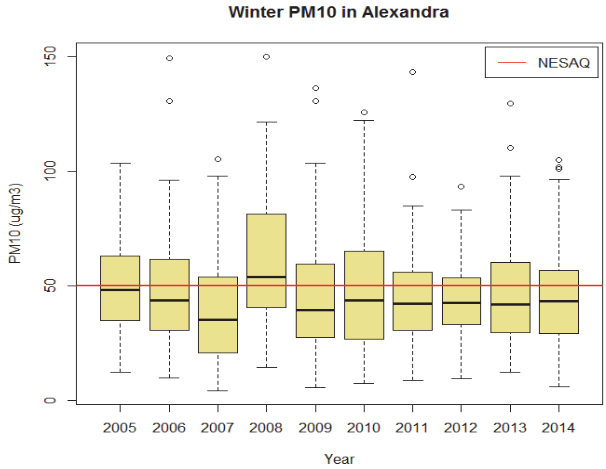
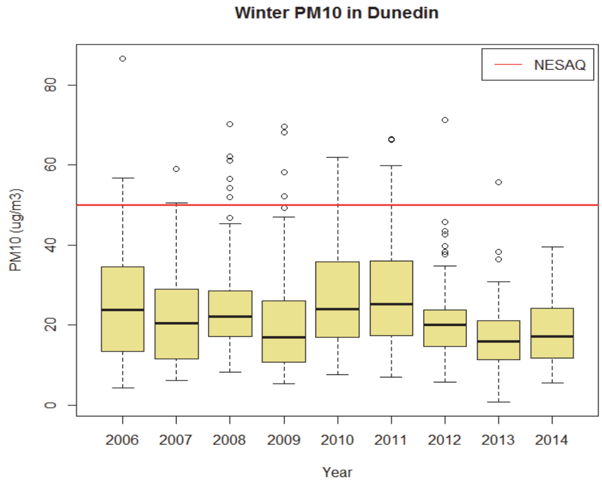
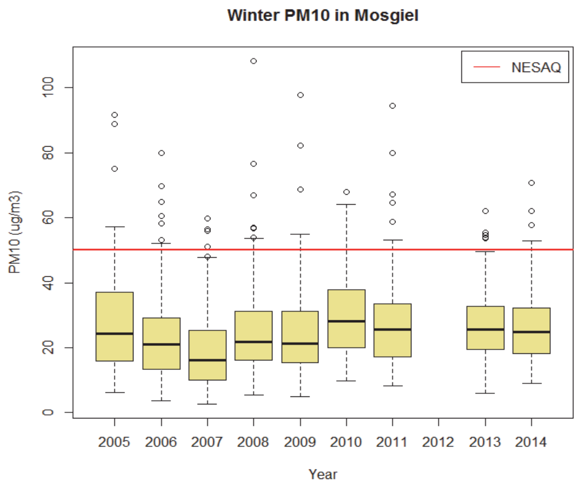


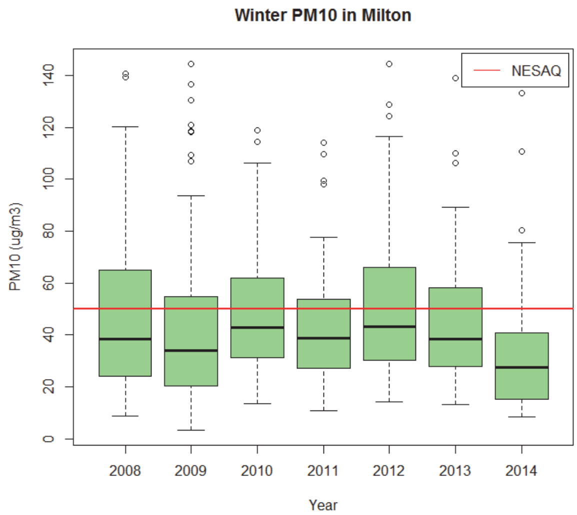
Figure 40. Milton airshed and air zone boundaries

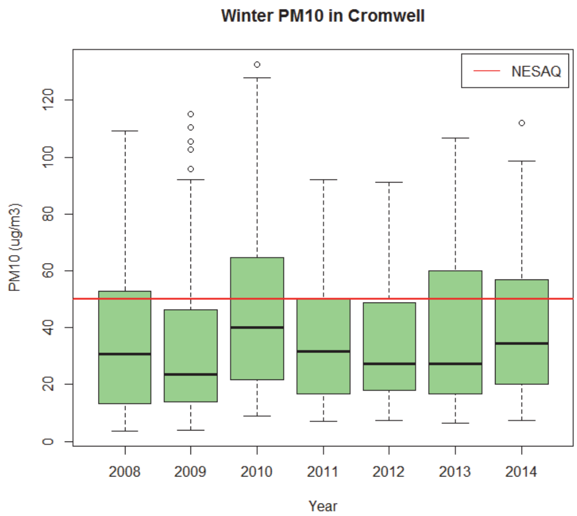
Appendix 2 Annual box plots of wintertime PM_{10} distribution

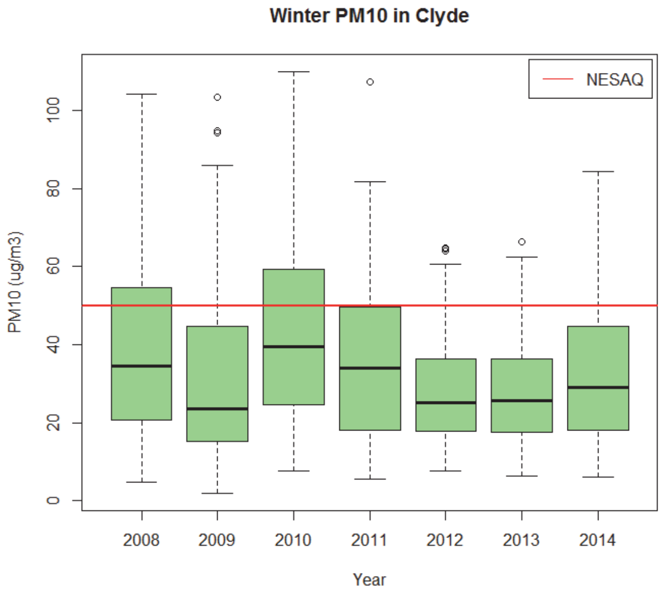


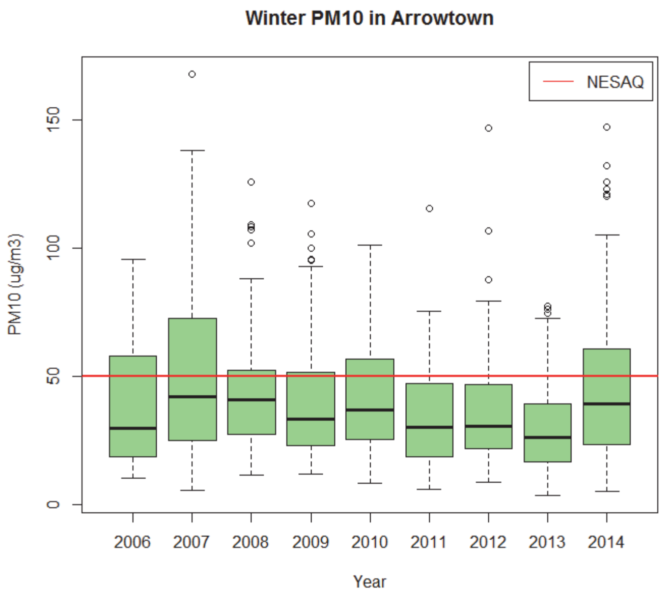


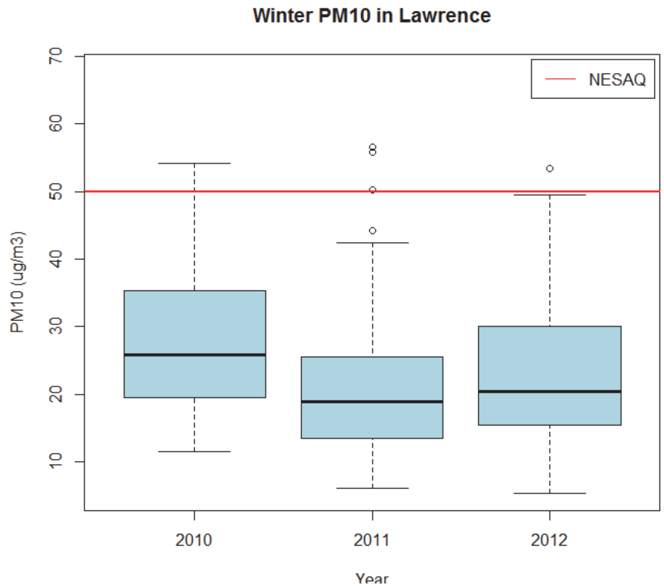







Winter PM10 in Clyde
NESAQ
PM10 (ug/m3)
0
20
40
60
80
100
2008
2009
2010
2011
2012
2013
2014
Year


Winter PM10 in Arrowtown
NESAQ
PM10 (ug/m3)
0
50
100
150
2006
2007
2008
2009
2010
2011
2012
2013
2014
Year


Winter PM10 in Lawrence
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PM10 (ug/m3)
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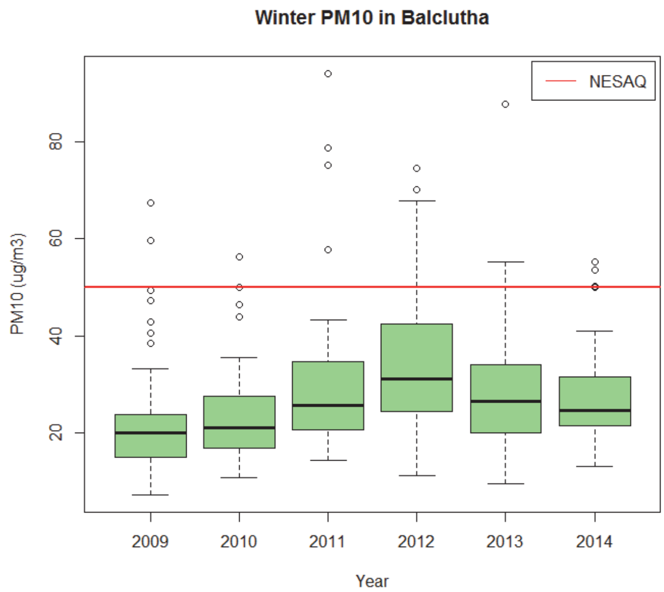
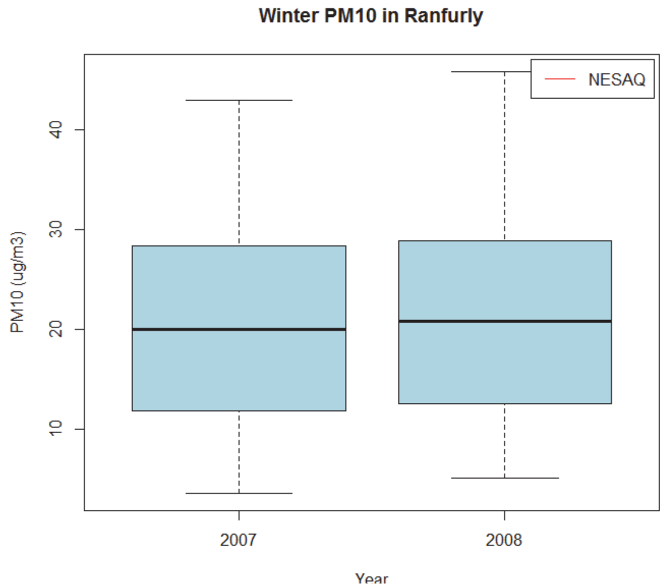
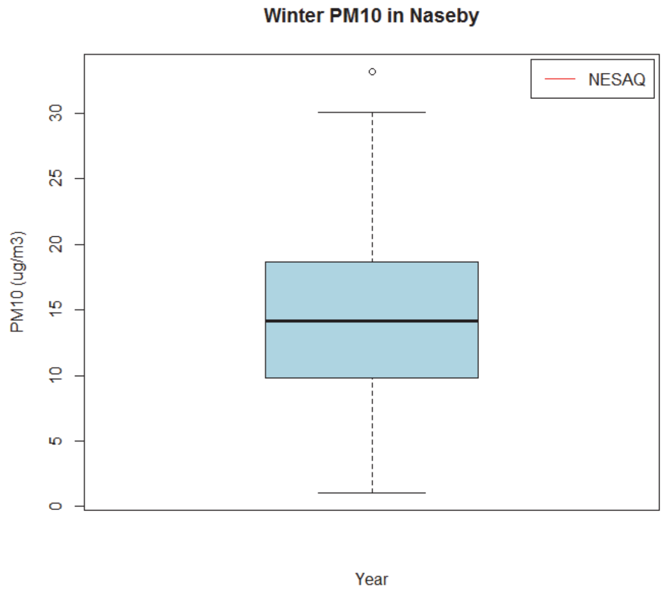
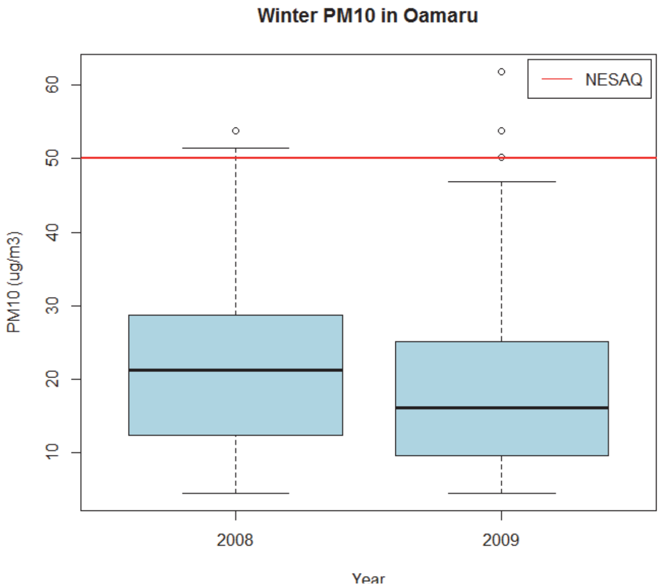
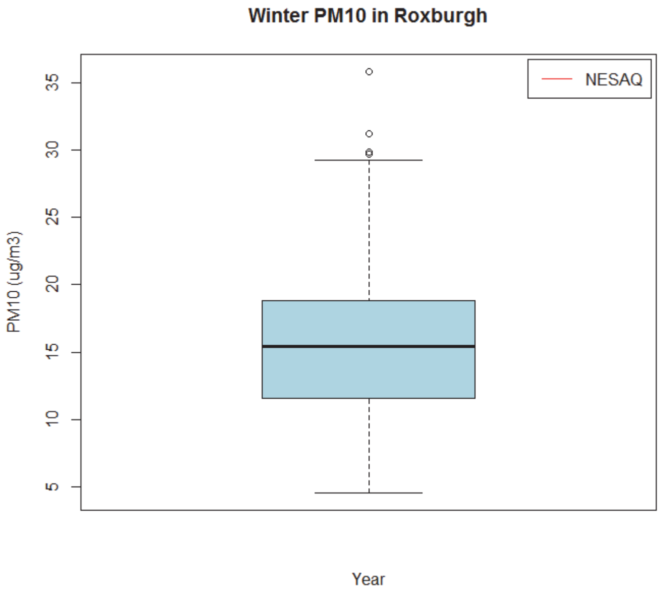
20
30
40
50
60
70
2010
2011
2012
Year


Winter PM10 in Balclutha
NESAQ
PM10 (ug/m3)
20
40
60
80
2009
2010
2011
2012
2013
2014
Year


Winter PM10 in Ranfurly
NESAQ
PM10 (ug/m3)
10
20
30
40
2007
2008
Year


Winter PM10 in Naseby
NESAQ
PM10 (ug/m3)
0
5
10
15
20
25
30
Year


Winter PM10 in Oamaru
NESAQ
PM10 (ug/m3)
10
20
30
40
50
60
2008
2009
Year


Winter PM10 in Roxburgh
NESAQ
PM10 (ug/m3)
5
10
15
20
25
30
35
Year

Appendix 3 Hourly air quality summaries by site

Table 19. Alexandra – year-round

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
% valid daily data	52*	96	98	99	100	98	86	100	89	100
Minimum	0	0	0	0	0	0	0	0	0	0
Mean	29	23	19	28	23	24	24	22	25	24
Max. hour	309	335	375	386	363	311	326	252	293	496
Max day	103	149	105	150	136	126	143	93	130	105
Median	14	9	8	12	11	11	12	11	12	12
95^{th} %ile	110	96	80	120	96	99	93	83	96	93

Table 20. Alexandra – winter only

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
% valid daily data	73*	100	99	100	100	100	100	100	100	100
Minimum	0	0	0	0	0	0	0	0	0	0
Mean	29	47	39	60	46	48	44	44	47	46
Max. hour	309	335	375	386	363	311	326	252	293	496
Max. day	103	149	105	150	136	126	143	93	130	105
Median	36	32	25	41	29	31	31	33	32	32
95^{th} %ile	138	143	125	173	146	148	126	119	136	130

Table 21. Dunedin (Central)

	2006	2007	2008	2009	2010	2011	2012	2013	2014
% valid daily data	61*	77	97	80	98	93	90	97	95
Minimum	0	0	0	0	0	0	0	0	0
Mean	21	20	24	20	25	25	18	18	18
Max. hour	309	135	319	197	211	504	338	192	189
Max. day	87	59	70	72	62	70	71	56	40
Median	15	16	19	15	20	20	15	15	15
95^{th} %ile	59	51	55	56	63	63	41	40	39

Table 22. Dunedin (Central) – winter only

	2006	2007	2008	2009	2010	2011	2012	2013	2014
% valid daily data	74*	100	100	100	100	98	89	98	100
Minimum	0	0	0	0	0	0	0	0	0
Mean	27	22	25	20	27	27	20	17	18
Max. hour	309	135	319	197	211	504	338	192	189
Max. day	87	59	70	72	62	70	71	56	40
Median	18	15	19	13	20	21	17	13	14
95^{th} %ile	75	61	66	60	70	72	49	44	45

Table 23. Mosgiel

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
% valid daily data	58*	72*	64*	93	90	68*	47*	15*	95	99
Minimum	0	0	0	0	0	0	0	0	0	0
Mean	20	17	16	18	19	24	26	14	20	21
Max. hour	458	217	229	717	289	329	289	88	167	217
Max. day	92	80	60	108	98	105	95	27	62	107
Median	12	9	10	10	12	17	20	12	16	17
95^{th} %ile	67	59	53	55	55	66	66	29	50	52

Table 24. Mosgiel – winter only

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
% valid daily data	75	100	100	100	99	98	94	0*	93	98
Minimum	0	0	0	0	0	0	0		0	0
Mean	28	24	19	25	25	30	32		27	27
Max. hour	458	217	229	717	289	329	289		167	217
Max. day	92	80	60	108	98	105	95		62	107
Median	17	15	11	15	16	21	21		20	20
95^{th} %ile	90	77	64	78	77	84	75		71	73

Table 25. Arrowtown – winter only

	2006	2007	2008	2009	2010	2011	2012	2013	2014
% valid daily data	45*	81	97	96	100	100	100	100	98
Minimum	0	0	0	0	0	0	0	0	0
Mean	38	52	44	40	42	34	36	30	45
Max. hour	278	762	455	288	318	280	725	241	392
Max. day	96	168	126	118	101	116	147	77	148
Median	21	27	27	22	24	19	21	17	25
95^{th} %ile	133	174	131	140	143	123	118	101	158

Table 26. Clyde – winter only

	2008	2009	2010	2011	2012	2013	2014
% valid daily data	98	95	100	72*	100	98	99
Minimum	0	0	0	0	0	0	0
Mean	40	31	44	36	28	28	32
Max. hour	288	283	261	249	167	161	224
Max. day	104	103	109	107	64	66	84
Median	26	16	28	23	19	19	23
95^{th} %ile	130	111	148	116	85	81	100

Table 27. Cromwell – winter only

	2008	2009	2010	2011	2012	2013	2014
% valid daily data	95	94	100	56*	99	95	99
Minimum	0	0	0	0	0	0	0
Mean	28	34	48	35	34	38	40
Max. hour	397	364	393	322	560	533	378
Max. day	109	115	133	92	91	107	112
Median	16	15	25	20	19	20	23
95^{th} %ile	161	154	191	124	125	142	140

Table 28. Milton – winter only

	2008	2009	2010	2011	2012	2013	2014
% valid daily data	98	98	98	56*	81	100	81
Minimum	0	0	0	0	0	0	0
Mean	47	42	49	43	50	44	31
Max. hour	396	476	300	347	290	306	324
Max. day	141	144	119	114	144	139	133
Median	30	25	35	29	33	31	20
95^{th} %ile	149	149	141	125	150	125	100

Table 29. Balclutha – winter only

	2009	2010	2011	2012	2013	2014
% valid daily data	72*	100	50*	89	100	64*
Minimum	0	0	0	0	0	0
Mean	22	22	30	34	28	27
Max. hour	168	474	223	231	211	318
Max. day	67	76	94	75	88	55
Median	16	17	22	24	22	22
95^{th} %ile	63	62	84	96	77	71

Table 30. Lawrence – winter only

	2010	2011	2012
Minimum	0	0	0
Mean	29	21	23
Max. hour	145	420	244
Max. day	54	57	68
Median	22	16	18
95^{th} %ile	74	57	62

Table 31. Naseby – winter only

	2007
Minimum	0
Mean	14
Max. hour	179
Max. day	33
Median	10
95^{th} %ile	41

Table 32. Roxburgh – winter only

	2007
Minimum	0
Mean	16
Max. hour	90
Max. day	36
Median	12
95^{th} %ile	44

Table 33. Ranfurly – winter only

	2007	2008
Minimum	0	0
Mean	21	22
Max. hour	125	150
Max. day	43	46
Median	13	15
95^{th} %ile	64	67

Table 34. Palmerston – winter only

	2013	2014
Minimum	0	0
Mean	26	21
Max. hour	112	141
Max. day	50	50
Median	21	17
95th %ile	62	52

Table 35. Oamaru – winter only

	2008	2009
Minimum	0	0
Mean	22	19
Max. hour	189	182
Max. day	54	62
Median	15	12
95th %ile	67	63