State and Trends of Air Quality in the Otago Region

2010 – 2019

September 2021

Otago Regional Council

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Executive summary

Otago Regional Council (ORC) operates a State of the Environment (SoE) air quality monitoring network at eight sites throughout the region – Alexandra, Arrowtown, Balclutha, Central Dunedin, Clyde, Cromwell, Milton and Mosgiel. The aims of the programme include reporting data in accordance with the National Environmental Standards for Air Quality (NESAQ) and the Resource Management Act (RMA), and to develop understanding of the influences of emissions and meteorology on pollutant concentrations. Over the past 15 years this monitoring has focused on PM_{10}, small particles with a diameter of less than 10 micrometres.

This report evaluates the PM_{10} results from the last ten years (2010 –2019) of air quality monitoring. The report assesses the current state and the long-term trends of PM_{10} in Otago airsheds.

Results indicate that for most of the year, air quality in Otago is very good, with annual PM_{10} values meeting national and international guidelines for ambient air. However, during winter months higher PM_{10} concentrations are observed in many towns, caused by home heating emissions combined with calm weather and temperature inversions. Alexandra, Arrowtown, Cromwell and Milton regularly exceed the NESAQ for PM_{10} up to 20 times per winter. Other airsheds, such as Clyde and Mosgiel, exceed the standard up to ten times per winter. Central Dunedin is currently the only site compliant with the NESAQ.

Recognising the challenge of improving air quality in Central Otago and Milton, ORC set strict rules for domestic heating appliances in the Otago Regional Plan: Air Plan. To assist residents meeting these rules, ORC operated the Clean Heat Clean Air programme (CHCA), a financial incentive that has improved both insulation and heating appliances. Long-term trend analyses indicate that PM_{10} concentrations have reduced in Alexandra, Arrowtown, Clyde, Cromwell and Milton due to these incentives, however this has not been enough to meet the NESAQ in these towns.

Understanding the required strategies for each airshed to reduce emissions and become compliant with the national standards will be an important next step for Otago's air quality programmes. The results of this report will be used to inform future work on air quality strategy and policy in Otago.

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Glossary

AAQG	Ambient Air Quality Guidelines (2002)
Airshed	Area designated by a regional council for air quality management
BAM	Beta Attenuation Monitor
CHCA	Clean Heat Clean Air
Coarse PM	Particulate matter sized between 2.5 and 10 µm in diameter
CO	Carbon monoxide
Exceedance	Where a contaminant exceeds its threshold concentration
Fine PM	Particulate matter less than 2.5 µm
HAPINZ	Health and Air Pollution in New Zealand Study
MfE	Ministry for the Environment
NESAQ	National Environmental Standard for Air Quality (2004)
NO_2	Nitrogen Dioxide
PM	Particulate Matter
$PM_{2.5}$	Particulate matter less than 2.5 µm in diameter
PM_{10}	Particulate matter less than 10 µm in diameter
SFB	Solid-fuel burner (wood, pellets and coal)
SO_2	Sulphur dioxide
ULEB	Ultra-low emission burner
Ultra-fine PM	Particulate matter less than 1 µm in diameter
µm	Micrometre, one millionth of a metre
µg/m^3	Microgram per cubic metre, unit of concentration
WHO	World Health Organization

1. Introduction

Clean outdoor (ambient) air is fundamental for human health and the natural environment. Ambient air quality is affected by the amounts and types of pollutants that are emitted into air, and the meteorological conditions that impact their dispersion. Otago has a varied and complex topography, producing varying climate zones from alpine to coastal environments.

Of the ambient air pollutants in New Zealand, particulate matter (PM) is the main concern in Otago, with many airsheds regularly failing to meet national standards. The main emission source of PM in Otago is solid fuel burning (wood, coal or pellets) for home heating, with lesser additional influence from vehicle emissions, industry, outdoor burning, and natural sources (ORC, 2016).

Four previous SoE reports have evaluated air quality in Otago. Two reports were released in 2005 for the period 1997 to 2004. The first was for PM_{10} (ORC, 2005a), and the second reported on sulphur dioxide, nitrogen dioxide and carbon monoxide (ORC, 2005b). Two further PM_{10} reports were released for the period of 2005 to 2008 (ORC, 2009) and 2005 to 2014 (ORC, 2016).

This report evaluates the results of the SoE monitoring for PM_{10} over the ten-year period of 2010 to 2019 and examines the current state and temporal trends. The differences between this report and the previous reports are: inclusion of analyses of home heating methods and subsequent emissions in key Otago towns due to the recent completion of two emissions inventories of 2016 and 2019; as well as spatial variability results within two airsheds due to monitoring site relocations.

1.1. Purpose of the report

This report aims to:

- Report the current state of PM_{10} in relation to the relevant standards and guidelines
- Evaluate the spatial and temporal trends of PM_{10} for the last ten years
- Inform future air quality policy and strategy work for Otago

1.2. Scope and outline

This report presents and analyses data collected by the monitoring network for the last ten years. Relevant information from other investigations, such as spatial studies and emissions inventories will also be included.

The following sections are included in this report:

- Section 2 describes the current air quality assessment framework
- Section 3 describes Otago's monitoring network
- Section 4 presents the current state of PM_{10} in an analysis of the three most recent years' data (2017-2019)
- Section 5 provides analyses of the temporal trends for 2010-2019 and describes the spatial distribution of PM_{10} in various towns
- Section 6 discusses the pressures and influences on air quality
- Section 7 discusses the results of the analyses, the health and cultural impacts of air pollution, and outlines the current knowledge gaps

2. Air quality assessment framework

2.1. National air quality indicators for ambient pollutants

The national Ambient Air Quality Guidelines (AAQG) were first established in 1994 by the Ministry for the Environment (MfE), based on international public health information (MfE, 2002). The AAQG was revised in 2002, and recommends limits on concentrations for certain ambient air pollutants.

In 2004 the National Environmental Standards for Air Quality (NESAQ) were adopted (revised in 2011) and established mandatory minimum requirements for five pollutants – PM_{10}, nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO) and ozone (O_3). The objectives of these standards are to provide an acceptable level of protection to human health and the environment. These standards are currently being revised to include $PM_{2.5}$ (particulate matter with a diameter of less than 2.5 micrometres). Table 1 provides the current ambient air quality standards and guidelines for the relevant pollutants.

Pollutant	Limit type	Threshold concentration (µg/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

Table 1 New Zealand standards and guidelines for ambient pollutants

Otago Regional Council's (ORC) current monitoring programme focuses on measuring PM_{10}, the most significant pollutant of concern both regionally and nationally. Earlier monitoring (1997 – 2004) of NO_2, SO_2 and CO indicated these pollutants were not present in significant concentrations and are expected to be below the standard and guideline limits. Ozone is a secondary pollutant formed during photochemical reactions between oxygen and nitrogen dioxide, when exposed to light. During a study on photochemical pollution potential in New Zealand (McKendry, 1996) no towns or cities in Otago were identified as having conditions conducive to the formation of ozone. More information for NO_2, SO_2, CO and ozone is provided in Appendix 4.

2.2. International air quality indicators

New Zealand standards and guidelines are consistent with the World Health Organization (WHO) recommendations (WHO, 2006) for NO_2, CO and O_3. In the cases of PM and SO_2 there are some significant differences.

Regarding particulate matter, international researchers agree that adverse health effects associated with $PM_{2.5}$ are greater than those associated with PM_{10}. As a result, many agencies including WHO, the European Union, the United States and Australia have introduced $PM_{2.5}$ standards alongside their PM_{10} standards. In formulating PM guidelines and standards, WHO assume that the ratio of $PM_{2.5}$ to PM_{10} is 0.5, thereby setting the $PM_{2.5}$ daily guideline limit at 25 µg/m³, which is half that of PM_{10}.

The WHO lowered the SO_2 24-hour guideline value from 120 µg/m³ to 20 µg/m³ in 2005. 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.

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

Pollutant	Threshold concentration (µg/m3)	Averaging period
$PM_{2.5}$	25	24-hour
	10	annual
Nitrogen dioxide NO_2)	40	annual
Sulphur dioxide (SO_2)	20	24-hour
	500	10-minute

Table 2 World Health Organization guideline values for $PM_{2.5}$, NO_2 and SO_2

2.3. Particulate matter

Particulate matter (PM) refers to particles or aerosols that are suspended in the atmosphere. PM can be natural or anthropogenic (produced by human activity) in origin and can either be directly emitted or formed in the atmosphere as a result of chemical reactions between other pollutants. Therefore, PM occurs in a range of sizes and chemical compositions. PM can be grouped into two categories – 'fine' and 'coarse'. Fine particulate matter consists of particle sizes up to 2.5 µm in diameter ($PM_{2.5}$). Coarse particulate matter is the group of particles with diameter sizes between 2.5µm and 10 µm. PM_{10} is the fine and the coarse fractions combined.

Fine particulate matter, or $PM_{2.5}$, is a result of incomplete combustion such as vehicle emissions, and the combustion of wood and coal for industry or heating. It is comprised of organic and inorganic compounds, metals and black carbon (soot). These particles can remain suspended in the air for many days and can be transported hundreds of kilometres.

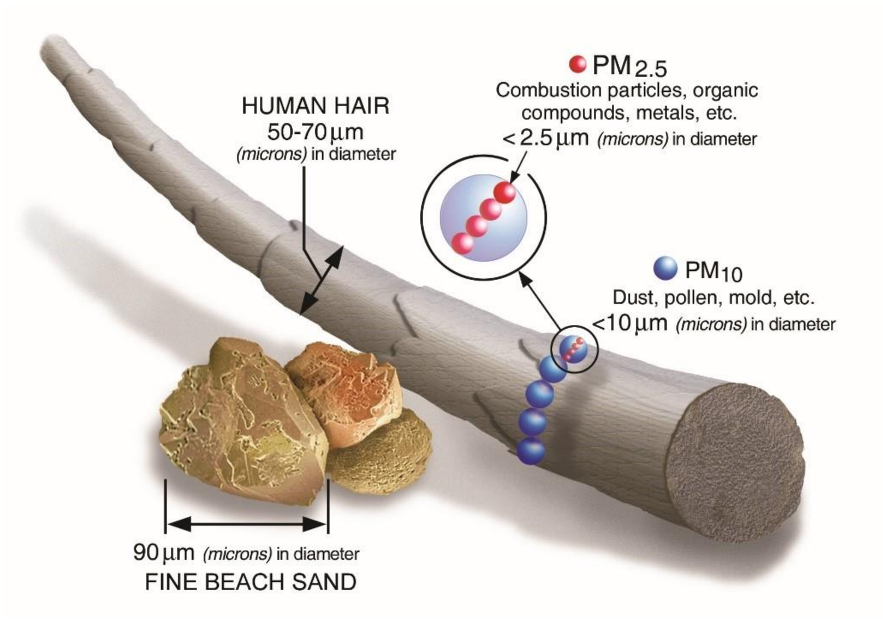


Figure 1 Comparison of particle sizes. Source: United States Environmental Protection Agency

Coarse particulate matter ($PM_{10-2.5}$) is a product of mechanical forces such as wind erosion, crushing and abrasion. Natural sources include pollen, soils and sea salt. Anthropogenic sources include dust suspended from roads and industrial activity. Coarse PM tends to fall out of suspension within minutes or hours and can travel up to 50 kilometres from the source.

Both short and long-term exposure to particulate matter can cause and exacerbate serious health issues, specifically to the respiratory and circulatory systems. The most vulnerable to PM are the young, the elderly and anyone with pre-existing conditions. Fine and ultra-fine (PM_1 and smaller) are the most dangerous as smaller particles can penetrate the respiratory system further and enter the blood stream (WHO, 2013). Currently there is no established safety threshold for exposure to particulate matter.

2.4. Otago airshed management

2.4.1. Airsheds

The Otago region has four designated Airsheds which were gazetted[1] in 2005 in accordance with NESAQ requirements. The Airsheds are ranked from Airshed 1 (most degraded air quality) to Airshed 4 (not expected to be degraded). Twenty-two towns and cities have been allocated into one of these four airshed groups based on similarities in their geography, climate and air pollution potential (Figure 2). Rural areas outside of town boundaries are considered to be a fifth airshed, where air quality is expected to be good.

2.4.2. Air Zones

The twenty-two airsheds are also categorised into management areas under the Air Plan, called Air Zones (Table 3). Air Zone 1 and 2 consists of towns expected to exceed the NESAQ for several days

[1] Gazetted airshed refers to those notified in the New Zealand Gazette

(>10), and a few days (<10) a year, respectively. Air Zone 3 are towns that are not expected to exceed the NESAQ. Maps of individual airsheds can be found in Appendix A1.

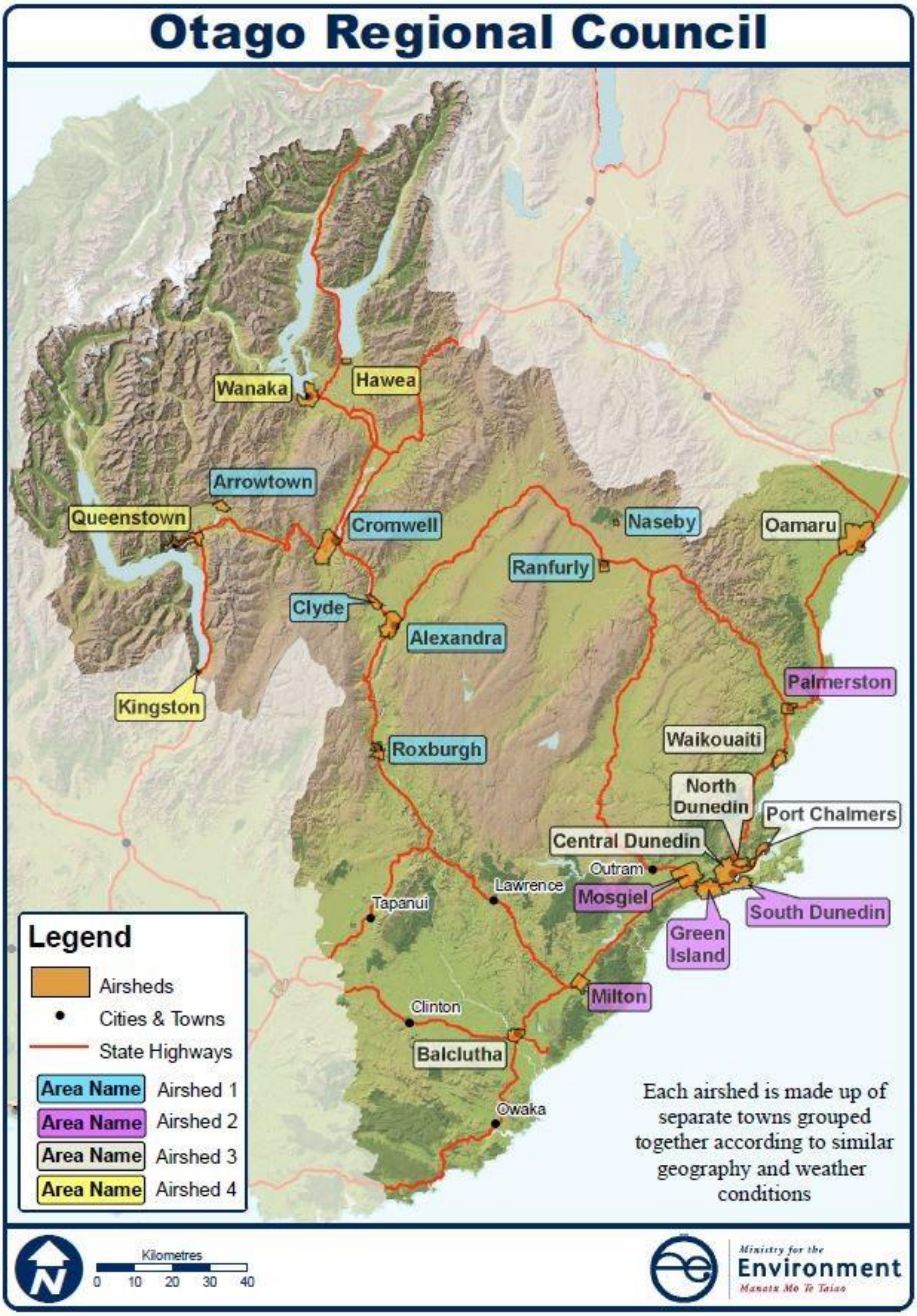


Figure 2 **Otago Regional Council gazetted airsheds**

<table>
<tr><th>Town</th><th>Gazetted Airshed (MfE)</th><th>ORC Air Zone</th></tr>
<tr><td>Alexandra</td><td rowspan="7">1</td><td rowspan="4">1</td></tr>
<tr><td>Arrowtown*</td></tr>
<tr><td>Clyde</td></tr>
<tr><td>Cromwell</td></tr>
<tr><td>Naseby</td><td rowspan="18">2</td></tr>
<tr><td>Ranfurly</td></tr>
<tr><td>Roxburgh</td></tr>
<tr><td>Green Island</td><td rowspan="5">2</td></tr>
<tr><td>Milton</td></tr>
<tr><td>Mosgiel*</td></tr>
<tr><td>Palmerston</td></tr>
<tr><td>South Dunedin</td></tr>
<tr><td>Balclutha</td><td rowspan="6">3</td></tr>
<tr><td>Central Dunedin *</td></tr>
<tr><td>North Dunedin</td></tr>
<tr><td>Oamaru</td></tr>
<tr><td>Port Chalmers</td></tr>
<tr><td>Waikouaiti</td></tr>
<tr><td>Hawea</td><td rowspan="4">4</td></tr>
<tr><td>Kingston</td></tr>
<tr><td>Queenstown</td></tr>
<tr><td>Wanaka</td></tr>
<tr><td><Rest of Otago></td><td>5</td><td>3</td></tr>
</table>

*Contains the regulatory monitoring site for the NESAQ Gazetted Airshed

Table 3 Airshed and Air Zone designations for Otago

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 50 locations throughout Otago. Most of the monitoring performed over the last 15 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 (2010-2019), monitoring has focused on PM_{10}.

Otago's large area, with varying terrain and climate make it challenging to provide a true and complete representation of ambient air quality. Therefore, monitoring sites are situated where it is considered that the most people may experience exposure to the highest concentrations of 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 fulfil the statutory requirements of the Resource Management Act 1991 (RMA)
- To measure and report on compliance with national standards and guidelines
- To measure the effects of ORC's air quality management initiatives

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

3.3. Monitoring programme

There are two types monitoring site used in the air quality monitoring network:

a) Key indicator monitoring - performed at long-term sites that run continuously in Arrowtown, Central Dunedin and Mosgiel. These sites are representative of the different MfE airshed categories and are considered characteristic of Otago's townships. Results from these sites are used to report to MfE on compliance with NESAQ and to track long-term trends
b) Survey monitoring - undertaken at sites that only run during winter months (May to August inclusive). Results are used to quantify air quality during winter and assist in tracking trends.

Table 4 lists all the sites monitored over the last ten years.

<table>
<tr><th>Site</th><th>Airshed</th><th>Air Zone</th><th>Purpose</th><th>Length of record</th></tr>
<tr><td>Arrowtown</td><td>1</td><td>1</td><td rowspan="3">Key indicator – Year-round</td><td>2007 - present</td></tr>
<tr><td>Mosgiel</td><td>2</td><td>2</td><td>2005 - present</td></tr>
<tr><td>Central Dunedin</td><td>3</td><td>2</td><td>2006 - present</td></tr>
<tr><td>Alexandra*</td><td>1</td><td>1</td><td>Year-round</td><td>2004 - present</td></tr>
<tr><td>Balclutha</td><td>2</td><td>2</td><td rowspan="4">Survey – winter only</td><td>2009 - 2018</td></tr>
<tr><td>Clyde</td><td>1</td><td>1</td><td rowspan="3">2008 - present</td></tr>
<tr><td>Cromwell</td><td>1</td><td>1</td></tr>
<tr><td>Milton</td><td>2</td><td>2</td></tr>
</table>

*Alexandra was the Key indicator for Airshed 1 for 2004-2017

Table 4 Air monitoring sites and their purpose in the network

3.4. Monitoring methods

3.4.1. Particulate matter monitoring and measurement

PM_{10} is monitored using two types of beta attenuation monitor (BAM), manufactured by MetOne in the USA. BAMs measure the particle mass density by comparing the sample deposited on the filter tape with the blank tape; as the particle mass increases, the beta count decreases. Standard sampling methods are required for regulatory reporting for compliance with the NESAQ. The BAM1020 is accepted by the US Environmental Protection Agency (USEPA) as an equivalent reference method for measuring PM_{10}. BAM1020 are used at the continuous sites Alexandra, Arrowtown, Central Dunedin and Mosgiel. The Dunedin BAM1020 installation is shown in Figure 3.

The winter only sites are monitored using an Environmental Beta Attenuation Monitor (EBAM). The EBAM is not considered an equivalent reference method, but it is designed to provide accurate daily PM_{10} averages. All stations are sited and operated where possible, using ASNZS 3580.1.1:2016.

3.4.2. Meteorological monitoring and measurement

Air temperature, wind speed and wind direction all influence the accumulation and dispersion of pollutants. These parameters are recorded continuously at the PM_{10} monitoring sites in order to describe localised meteorological effects on PM_{10}.

Figure 3 **PM_{10} and meteorology site in Central Dunedin and the filter tape a BAM1020 monitor; each filter tape spot represents one hour of sampled PM_{10}**

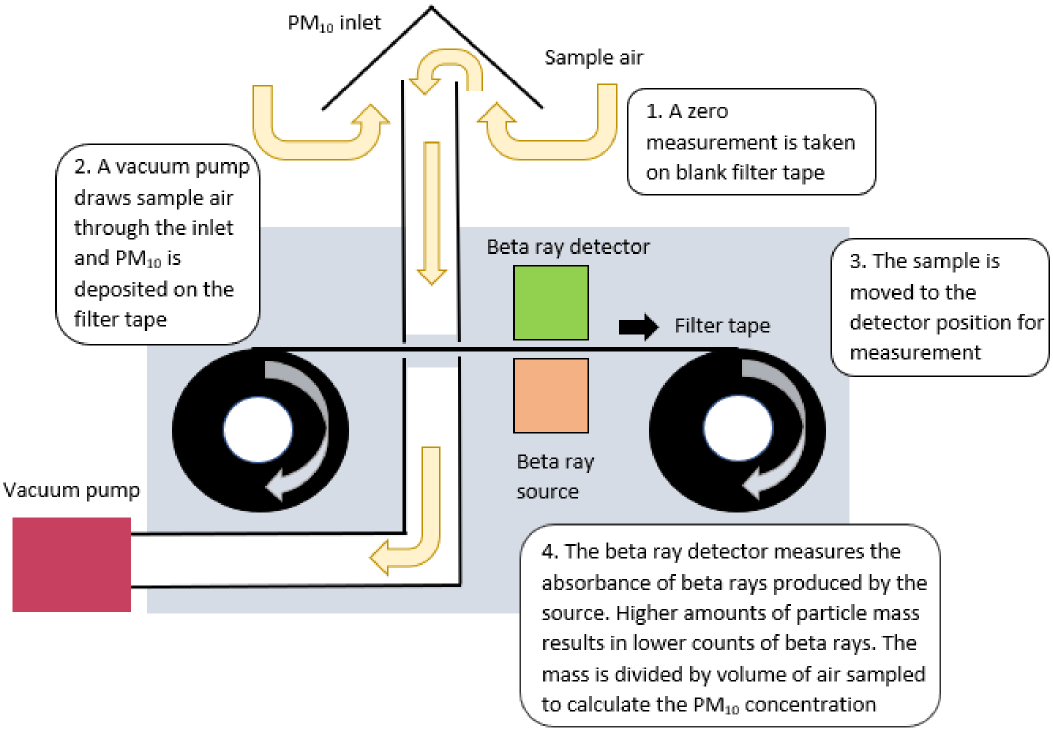


Figure 4 **Principles of BAM operation**

4. State of Otago's air quality

This section compares the last ten years of PM_{10} data from each monitoring site with the relevant standards and guidelines and describes the current state of air quality in Otago.

4.1. Compliance with standards and guidelines

4.1.1. 24-hour PM_{10} standard

The following table shows the number of NESAQ exceedances, where PM_{10} exceeds 50 µg/m³ over an average of 24-hours (midnight-midnight). The number of exceedances at a given site can vary vastly between years, for example the number of exceedances between 2017 and 2018 decreases by more than half at Clyde, Cromwell and Milton (Table 5), due to meteorological variation between the years. Central Dunedin is the only site that is currently compliant with the NESAQ, with one exceedance in the last three years. The NESAQ allows one exceedance per year; only after a second one is the airshed considered in breach of the standard.

Site	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Alexandra - 65 Ventry Street	51	40	40	46	51	22	38			
Alexandra - 5 Ventry Street								3	2	6
Arrowtown - School	39	27	24	15						
Arrowtown - Alexander Place					48	30	32	45	29	19
Balclutha	2	4	13	4	3	9	10	14	5	
Central Dunedin	11	14	1	1	0	0	0	0	1	0
Clyde	40	23	9	10	21	10	18	23	6	4
Cromwell	43	27	30	33	49	27	34	41	13	13
Milton	46	20	37	44	14	30	35	48	16	20
Mosgiel	8	8	NA	5	5	7	9	9	4	4

Table 5 **Number of NESAQ exceedances per site for 2010-2019. Shaded squares represent sites that were not in operation. Alexandra and Arrowtown monitors were relocated due to site availability and are discussed further in Section 6.**

4.1.2. Annual PM_{10} guideline

The following graph shows the annual averages of the year-round sites relative to the AAQG and WHO guideline of 20 µg/m³. Central Dunedin has been meeting the annual guideline since 2012, which indicates good air quality at this site. For the last two years all the other sites have also met the guideline, and 2017 was the most recent year for Arrowtown to be above the limit (Figure 5). Some sites show variation between years and further analysis of trends is undertaken in Section 5.

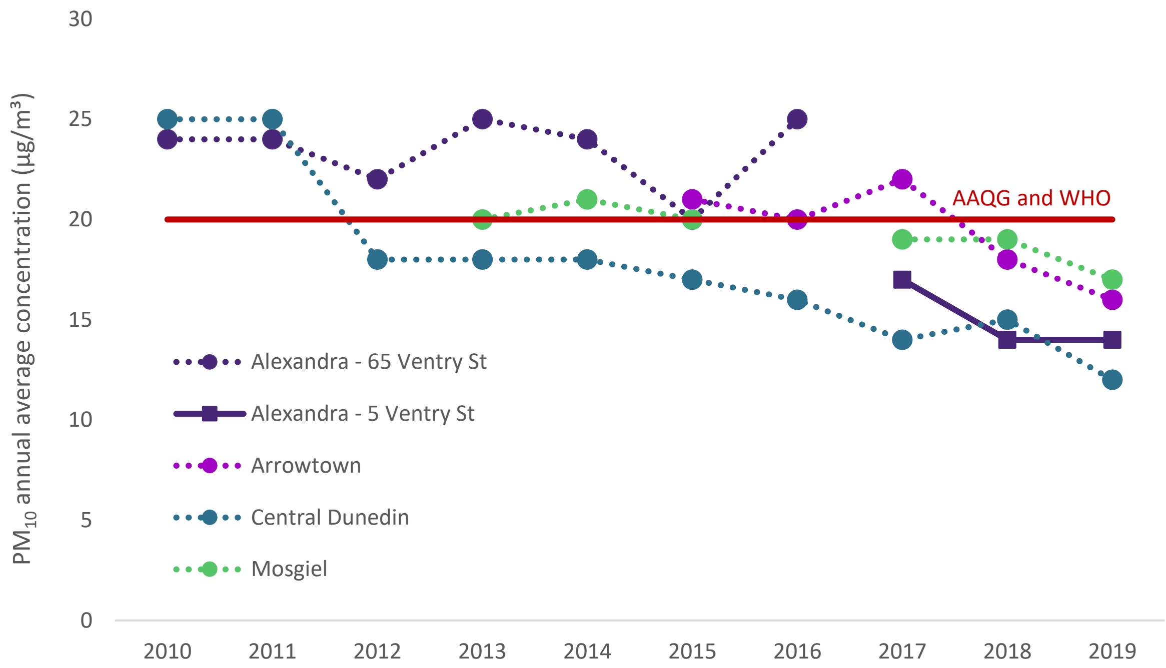


Figure 5 **Annual average PM_{10} for 2010-2019 compared with the annual AAQG and WHO guideline**

4.2. Statistics

Data from 2017-2019 is presented to show the current state of air quality at each site for comparison purposes. The three-year period was chosen to represent the current state because it should smooth some of the variation in particulate concentrations due to changing weather patterns year to year. Additionally, three years is too short to discern any significant change in PM_{10} due to interventions designed to reduce emissions.

Table 6 shows that Arrowtown and Milton have the highest values for the following: winter means (39 and 36 µg/m³) maximum daily concentration (158 and 154 µg/m³) and average number of exceedances over the last three years (31 and 28). Apart from Dunedin, Clyde has the lowest winter mean of 25 µg/m³, and Mosgiel and the current Alexandra site have the least number of exceedances on average, with 5.3 and 3.7 respectively. This data also indicates that it is normal for the airsheds Arrowtown, Cromwell and Milton to experience between 15 and 50 exceedances in a given year, and that winter means can vary greatly between years. A comprehensive list of parameters is given by site in Appendix 3:

Figure 6 ranks the sites in order of their winter average PM_{10} and shows that for most sites high winter averages and high numbers of exceedances occur together. Balclutha and Mosgiel go against this pattern slightly as they have a lower exceedance count for their winter averages. Figure 7 plots the relationship between winter average and number of exceedances for all sites. The relationship indicates that a winter average of below at least 20 µg/m³ is required to meet the NESAQ.

Site	Maximum 24-hour average concentration	2nd highest 24- hour average concentration	Mean winter PM_{10}				Average number of exceedances
			2017	2018	2019	Average	
Alexandra (5 Ventry Street)	98	91	26	23	23	24	3.7
Arrowtown (Alexander Place)	158	132	47	38	32	39	31.0
Balclutha	98	69	34	26	NA	29	9.5
Central Dunedin	52	41	15	15	12	14	0.3
Clyde	87	74	32	22	22	25	11.0
Cromwell	123	100	43	27	26	32	22.3
Milton	154	137	46	32	29	36	28.0
Mosgiel	95	89	26	26	25	26	5.3

*Balclutha was decommissioned after winter 2018

Table 6 **Maximum and second highest 24-hour average concentration, winter mean and average number of exceedances of the NESAQ for 2017-2019**

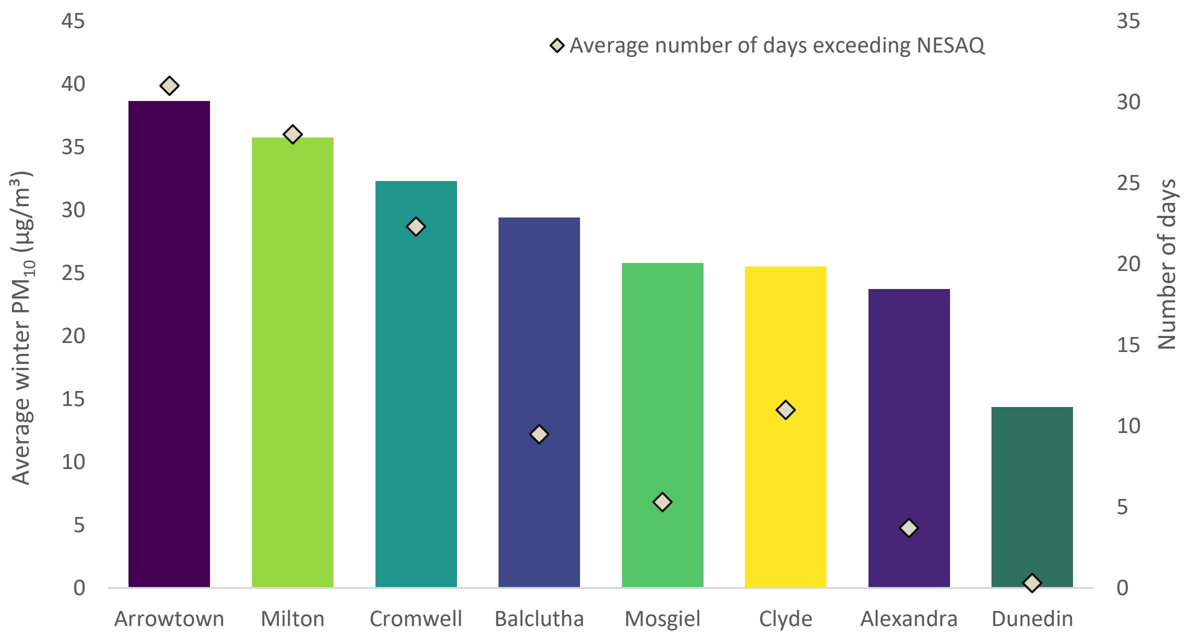


Figure 6 **Average winter PM_{10} (bars) and average number of exceedances (points) for Otago's SOE sites 2017-2019**

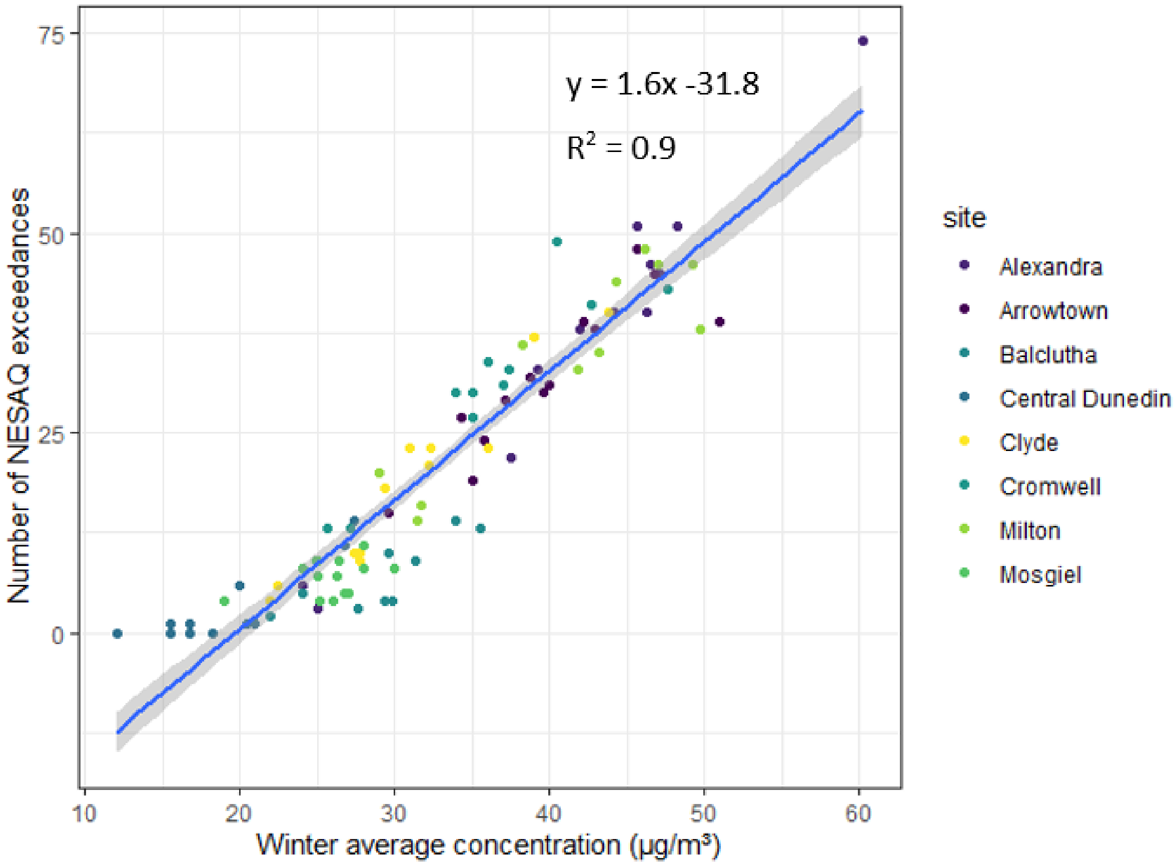


Figure 7 **Relationship between number of exceedances and winter average PM_{10} concentration for every year of monitoring (2005-2019)**

4.3. State: Key indicator sites

Arrowtown, Central Dunedin and Mosgiel are the three indicator monitoring sites for Otago, with each town representing one of the three airshed groups. Each site has different emission source characteristics and a unique relationship between climate and topography. The timeseries graph of these sites show that Central Dunedin has the most consistent concentrations throughout the year, which reflects the mixed emission sources (home heating, industrial and vehicle), and a climate conducive to dispersion of PM. Arrowtown data shows extreme seasonality of high winter concentrations and very low summer concentrations, with Mosgiel a mixture of these two extremes: moderate 24-hour averages all year with some seasonal variation in winter (Figure 8).

Between 2017 and 2019 Arrowtown had the largest range of 24-hour average concentrations and the highest frequency of days that exceed the NESAQ limit. Mosgiel PM_{10} also exceeded several times, and Dunedin only the once (Figure 9). Many of the highest values for Arrowtown and Mosgiel occurred in 2017, which was estimated to have more cold and calm conditions than 2018, producing higher PM_{10} concentrations. The difference between 2017 and 2018 highlights that inter-annual variation in pollutant concentrations can be quite high.

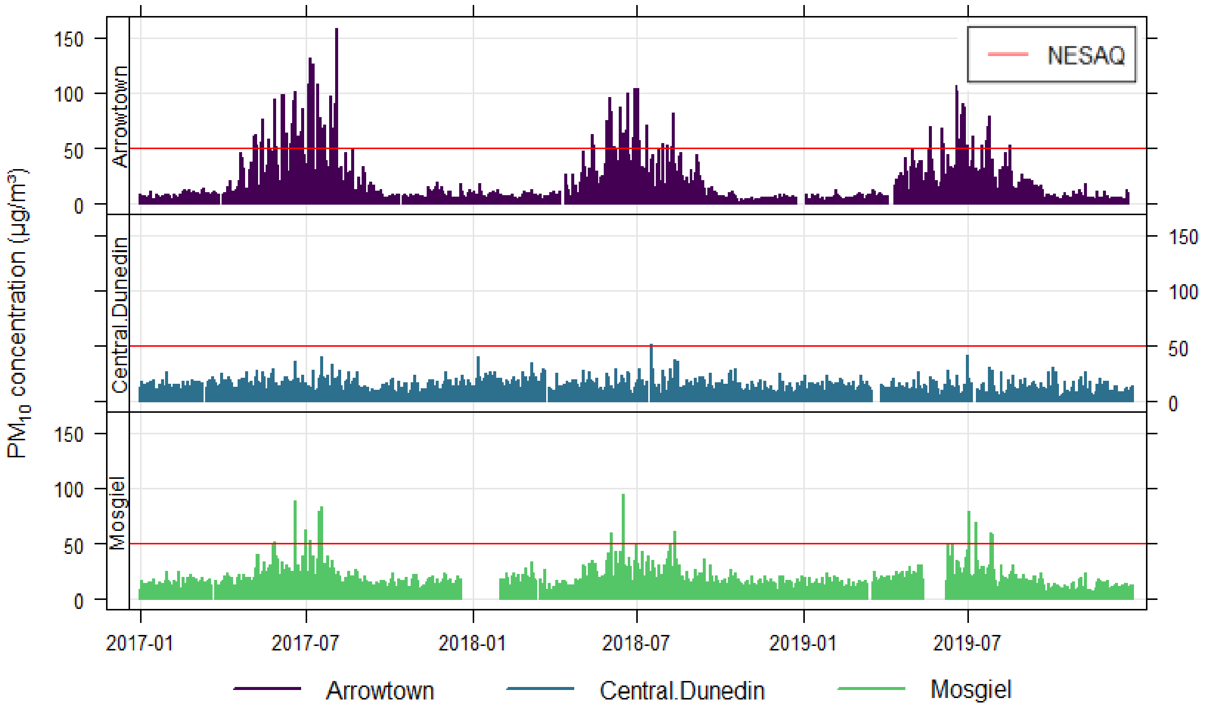


Figure 8 **Timeseries of PM$_{10}$ at key indicator sites for 2017-2019 (24-hour average)**

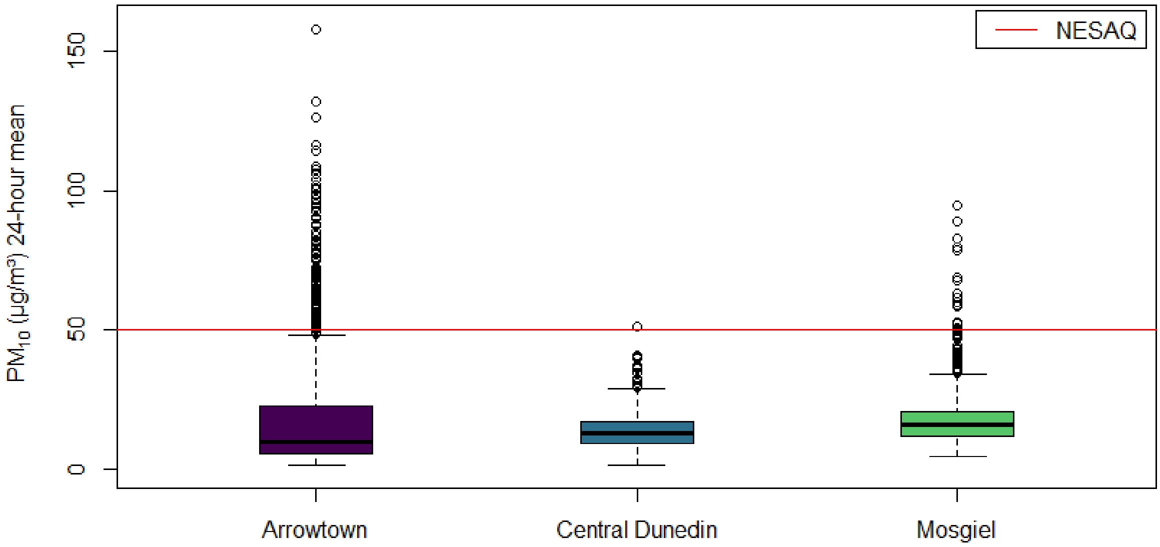


Figure 9 **Distribution of PM$_{10}$ at key indicator sites 2017-2019, see Appendix A3 for plot interpretation**

4.4. State: Survey sites

Alexandra, Clyde, Cromwell and Milton are the survey sites in Otago, meaning that they are only monitored during winter (excepting Alexandra which is year-round) to record exceedances and track trends in these locations. The 2017-2019 boxplot for the survey sites show that all sites regularly exceed the NESAQ limit. Similarly to Figure 8 many of the highest pollution nights occur in 2017. In Milton the highest 25th percentile of days are above the NESAQ limit. Milton and Cromwell have the largest range of 24-hour averages (Figure 10).

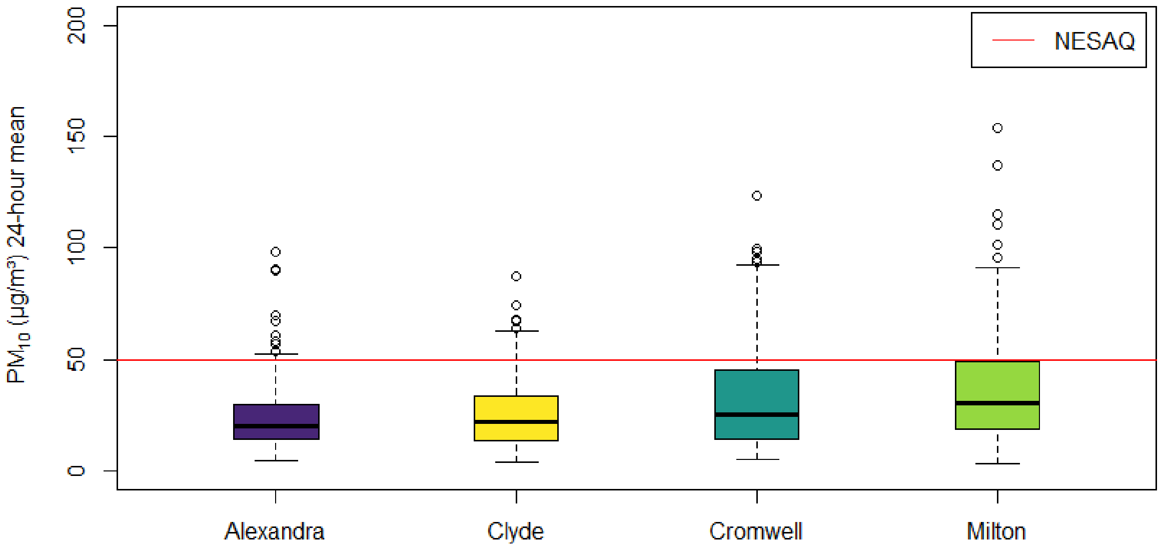


Figure 10 **Distribution of PM_{10} at survey sites during 2017-2019 (winter-only)**

5. Temporal and spatial trends in ambient air quality

Air quality varies greatly both spatially between and within airsheds, and temporally over short and long-term periods. Spatial variability can be attributed not only to different sources of pollutants, but to large scale weather differences between airsheds, and micro-climates within airsheds. Temporal changes can result from multiple factors including regulatory requirements, changes to fuel choices, addition or removal of point sources of emissions, and natural variability of weather patterns.

5.1. Short-term temporal trends

5.1.1. Short-term trends: key indicator sites

Patterns in particulate concentrations can be seen at various timescales, i.e., hourly, daily, weekly and seasonal. The following graphs show the three key indicator sites data compared at these scales for the years of 2017 - 2019. All three sites have different patterns over the different time scales. The daily pattern for Dunedin shows a rise of PM during the morning which remains constant then decreases through the evening. Arrowtown, and to a lesser extent Mosgiel, show distinct bi-modal peaks during the day. These are common in towns with domestic heating emissions as the main emission source (ORC, 2016). Concentrations in both towns increase at around 4pm, as temperature decreases and fires start being lit within residential homes, and remain high until midnight. In the morning at 8-9am they rise again to a smaller peak (Figure 11B).

Similarly, Arrowtown has very high monthly means (up to 50 µg/m^3) in the winter months, and very low means (<5 µg/m^3) in the summer months. Mosgiel monthly averages are similar to Dunedin's during non-winter months, but display a peak of up to 30 µg/m^3 in winter. Dunedin has very consistent PM_{10} concentrations throughout the year, with each monthly mean falling between 12 and 15 µg/m^3 (Figure 11C). Dunedin is the only site that displays a weekly pattern, with significantly lower daily concentrations on Saturday and Sunday, which indicates traffic and industry as a major source (Figure 11D).

Figure 12 shows the hourly patterns during winter months only, which displays the full extent of Arrowtown and Mosgiel's morning and evening peaks during the colder months. Arrowtown concentrations are roughly double that of Mosgiel's, with an hourly mean of up to 80 µg/m^3 during the evening peak.

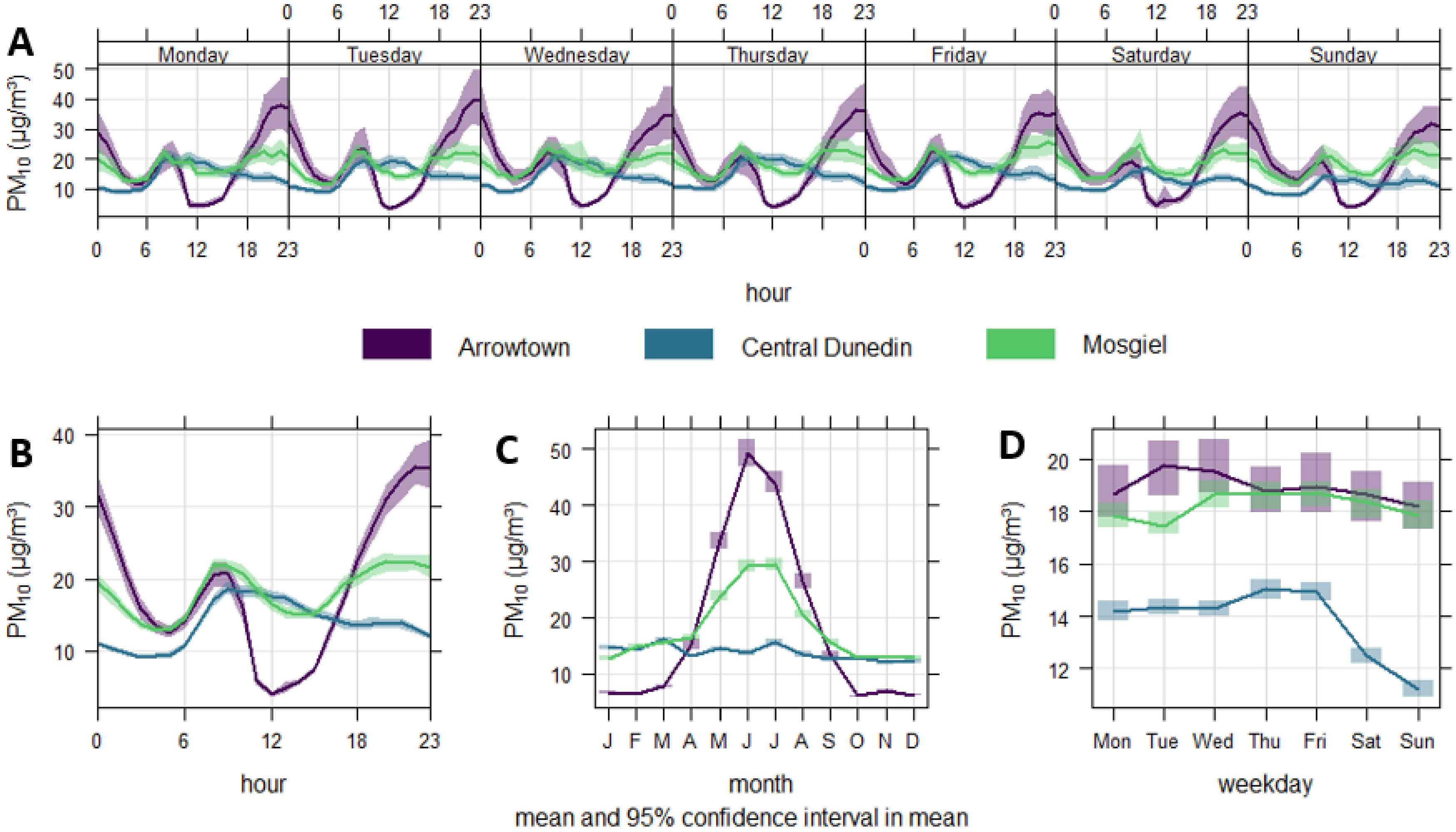


Figure 11 Key indicator sites: daily, monthly and weekday patterns, see Appendix A3 for plot interpretation

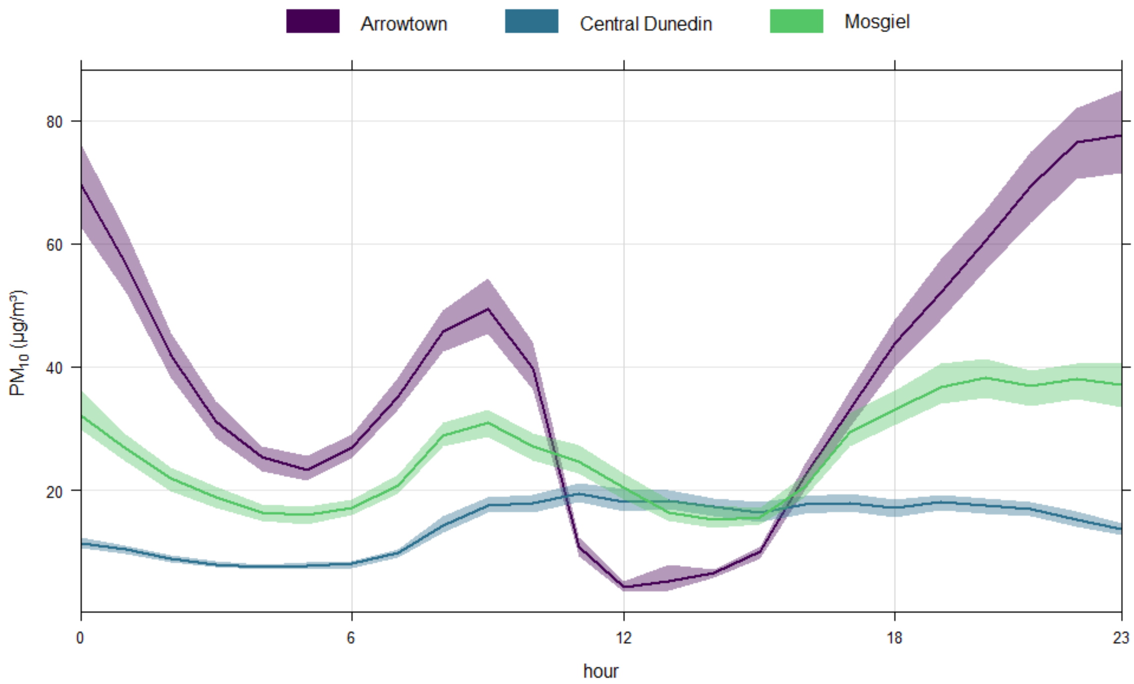


Figure 12 **Key indicator sites: diurnal PM_{10} concentrations for winter (May-August) months**

5.1.2. Short term trends: survey sites

The four winter-only survey sites – Alexandra, Clyde, Cromwell and Milton – show temporal patterns similar to Arrowtown's with bi-modal daily peaks. Alexandra's evening peak doesn't continue increasing, and flattens out between 6pm and midnight (Figure 13B), indicating an increased dispersion of pollutants, which is discussed further in Section 5.3. Milton and Cromwell have higher daily and monthly averages compared to Alexandra and Clyde, but all sites reach their annual peak in the month of July (Figure 13B and C).

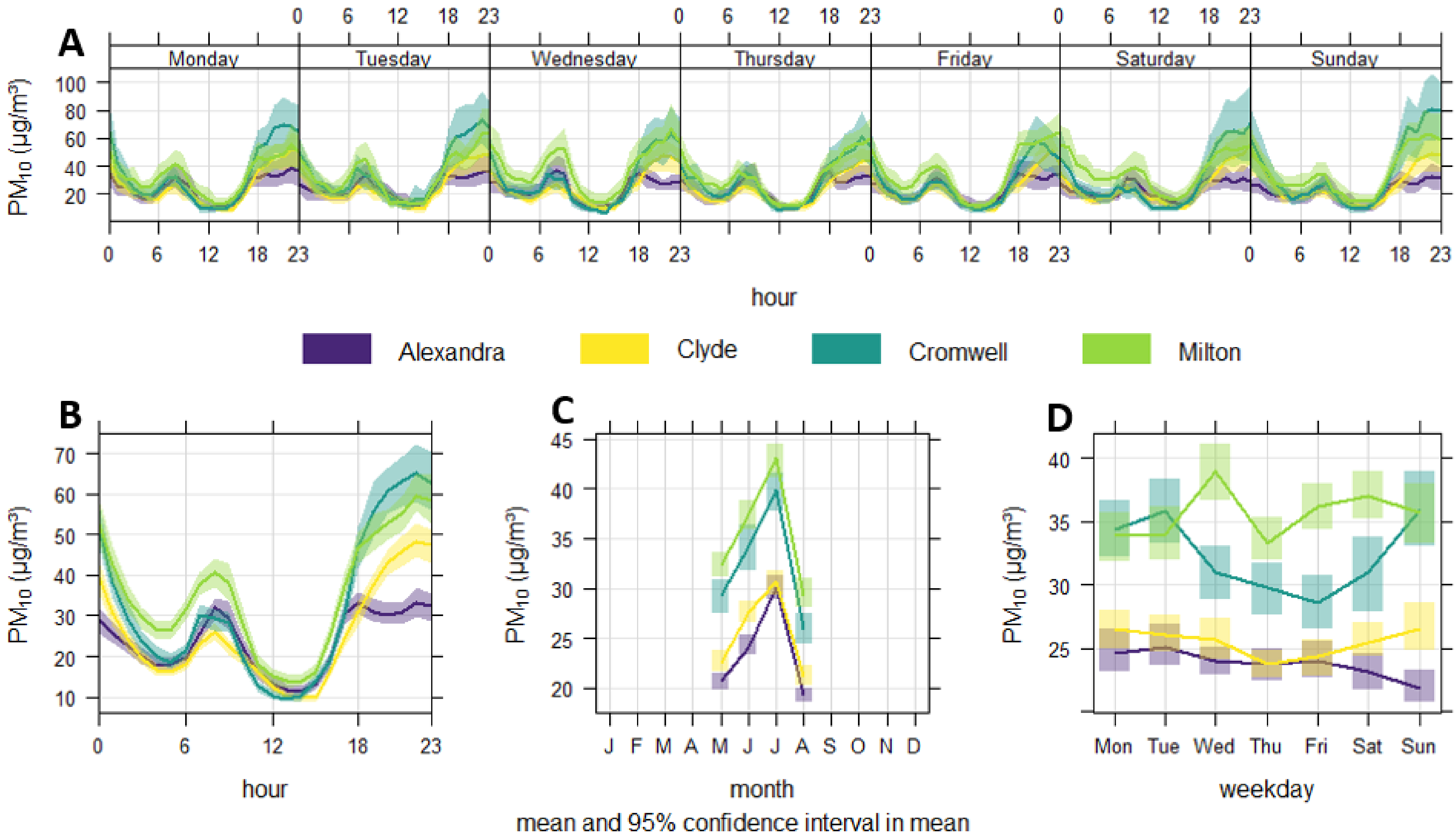


Figure 13 **Survey sites: daily, monthly and week day patterns for winter (May-August) months**

5.2. Long-term temporal trends

Statistical testing of long-term air quality data can be used to infer the effectiveness of clean air policies on emissions, provided that the impact of meteorology and other variables such as urban growth, are accounted for. For example, changes in air quality concentrations between towns can be compared to assess relative effectiveness of the programmes aimed at improving air quality. Long-term analysis was undertaken to determine whether PM_{10} concentrations are increasing, decreasing or unchanged over a specified time-period. The analysis tests whether the slope of the trend is different from zero (i.e., no trend) at the 95% confidence limit (p-value, 0.05). The trend results are presented as a percentage change per year so that the scale and direction of change can be compared between sites.

For this report trend analyses were performed at all sites for the last five and ten years. However, some sites have been re-located to an area with different typical concentrations within this timeframe, such as Alexandra and Arrowtown. Analysis can only be performed using data from a single location over consecutive years, so these two sites have slightly different time frames for their trends.

Trends were evaluated using two types of techniques – the Theil-Sen and the smooth-trend. The Theil-Sen is a non-parametric regression analysis customised for air quality data (Carslaw and Ropkins, 2012). Theil-Sen analyses work best when applied to monotonic trends i.e., data that is either increasing or decreasing steadily.

The smooth-trend analysis fits a smooth line to the dataset using the median and 95th percentile concentrations. The line is fit to show important features and variation within the data without including excessive noise from the dataset (Carslaw, 2019). Both analyses were applied to de-seasonalised data to remove the seasonal trends of high winter concentrations and low summer concentrations.

5.2.1. Trend results for key indicator sites

Theil-Sen analyses were done for year-round and winter-only (May-August inclusive) monthly mean data for Arrowtown, Central Dunedin and Mosgiel. Arrowtown and Mosgiel data were deseasonalised. A five-year and a ten-year analysis was conducted. Table 7 shows the results of these analyses.

Site		Ten-year trend 2010-2019		Five-year trend 2015-2019	
		Average % change per year [95% confidence interval]	Significance	Average % change per year [95% confidence interval]	Significance
Arrowtown[1]	Year-round			-3.6 [-6.5, -1.6]	p <0.001
	Winter			-3.5 [-5.1, -1.4]	0.001< p <0.01
Central Dunedin	Year-round	-5.3 [-5.8, -4.6]	p <0.001	-6.4 [-7.9, -4.9]	p <0.001
Mosgiel	Year-round	-3 [-3.8, -2.1]	p <0.001	-1.9 [-3.7, -0.6]	not significant
	Winter	-1.8 [-1.8, -1.8]	p <0.001	1.6 [1.5, 5.6]	p <0.001

[1]Arrowtown site was relocated in 2014, Theil-Sen analysis was applied to data for years 2014-2019 (winter only) and 2015-2019 (year-round, this accounts for 2015 being the first full year of data after relocation).

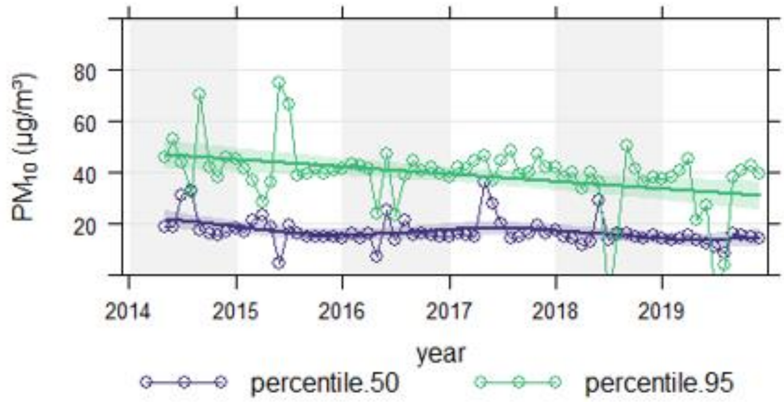
Table 7 Theil-Sen analysis results of PM_{10} monthly means at the key indicator sites

There has been a statistically significant 3.6% decrease of PM_{10} concentrations per year in Arrowtown, which equates to an 18% decrease in total since 2015. These values are similar to the previous analysis on Arrowtown 2006-2013 data, where a 4% decrease per year was reported for winter months. This confirms that Arrowtown PM_{10} concentrations have been decreasing consistently since the monitoring started; this trend is shown in both site locations and agrees with the latest emissions inventory for Arrowtown that indicated between 2006 and 2016 there was a 48% reduction in PM_{10} emissions (Wilton, 2017). The smooth trend analysis shows that the 95th percentile has been decreasing over the years, while the mean has stayed roughly the same (Figure 14A). This means that the highest pollution days have been decreasing in magnitude over time.

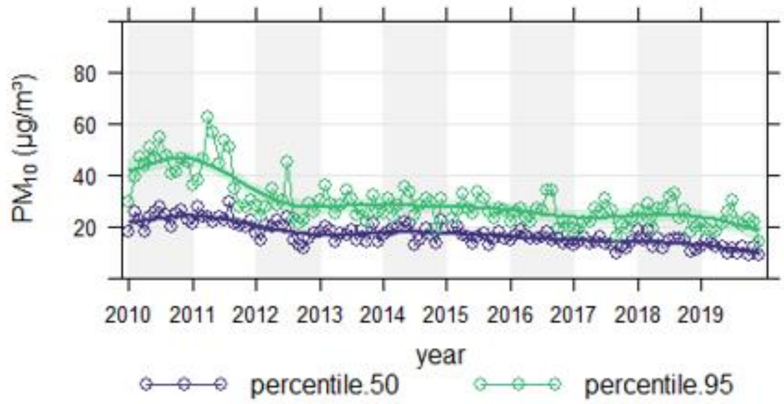
Central Dunedin shows significant PM_{10} decreases for both the ten- and five-year Theil-Sen trend analyses, between 5 and 7% per year. The improvement seen in Dunedin was partially due to the resource consent renewals during the early 2010's, where stricter conditions were introduced, but also the adoption of NESAQ-compliant home-heating. This decrease can be seen in the 95th percentiles for the smooth-trend for years 2010-2013 (Figure 14B). The years 2010 and 2011 were also notable for having high amounts of crustal matter (dust), due to construction and associated increase in vehicle activity (Davy *et al.*, 2011) at both the site of the Forsyth Barr Stadium and the university campus, which contributed towards the 24-hour exceedances and higher monthly averages (Figure 15). Figure 15 also shows that excluding these two years, it is clear that monthly averages have been declining since 2012. The five-year trend improvement may be due to a range of factors, such as further combustion technology improvements for industry and/or vehicles, or land use changes in the area, but further analysis of emission sources in Dunedin is required to confirm this.

Mosgiel shows a change in trends between the ten- and five-year trend analyses. Over the ten years PM_{10} concentrations were decreasing by 3% per year, and 1.8% per winter. Some of this has been attributed to the same industrial consent restrictions that improved concentrations in Central Dunedin, and/or the expiry of some consents (ORC, 2016). The winter percentage decrease is lower than the overall improvement, which indicates that there either haven't been significant improvements made to home heating emissions, or the urban growth within the airshed has cancelled out some of the improvement that otherwise may have occurred. Over the short-term, winter concentrations have increased by 1.6% per year, and there is no significant trend for the year-round data. Because this is a short-term trend, this will be subject to change when more data is available. The monthly 95th percentile and median have decreased between 2010 and 2013 (Figure 14C), which is similar to the pattern seen at Central Dunedin for the same time period.

A: Arrowtown



B: Central Dunedin



C: Mosgiel

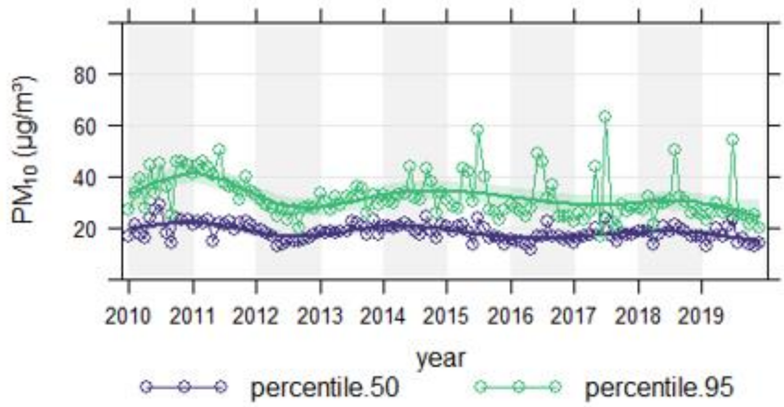
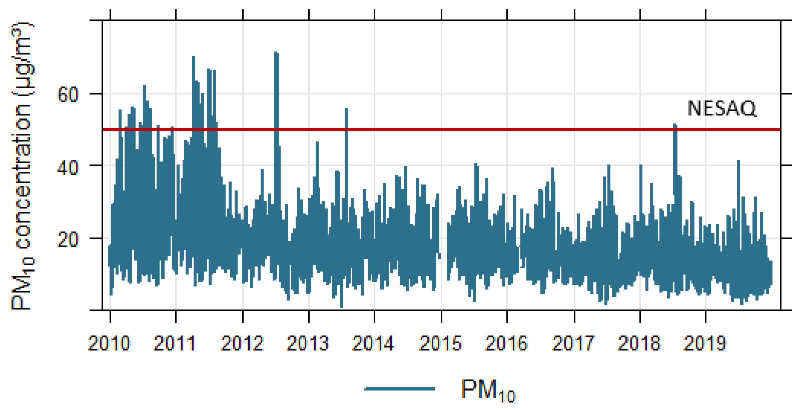


Figure 14 **Smooth-trend analysis for the key indicator sites – 95th percentile and median (based on 95th percentile and median 24-hour average in each month) indicate decreasing concentrations over time. The 95th percentile displays the top 5% 24-hour averages. The Arrowtown 95th percentile has negative values in 2018 and 2019 due to having lower concentrations than normal on high pollution nights.**

A: 24-hour average



B: Monthly average

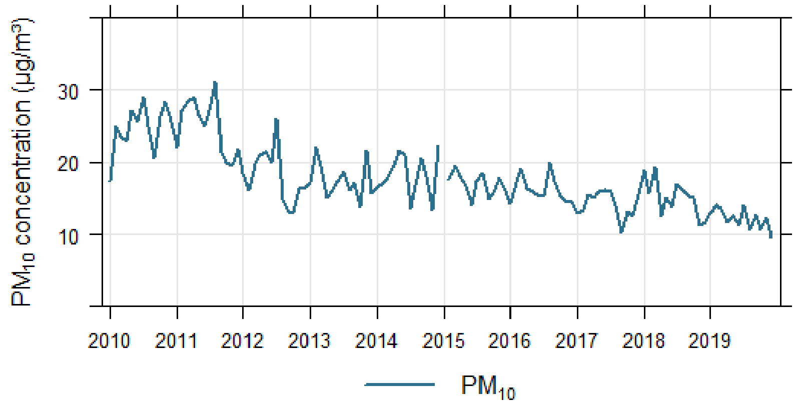


Figure 15 **24-hour and monthly average PM$_{10}$ for Central Dunedin (2010-2019)**

5.2.2. Trend results for survey sites

Table 8 displays the Theil-Sen results for the survey sites during winter months; the data for all sites were deseasonalised.

Site		ten-year trend 2010-2019		five-year trend 2015-2019	
		Average % change per year [95% confidence interval]	Significance	Average % change per year [95% confidence interval]	Significance
Alexandra[1]	Year-round	-0.9 [-.2.0, 0.4]	not significant		
	Winter	-2.3 [-2.8, -1.2]	p <0.001		
Balclutha[2]	Winter	1.3 [0.2, 2.5]	0.01< p <0.05		
Clyde		-3.5 [-4.1, -2.6]	p <0.001	-6.0 [-9.8, -3.5]	p <0.001
Cromwell		-1.3 [-2.1, -0.4]	0.01< p <0.05	-6.3 [-6.1, -2.7]	p <0.001
Milton		-2.7 [3.3, -2.0]	p <0.001	-7.4 [-10.5, -3.7]	p <0.001

[1] Alexandra site was relocated in May 2017, Theil-Sen analysis was applied to data for years 2010-2016
[2] Balclutha site was decommissioned in September 2018, Theil-Sen analysis was applied to data for years 2010-2016

Table 8 **Theil-Sen analysis results of PM$_{10}$ at the survey sites**

Alexandra shows a statistically significant decrease in concentrations for winter values only, of 2.3% per year, which means that winter concentrations improved by 16% in total over the seven years. There is no significant trend for the year-round data, but seasonal analysis show that summer concentrations are increasing slightly, which may counteract the other seasons. The smooth-trend analysis indicates that the de-seasonalised monthly 95th percentiles and medians do not trend upwards or downwards but remain consistent (Figure 16A).

Balclutha demonstrates an increase in concentrations between 2010 and 2018, with the years 2012 and 2017 showing higher monthly 95th percentiles in the smooth trend analysis (Figure 16B).

Clyde, Cromwell and Milton have all experienced significant decreases in PM_{10} concentrations over the five- and ten-year time periods. Clyde showed a 35% improvement over the ten years, which can be seen in the smooth-trend plot (Figure 16C). In the Clyde and Cromwell sites the impact of 2017, a cold winter, can be seen as a peak of the median and 95th percentile in the smooth-trend analyses.

Cromwell shows the least improvement, with only 13% over the last ten years, which is estimated to be attributed to urban growth and contribution of new burners adding to the airshed, offsetting the improvements made via the implementation incentives.

Milton has improved by 27% in total over the last ten years. Clyde, Cromwell and Milton each demonstrate a larger rate of improvement in the five-year trend (between 6 and 7% improvement per year), than the ten-year trend, but further data for future years is required to confirm this.

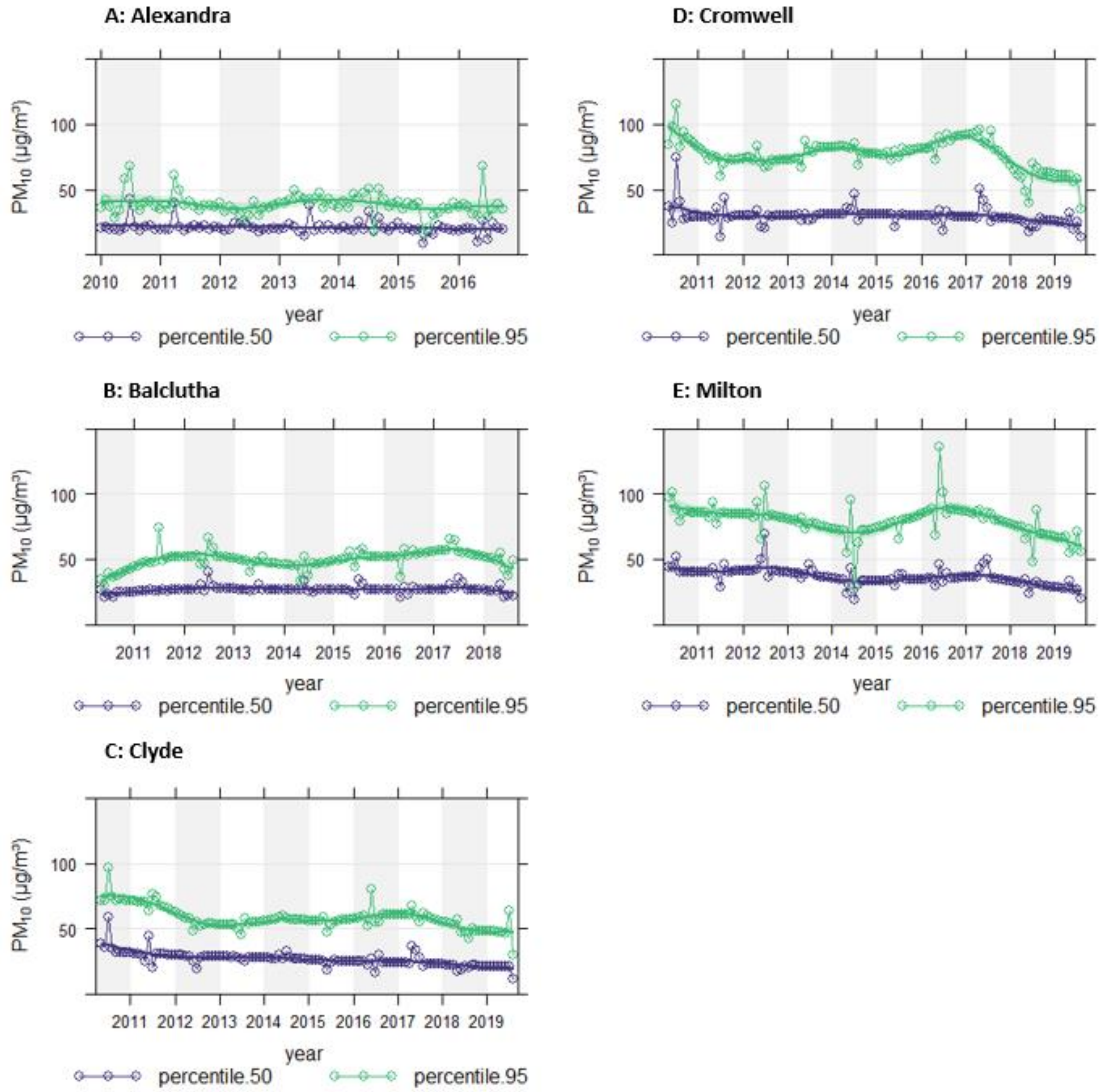


Figure 16 **Smooth-trend analysis for the survey sites – 95th percentile and median (based on 95th percentile and median 24-hour average in each month). Alexandra smooth trend is based on year-round data.**

5.3. Spatial distribution of PM_{10}

Stationary instruments 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 may not be representative of the entire area. The NESAQ requires monitoring to be undertaken where the air quality standards are likely to be breached by the greatest margin or the highest frequency.

Mobile monitoring across a town using a portable air monitor offers a spatial snapshot of ambient air quality. As of 2019 ORC has conducted 14 spatial studies to either provide context for the existing monitoring or investigate relative PM levels in towns without monitors. New technology has also been developed in the form of low-cost sensors, multiple units of which can be deployed in a network to allow the detection of spatial and temporal differences in PM concentrations across an airshed.

It has been found that PM can vary from one street to the next, depending on emissions and wind conditions. Nocturnal wind drainage can have the effect of pushing the concentrations towards one part of town, such as the southern area in Milton; or of dispersing pollutants and reducing the relative concentrations such as in the central area of Balclutha.

Housing age and housing density can also contribute to the variation, with the central area of older housing in Cromwell experiencing the highest concentrations of that airshed, while the denser housing areas of towns such as Wanaka also show that high PM_{10} can occur in pockets across an airshed in complicated concentration gradients.

Topography can also have a significant influence on particulate dispersion, along with nocturnal drainage winds, allowing PM_{10} to accumulate in topographical basins, in a zone of convergence like central Alexandra, or up against barriers such as hills in north-east Arrowtown.

These spatial differences were demonstrated by the relocation of two monitoring sites – Alexandra and Arrowtown. Both were relocated due to loss of site availability, and demonstrate the complexity of air quality in small urban areas. In the case of Alexandra, the current site was moved 700 m to the southeast of the original site, and has been recording lower PM_{10} concentrations than the previous site. The morning and evening peaks are much smaller, which indicates that there are fewer pollutant sources, and/or more favourable dispersion conditions (Figure 17). The previous site had more frequent calm periods (25%, where calm is equal to a wind speed of 0 m/s) than the current site (0%), which indicates an increased likelihood of pollutants accumulating rather than dispersing. Wind direction also varies between the sites, with the previous site's dominant wind direction from the north to northeast directions, the direction of residential areas and the newer site having one dominant wind direction of the northeast, which is adjacent to the commercial area of town (Figure 18).

The meteorology of the Alexandra basin is very complex and has a significant part to play in the spatial and temporal characteristics seen in the data. Spatially, the previous site was found to be an area of katabatic convergence of air flows from the northeast and southeast directions (Tate, 2011) which are likely to create an area of stagnant air for pollutants to accumulate (Price, 2014). Temporally, PM_{10} data in Alexandra has been identified as having a unique dip in evening concentrations, essentially creating a third diurnal peak. This can be seen in both sets of data in Figure 17. This dip is likely to be caused by turbulence in the boundary layer, causing a period of vertical pollution dispersion (Price, 2014).

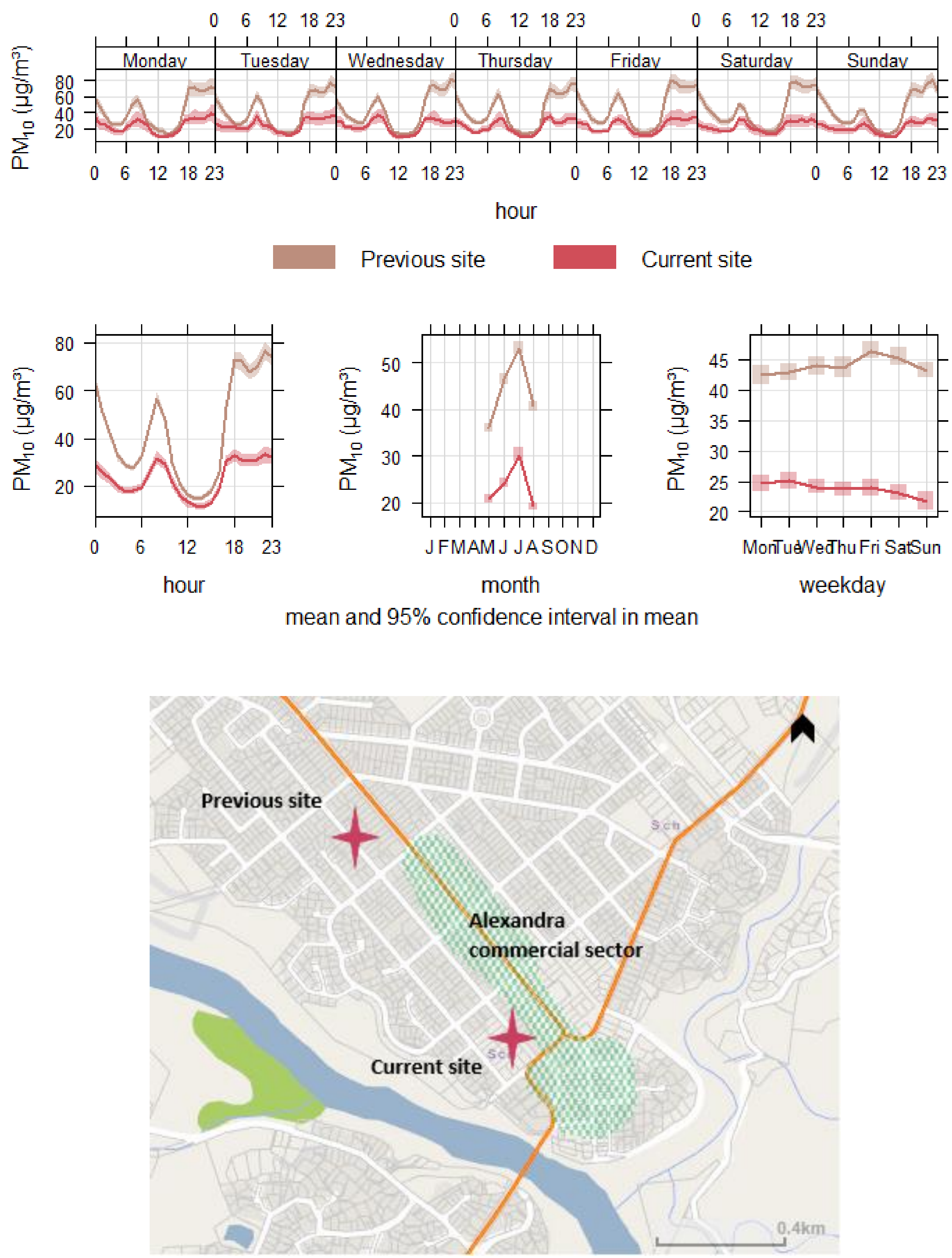


Figure 17 **Winter temporal variation between different monitoring locations in Alexandra where recorded PM$_{10}$ concentrations are much lower at the current site**

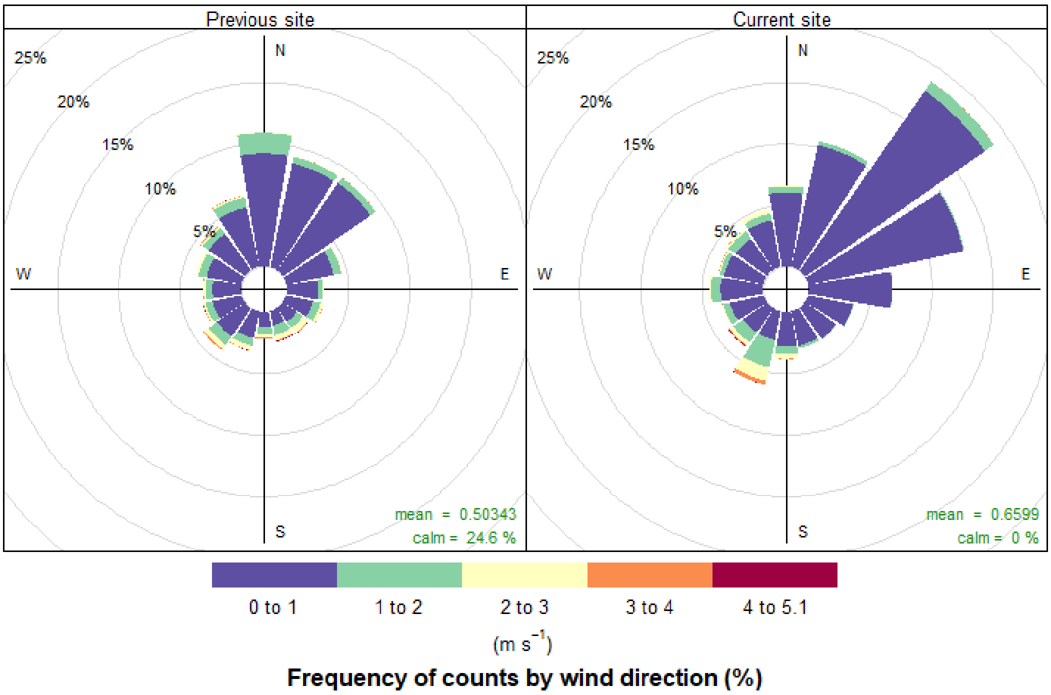


Figure 18 **Alexandra: winter wind roses (1-hour average) for the previous and current site location, showing a change in wind speeds and predominant direction.**

The site relocation in Arrowtown, 400m to the east of the previous site, has resulted in slightly higher concentrations being recorded than those at the previous site, with diurnal patterns indicating a later evening peak, and much slower dispersion time in the early hours of the morning (Figure 19). This is likely due to Arrowtown having a clear pollution gradient, from low PM in the northwest, to higher PM to the southeast, where the new site is located (Longley, 2020). It is probable that low north-westerly breezes cause concentrations to accumulate at the eastern side of the town where the mountains act as a barrier to dispersion. In addition, the wind direction is different between the sites, with the previous site having a predominantly westerly wind direction and the current site having a predominantly northerly wind (Figure 20). This may indicate that the breeze turns northerly as it moves south along the river valley, bringing the accumulated particulate matter with it.

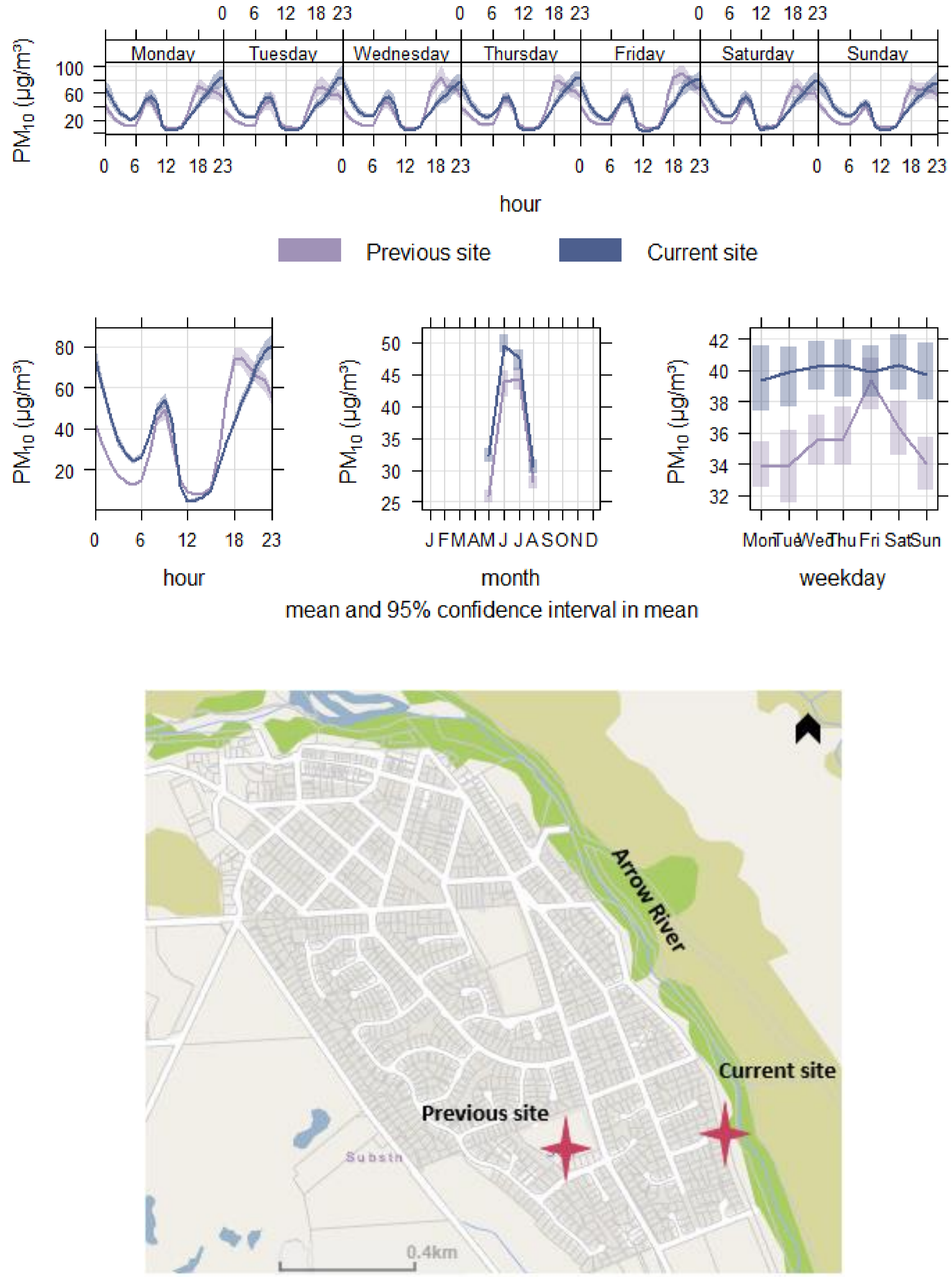


Figure 19 **Temporal variation between different monitoring locations in Arrowtown where recorded PM_{10} concentrations are slightly higher at the current site**

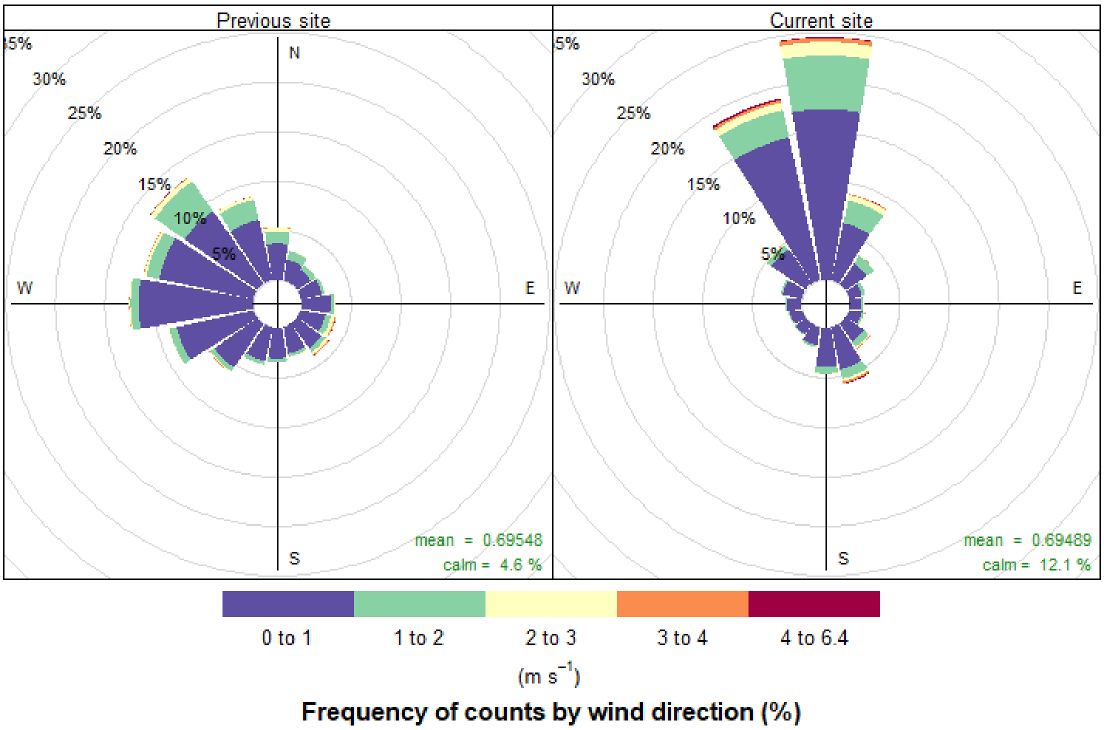


Figure 20 **Arrowtown: winter wind roses (1-hour average) for the previous and current site location, showing a change in predominant wind direction.**

6. Pressures and influences on air quality

As discussed in Section 5, ambient air quality at any location is the result of a complex relationship between the type and amount of emissions, and the meteorology and topography. This section discusses the major emission sources found in Otago and the meteorological conditions that affect them.

6.1. Emissions

Woodsmoke is the main source of PM_{10} emissions in Otago. However, it is made up of several other components, many of which are toxic and/or carcinogenic, which can vary depending on what is burnt and how it is burnt. For example, lead can be emitted from burning old painted wood, and arsenic is an emission from burning treated wood. Incomplete combustion, caused by reduced air flow to the fire, produces pollutants such as benzo(a)pyrene, a polycyclic aromatic hydrocarbon (PAH) which is a human carcinogen and black carbon which is a climate change pollutant. Gases such as oxides of nitrogen and carbon monoxide are also produced by the burning of wood and other biomass (Naeher *et. al.*, 2007).

6.1.1. Household emissions

To obtain information on home heating emissions, both census data and emissions inventories are used. Census data provides the fuel types used in home heating and emissions inventories are a tool for compiling total estimated emissions for a town using fuel types, burner age estimations and fuel usage.

6.1.2. Wood burners

Data from the most recent census (Statistics New Zealand, 2018) can provide trend information when compared to census results from 2006 and 2013. 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 9. 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 most towns (e.g. Alexandra, Arrowtown, Clyde, Cromwell and Mosgiel).

Currently, in Otago, the use of wood burners is reported in 51% of all households, well above the national average of 31%. Much higher than average percentages of wood use are reported in Clyde and Milton (62% and 67% respectively).

Site	2006		2013		2018	
	# wood burners	% wood burners	# wood burners	% wood burners	# wood burners	% wood burners
Alexandra	1,101	55%	1,083	51%	1,206	51%
Arrowtown	549	62%	555	57%	579	57%
Balclutha	960	58%	963	58%	849	50%
Clyde	252	64%	273	62%	333	62%
Cromwell	864	59%	981	56%	1,200	56%
Dunedin	22,602	50%	21,918	47%	20,082	41%
Milton	558	68%	585	69%	576	67%
Mosgiel	2,037	48%	1,989	44%	2,055	41%

Table 9 Census data on reported wood burner use for Otago towns

The most recent emissions inventories were undertaken in the towns of Alexandra, Arrowtown, Milton and Mosgiel (Wilton 2016); and Clyde, Cromwell and Wanaka (Wilton 2019). The following graphs show the different proportions of types of wood burner used in each airshed, and the subsequent emissions these burners account for. Each airshed is dominated by wood burner use, however there are higher frequencies of multi-fuel burners in Milton and Mosgiel compared to other airsheds. Wanaka has the highest number of open fires (Figure 21).

The different types of burners impact the quantity of PM_{10} emissions. Mosgiel has the highest daily emissions in winter, with 362 kg/day, and the highest emission density, 630 g/ha. Most of these are from wood-burners, but the difference between Figure 21 and 21 illustrate the disproportionate amount of emissions from multi-fuel burners, relative to the burner numbers.

The emission densities are also affected by the size (area) of the airshed. Arrowtown and Milton's winter emissions are both around 100 kg/day, which is among the lowest, however they both have relatively small airsheds, with 236 and 202 hectares respectively. This results in these two towns having among the highest emission densities of 397 and 488 g/ha. Conversely Wanaka has high emissions of 300 kg/day in winter, and the lowest emission density of the airsheds, at 105 g/ha, due to having a large airshed area (Figure 22). Comparing emissions densities between years in future studies will help identify emissions trends through time, and further assess strategies to reduce them.

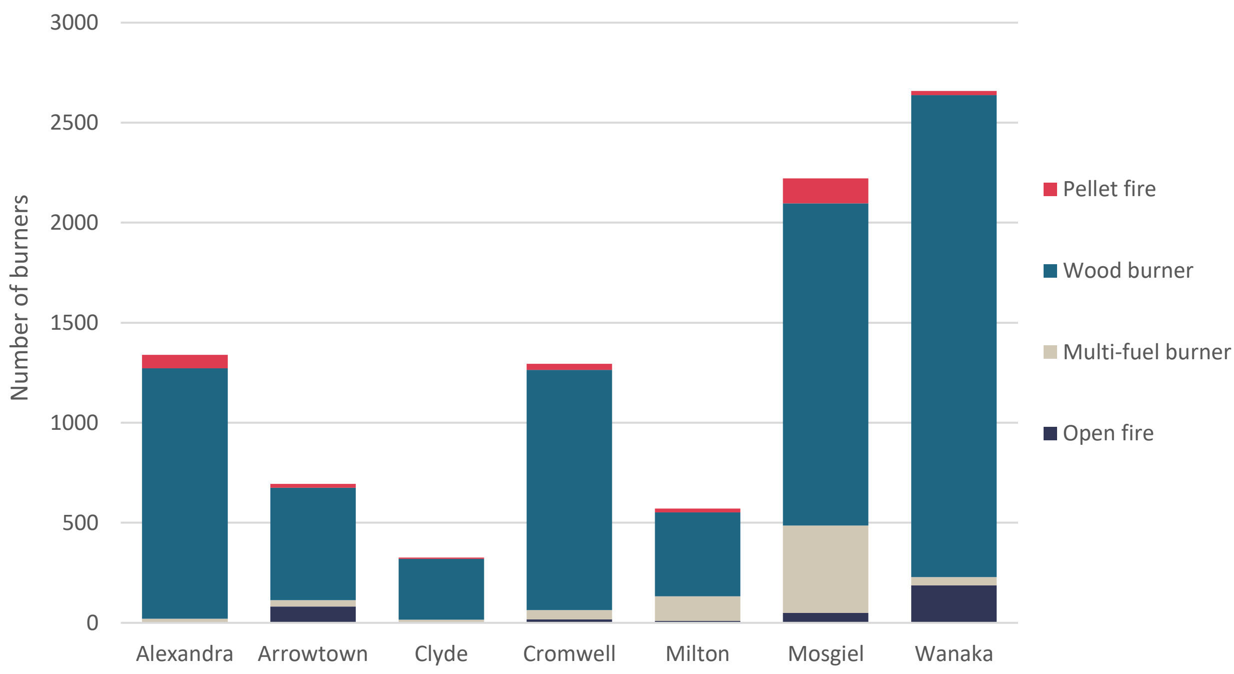


Figure 21 **Number of households with solid-fuel burners (2016 and 2019 emission inventories)**

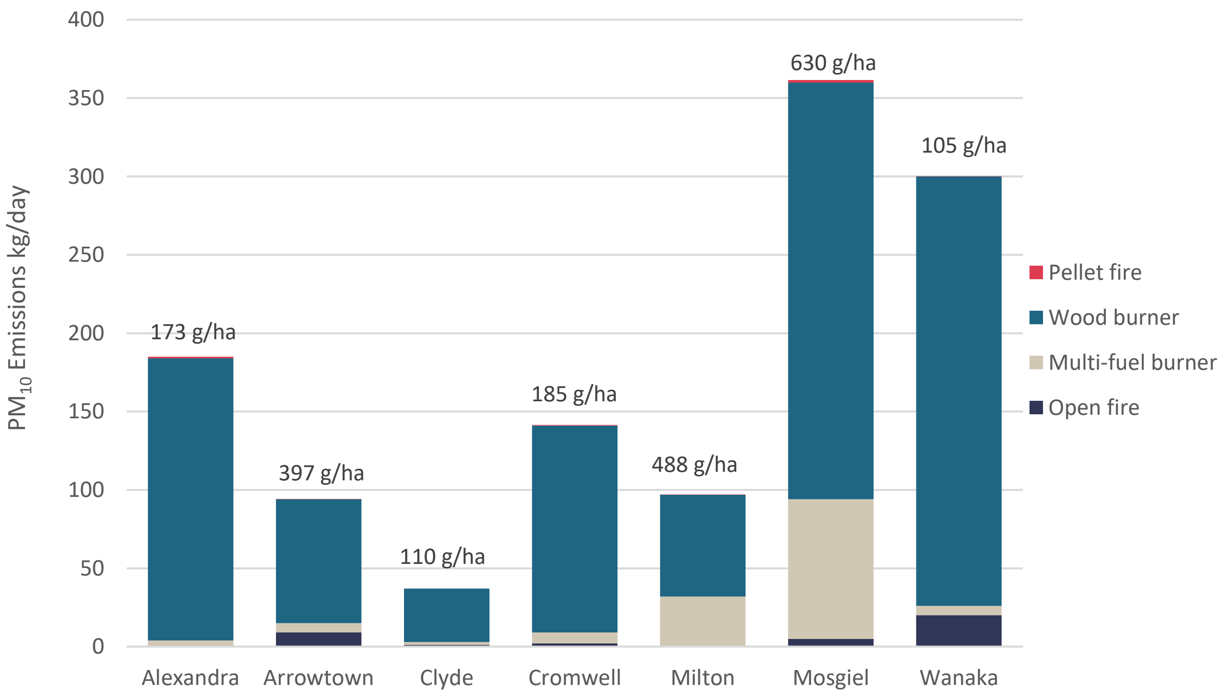


Figure 22 **Winter PM_{10} emissions (kg/day) by appliance type for Otago towns, with emissions density (g/ha/day) above each bar (2016 and 2019 emission inventories)**

Wood burner age also has an impact on emissions, with burners more than 15 years old contributing significantly to each airsheds' total emissions (Figure 23). Alexandra, Arrowtown, Cromwell and Clyde have all had past campaigns encouraging upgrading of older burners during the late 2000's onwards, so there is a higher proportion of newer burners of less than 10 years old in these towns. Milton has also been part of these campaigns but has been slightly less successful in switching to newer burners. Mosgiel and Wanaka have the highest number of older burners, which is in accordance with not having had any active management for replacing them with low-emission appliances.

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 sets stricter standards in Air Zone 1 towns, requiring all domestic-heating appliances to be fully compliant with either 0.7 g/kg or 1.5 g/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 (ORC, 2016).

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

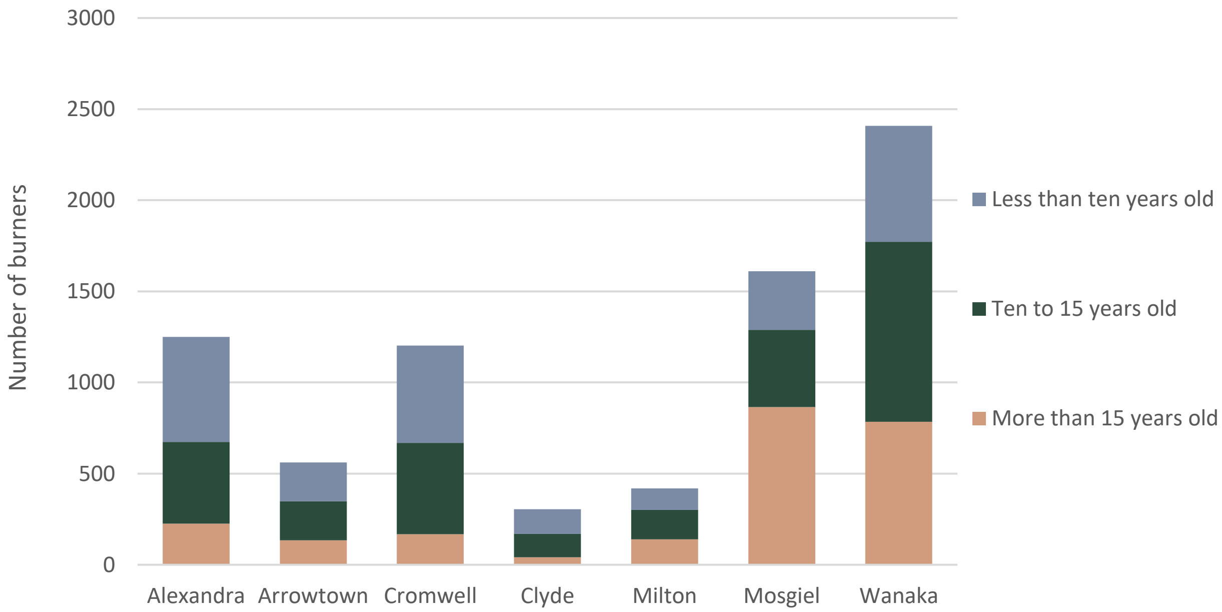


Figure 23 **Age of wood burners in Otago towns (2016 and 2019 emission inventories)**

6.1.3. Coal burners

In the 2018 Census, 4.8% of all Otago households (4134 dwellings) reported using coal for domestic heating, down from 14% in 2013. This is above the national average of 1.2%, with most of the usage reported in southern areas of Otago. The number of coal burners has reduced over time, to less than 4% in most districts. Of the five Otago territorial areas, the Clutha district has the highest percentage of households (20%, 1401 dwellings) using coal for home heating (Figure 24).

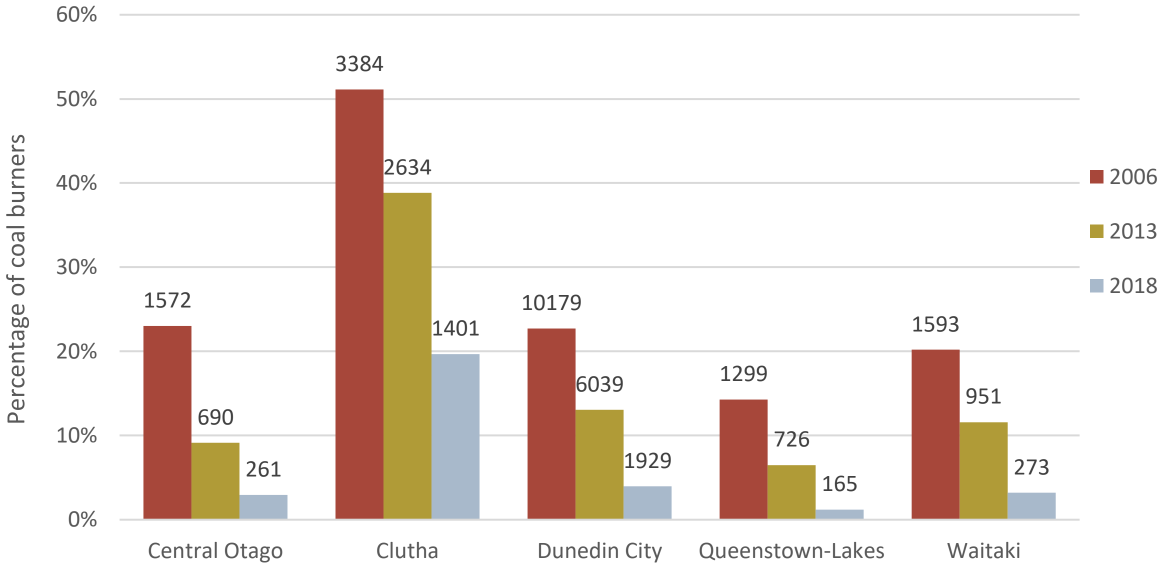


Figure 24 **Percentage of households that use a coal burner for domestic heating from 2006 to 2018. The number of coal burners present in each district are displayed above each bar**

6.1.4. Other sources of heat

In addition to solid-fuel burners, other sources of heating reported in the 2018 census include heat pumps, electric heaters, mains and bottled gas, and pellet burners. Heat pumps are the most widely used form of heating, with anywhere between 37% and 64% of households (depending on district) reporting its use. Dunedin City district records the highest percentage of heat pump and electricity use, with 64% and 47% respectively (Table 10).

Pellet burners and bottled gas are not commonly used, and mains gas is used more frequently in Queenstown Lakes (16%) followed by Central Otago (9%). Other sources of heating may include diesel burners, and solar power, and varies among the districts, between 10% and 20% of households.

District	Heat pump	Electric heater	Mains gas	Bottled gas	Other
Central Otago	50%	31%	9%	3%	17%
Clutha	37%	26%	3%	4%	14%
Dunedin City	64%	47%	5%	3%	10%
Queenstown-Lakes	52%	40%	16%	2%	20%
Waitaki	49%	34%	4%	3%	10%

Table 10 **Percentage of households using other sources of heating in 2018**

6.1.5. Emissions from outdoor burning

Nationally, outdoor burning is estimated to account for 22% of PM_{10} emissions (Metcalfe *et al.* 2015). 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 the nature of the material burned and the distances to the property boundaries. The strictest rules are for residential properties in Air Zones 1 and 2 (Table 7).

Rule	Air Zones 1 & 2		Air Zone 3	
	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	50m	100m	n/a	n/a
Smoke or odour or PM must not be offensive or objectionable at or beyond the property boundary	✓	✓	✓	✓

Table 11 ORC Air Plan: outdoor burning rules

In almost all instances[2], the discharge of contaminants from a variety of materials, such as tyres, treated timber and painted material 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 outdoor burning.

6.1.6. Industrial discharges

Industrial and commercial discharges to air are regulated through the Air Plan, with larger discharges requiring consent. 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. It is estimated that about 10 tonnes of PM_{10} have been removed from the Central Dunedin airshed annually due to this initiative (ORC, 2016).

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

6.2. The influence 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. Otago has 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.

6.2.1. Arrowtown

Arrowtown is a small town in the Queenstown Lakes District, and has very poor air quality during winter months, due to home heating emissions, but is profoundly influenced by the weather and topography. Arrowtown has a dry climate with extreme temperatures during winter and summer. It is not unusual for overnight temperatures in winter to reach -5° C for several consecutive nights.

Anticyclones, or high-pressure systems are responsible very calm atmospheric conditions which can lead to low wind speeds and strong temperature inversions. 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 emissions to become trapped near the ground instead of being able to disperse into the atmosphere because vertical mixing is inhibited (Figure 25).

The relationship between air temperature and PM_{10} in Arrowtown indicates that the high pollution nights occur when daily temperatures drop below about 5°C, and when average wind speeds are below 2 m/s. (Figure 26). Figure 27 shows that most hourly wind speeds are below 2 m/s, and the dominant wind direction is from the north. The highest hourly concentrations of PM_{10} occur when wind speed is very low, and these concentrations originate from the west of the monitor (Figure 28). This relationship is further demonstrated in Figure 29, which shows that the highest hourly concentrations of PM_{10} occur at the lowest wind speeds and temperatures.

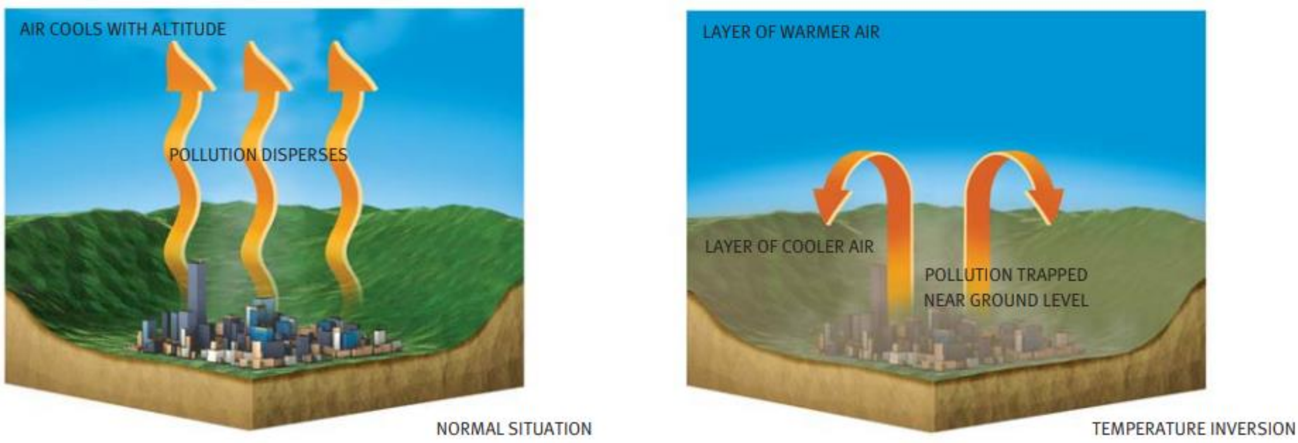


Figure 25 **A temperature inversion traps cool air and pollutants at ground level. Source: Ministry for the Environment**

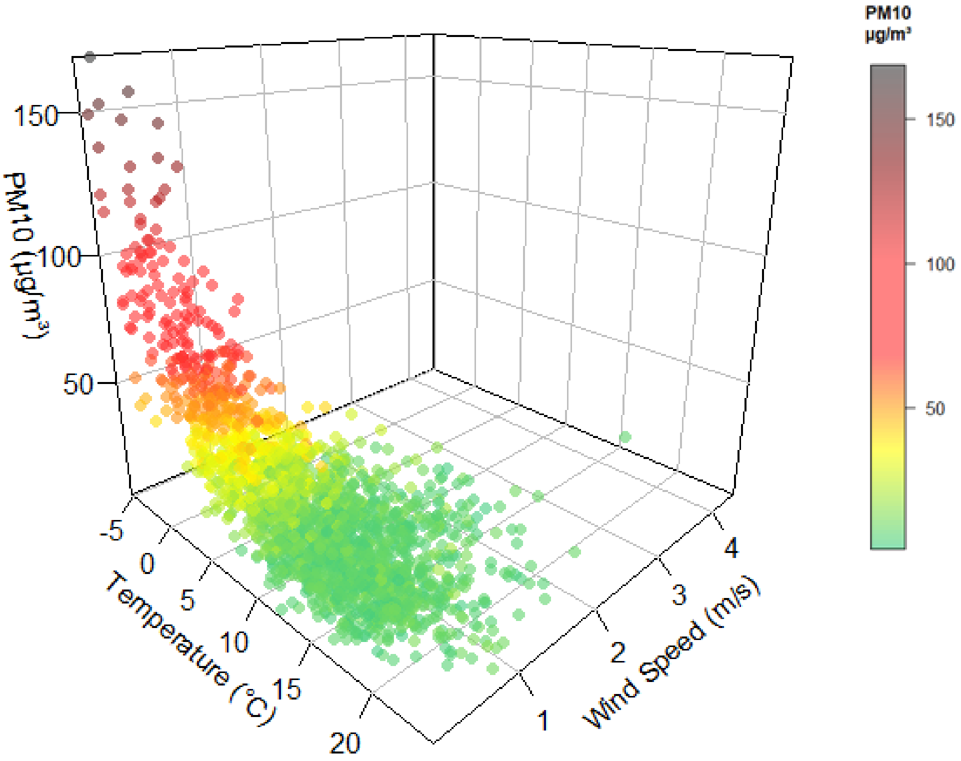


Figure 26 **Arrowtown: Three-axis plot of the relationship between PM_{10}, air temperature and wind speed (24-hour average)**

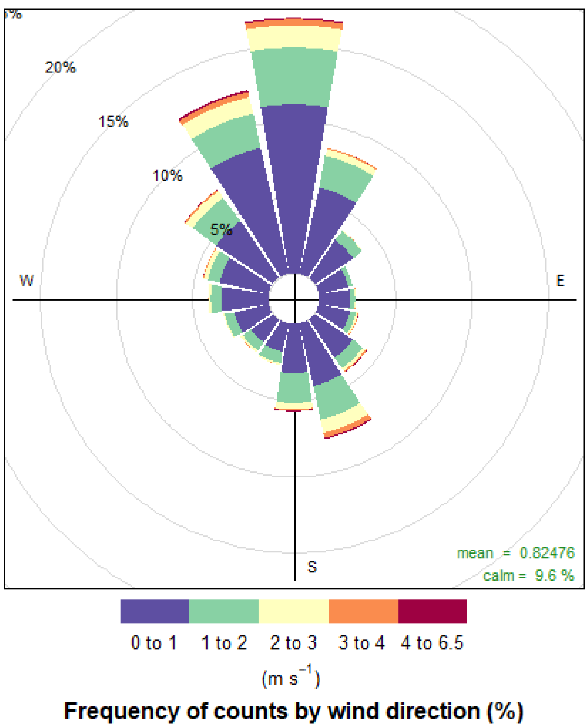


Figure 27 **Arrowtown: wind rose (1-hour average)**

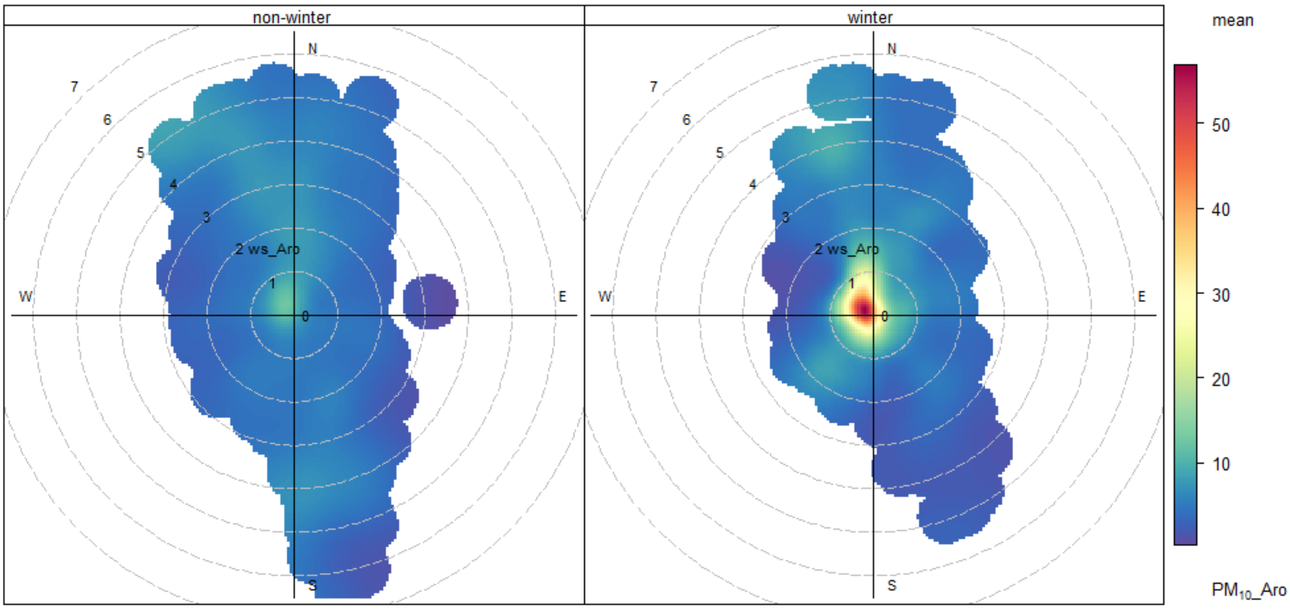
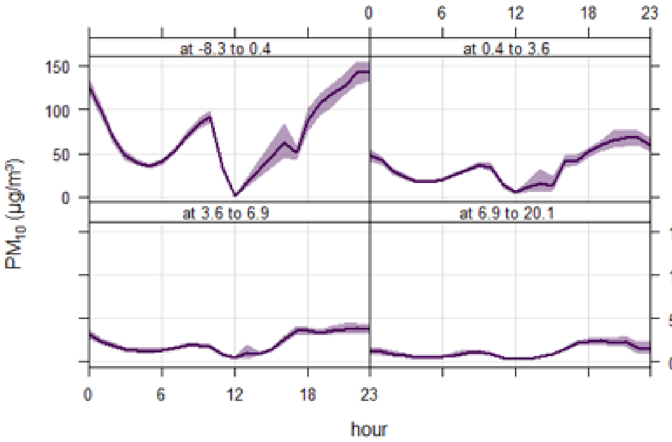


Figure 28 **Arrowtown: Bivariate polar plot of non-winter (Sep-Apr) and winter (May-Aug) PM_{10} by wind speed and direction (1-hour average), showing high winter concentrations at low wind speeds from the north and west directions. See Appendix A3 for plot interpretation.**

A: Arrowtown PM_{10} conditioned by temperature



B: Arrowtown PM_{10} conditioned by wind speed

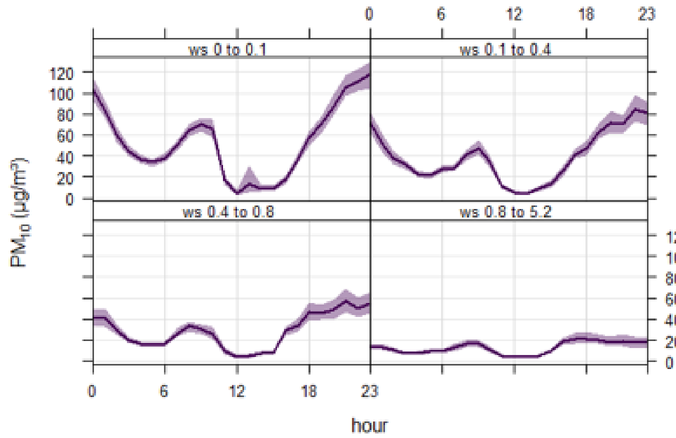


Figure 29 **Arrowtown: winter diurnal PM_{10} at temperatures and wind speeds divided by quantiles of equal sizes. High concentrations and dirunal peaks occur at the lowest quantiles of temperature and wind speeds.**

6.2.2. Central Dunedin

The Central Dunedin airshed's daily PM_{10} concentrations are not correlated with air temperature, and moderate pollution levels occur throughout the range of temperatures experienced. Higher PM_{10} concentrations usually occur at lower wind speeds but this relationship is not very strong (Figure 30).

Compared to the inland airsheds, Dunedin weather is characterised by milder temperatures and stronger, coastal winds. Prevailing winds are from west-northwest and the northeast to east-northeast directions (Figure 31). This air movement helps disperse pollution, lowering the overall PM_{10} concentrations. The air quality monitor is located within the university campus, in an area of mixed industrial, commercial and residential property, 500 m east of the main highway. This site also has the potential influence of natural PM_{10} such as sea salt – up to 20% of coarse PM fraction in 2011 (Davy *et al*., 2011). Consequently, it has a complicated pattern of contributing emission sources that are not particularly seasonal (Figure 32).

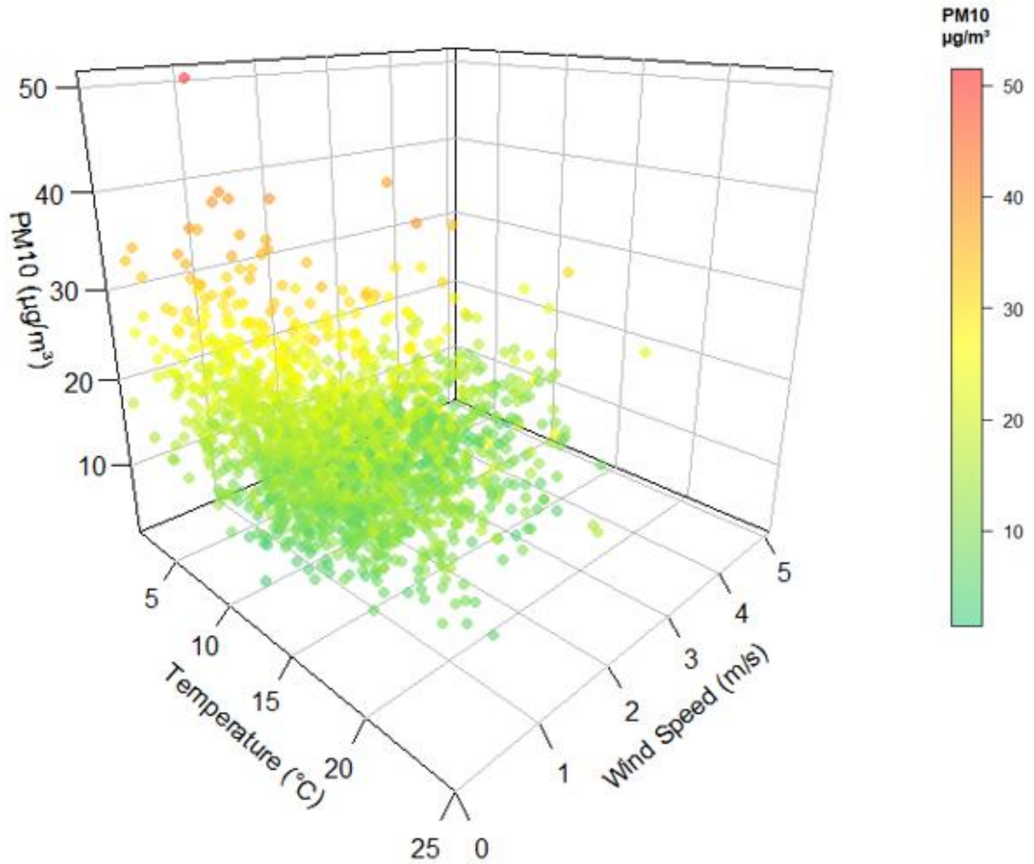


Figure 30 **Central Dunedin: Three-axis plot of the relationship between PM_{10}, air temperature and wind speed (24-hour average)**

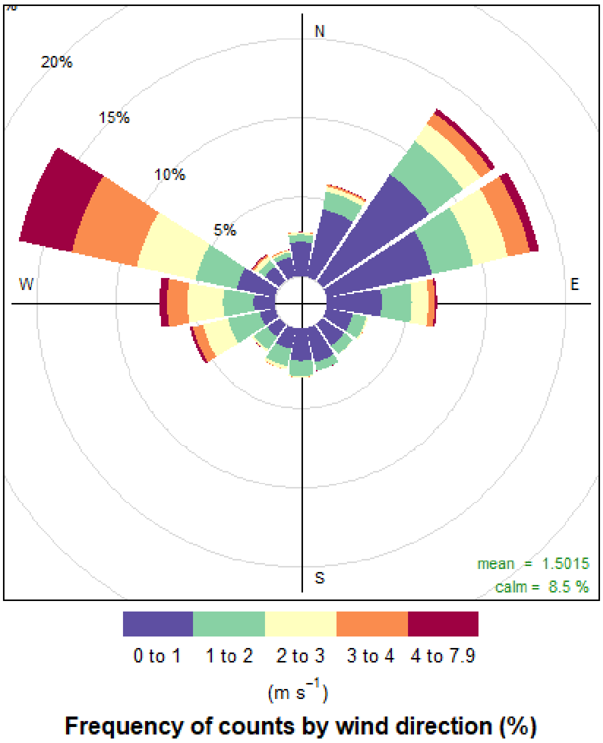


Figure 31 **Central Dunedin: wind rose (1-hour average)**

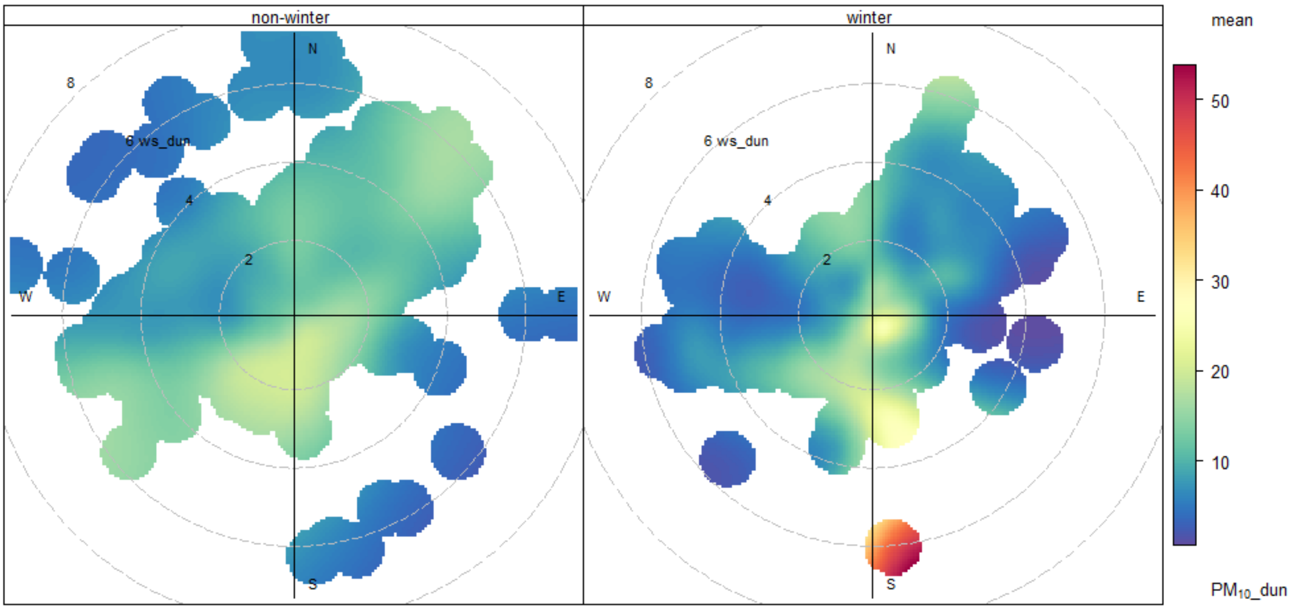


Figure 32 **Central Dunedin: Bivariate polar plot of non-winter (Sep- Apr) and winter (May-Aug) PM_{10} by wind speed and direction (1-hour average). Dunedin has a more complex pattern of emission sources than the other sites.**

6.2.3. Mosgiel

Mosgiel is a town located on the Taieri Plain just inland from Dunedin and has weather characteristics that are a combination of the coastal and continental climates. Temperatures are more extreme than in Dunedin but not as extreme as Arrowtown, and wind speeds are low enough that temperature inversions often form on the Taieri Plain. The monitoring instrument is located in central Mosgiel.

High daily PM_{10} concentrations are most often correlated to cold temperatures and lower wind speeds (Figure 33). At 47%, Mosgiel has a very high percentage of calm winds. The predominant wind directions are west-southwest, north-northeast and the southeast directions (Figure 34). The bivariate polar plot of Mosgiel shows that it has multiple sources of emissions in non-winter months (September to April) with the south-east direction shown to have higher concentrations occurring when wind speeds are between 3 and 5 m/s, which indicates they are sources further away from the monitor. During winter months (May to August) the high concentrations occur at low wind speeds, which indicates emission sources from home heating (Figure 35).

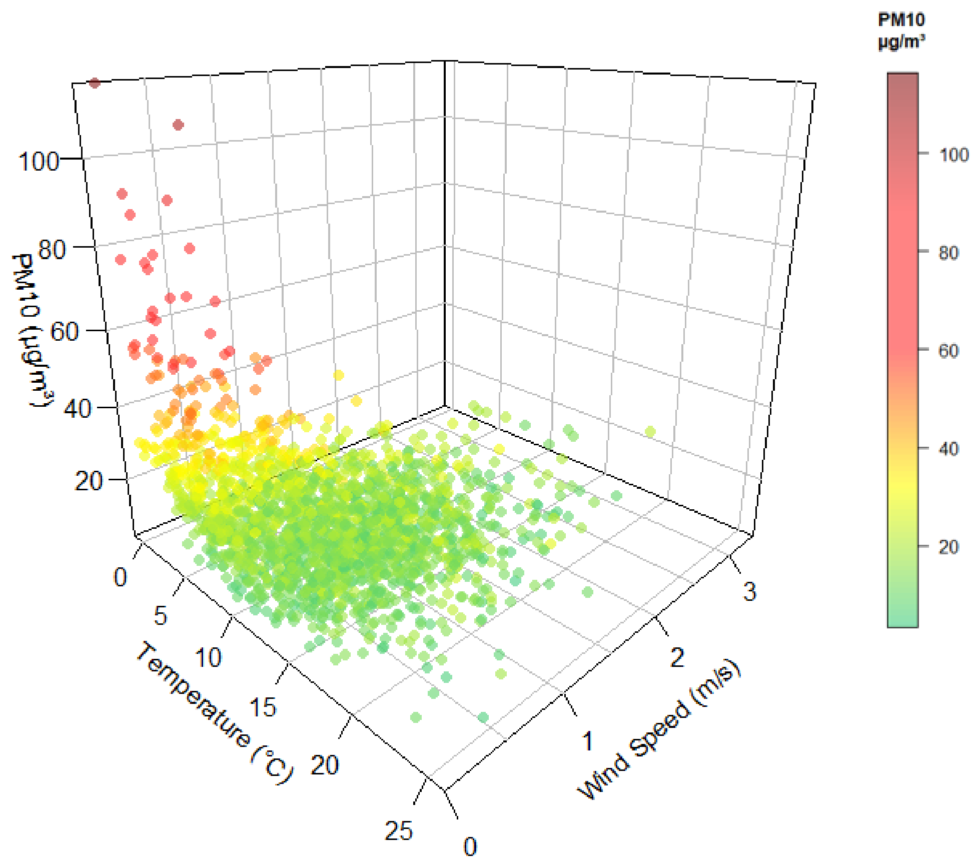


Figure 33 **Mosgiel: Three-axis plot of the relationship between PM_{10}, air temperature and wind speed (24-hour average)**

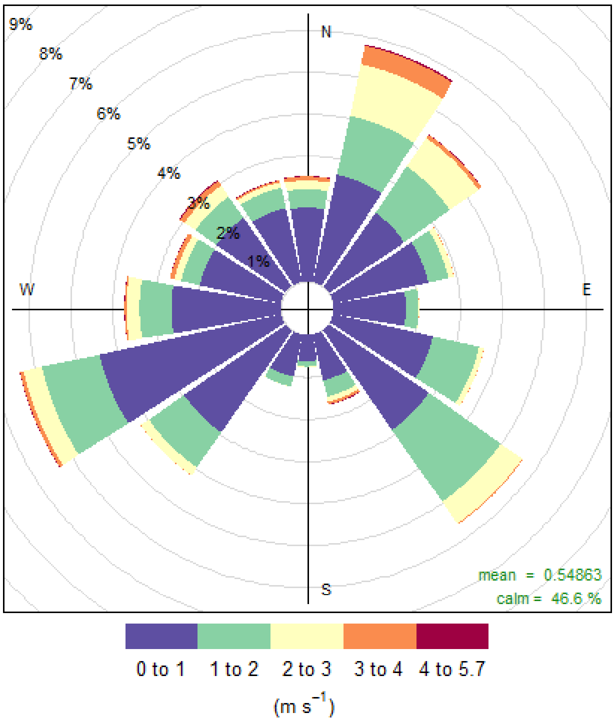


Figure 34 **Mosgiel: wind rose (1-hour average)**

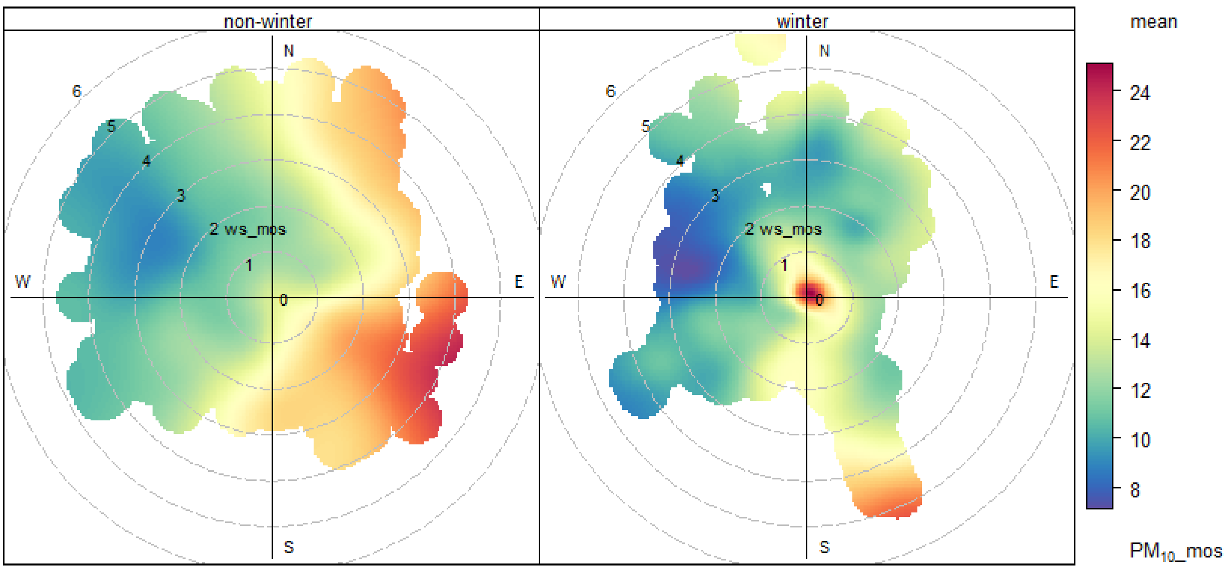


Figure 35 **Mosgiel: Bivariate polar plot of non-winter (Sep- Apr) and winter (May-Aug) PM_{10} by wind speed and direction (1-hour averages), showing high winter concentrations at low wind speeds, and moderate concentrations from the south-east at higher wind speeds during non-winter months.**

7. Discussion

7.1. State and trends 2010 – 2019

Air quality monitoring results indicate a wide range of ambient air quality throughout the region over the last ten years. Emissions from solid-fuel burners used for domestic heating are the primary contributor of PM_{10} in the residential areas of Otago (Wilton 2016 and 2019), which means that degraded air quality occurs in winter.

Central and local government programmes to improve insulation and upgrade wood burners in towns such as Alexandra, Arrowtown, Clyde, Cromwell and Milton have resulted in the replacement of over 1,400 appliances. While this has led to a reduction in emissions in these towns, this has not been enough for concentrations to meet the NESAQ limit for PM_{10}. Trend analysis shows that there have been significant decreases in PM_{10} concentrations in each of these towns but not to the extent originally predicted for Otago's air quality management strategy (ORC, 2007). The current strategy (ORC, 2018) recognises this, and has been adjusted to promote the installation of cleaner heating in Otago towns, such as ultra-low or no-emission appliances.

In Air Zone 2 towns, such as Balclutha and Mosgiel, PM_{10} has been exceeding the limits set by the NESAQ to provide a minimum level of health protection, and there are no consistent downward trends for winter concentrations. 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, and active management would be beneficial in these areas.

Central Dunedin has experienced the most significant improvement in air quality over the last ten years. The improvements are due to a combination of the introduction of new resource consent limits for industrial and commercial discharges, and improvements to home heating methods. This continued steadily over the years as industrial emissions control technology continues to improve. Dunedin is no longer considered a polluted airshed and has not breached the NESAQ in the last five years.

The contrast between Dunedin and the other airsheds highlights the challenges of improving air quality when the main emission sources are individual wood burners in areas where local weather patterns lead to high pollution nights. There is no single approach to meeting these challenges, but education, engagement and financial incentives are very important factors in air quality implementation projects. Technology advances in the home heating and building industries must not be overlooked in their impact on air quality and potential for providing solutions to reduce pollutant emissions.

7.2. National context

In 2018 MfE and Stats NZ released the latest national summary of air quality data. Nationally, many other regions have also struggled to meet the NESAQ for PM_{10}. In particular, the South Island has had more challenges meeting the standard due to the colder climate, but there are some parts of the North Island that also experience high PM_{10} concentrations. The 22 airsheds that had more than one exceedance in 2016 were all in the South Island, apart from Masterton, Tokoroa and Rotorua. The majority of the airsheds with exceedances were residential, or partially residential sites. In 2016 Otago sites had the highest frequency of exceedances (Figure 36).

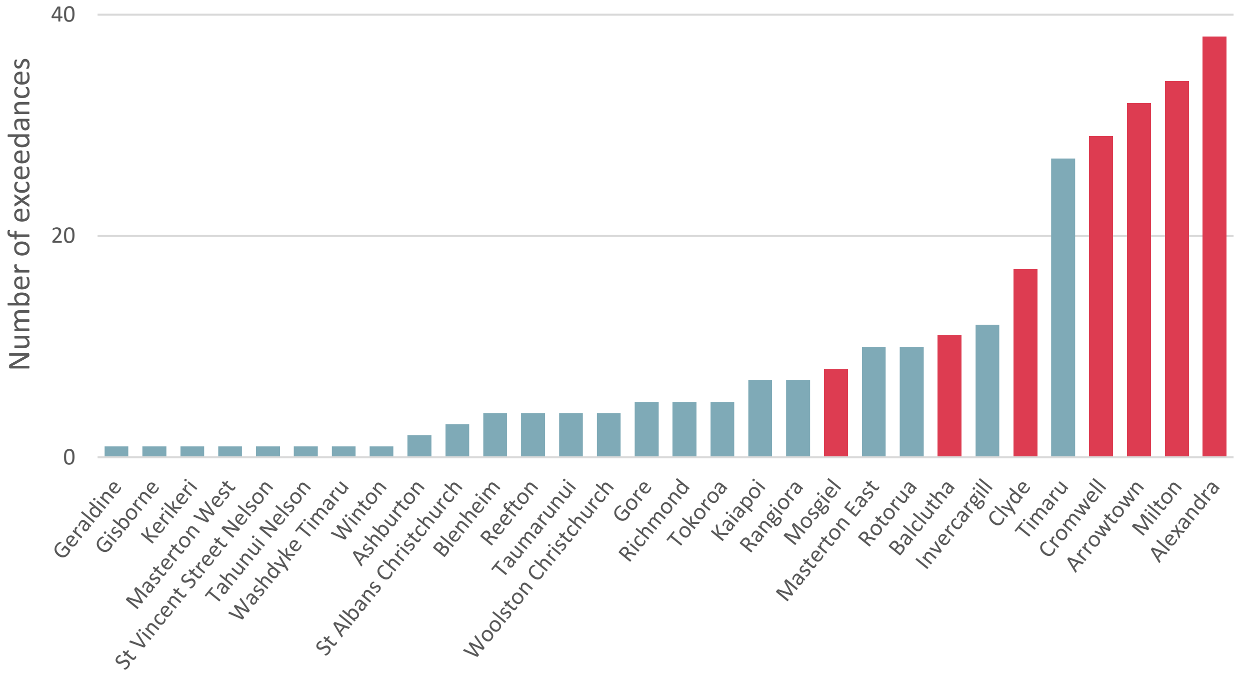


Figure 36 **Number of NESAQ annual PM_{10} exceedances in New Zealand monitoring stations for 2016, Otago airsheds in red. Source: MfE and Stats NZ (2018)**

7.3. Health impacts of air pollution

As discussed in section 2.2, exposure to particulate matter can cause and aggravate existing health issues, on both short and long-term scales. PM exposure mostly affects the respiratory and cardiovascular systems (Figure 37). Short term exposure can result in reversible symptoms such as respiratory irritation and heart-rhythm disturbances but can also result in inflammation of lungs and blood vessels. Repeated exposure can lead to chronic respiratory and cardiovascular diseases such as lung cancer and chronic obstructive pulmonary disease (Kuschel *et al*., 2012). The pyramid of health effects (Figure 38) describes that the most severe conditions occur to the smallest proportion of a population, and these incur the greatest social costs.

The impacts of air pollution on individuals varies by unique factors (age, health status, etc) and exposure (proximity to pollution sources). The groups within the population that are more affected by air pollution are children, the elderly, those with pre-existing conditions such as asthma, other lung and heart conditions, pregnant women and Māori (MfE, 2011b).

The impact of air quality on health is well documented. Conversely, there is global evidence that when air pollution is reduced there are subsequent health improvements, both with legislative intervention, such as clean air regulations, residential wood burning interventions, low emission zones for traffic within major cities; and by unplanned events such as industry strikes and economic recessions (WHO, 2013).

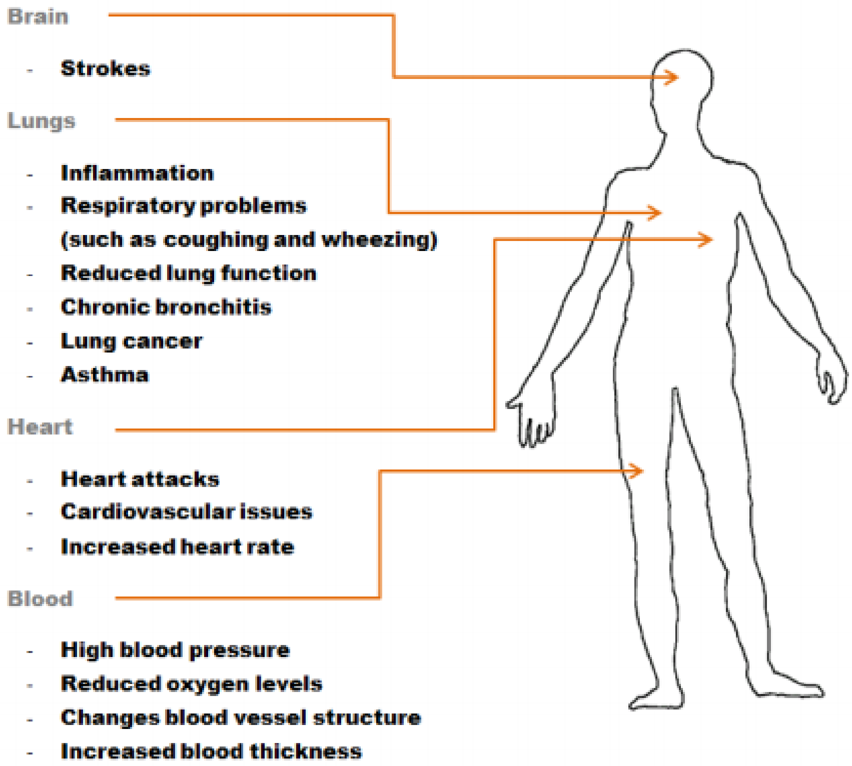


Figure 37 **Types of heath effects from PM_{10} exposure. Source MfE (2011b), adapted from Aphekom (2011)**

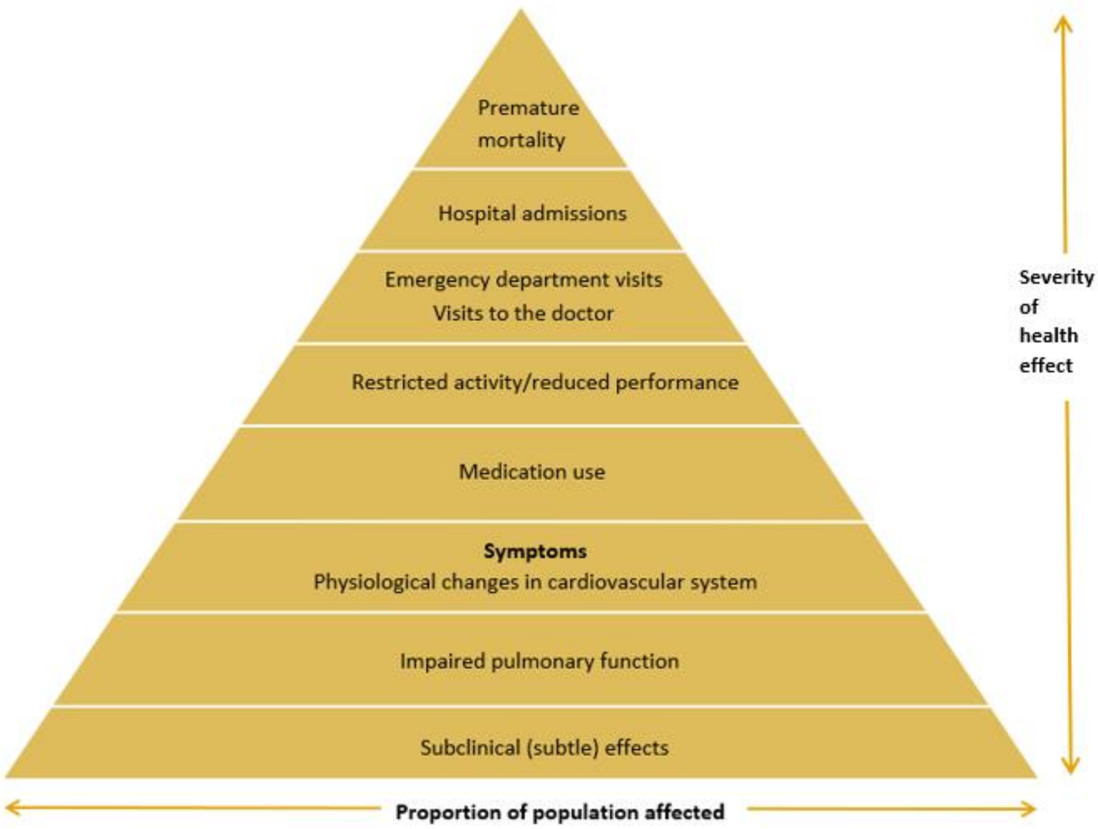


Figure 38 **Pyramid of health effects for PM_{10}. Source: WHO (2006)**

The Health and Air Pollution in New Zealand (HAPINZ) exposure model was developed to estimate the health impacts and social costs of anthropogenic air pollution in New Zealand. It was found that the overall social cost is $4.28 billion per year, or $1,061 per person. Table 12 shows the estimation of the HAPINZ model for Otago districts. These estimates were determined from the exposure of the census area unit (CAU) populations to 2006 PM_{10} concentrations, and the estimated health impacts of annual PM_{10} (long-term effects; premature mortality), and daily PM_{10} (short-term effects; hospital admissions and restricted activity days). Restricted activity days are days when symptoms limit usual daily activities such as work and school.

District (population in 2018)	Number of cases per 100,000			Restricted activity days
	Premature mortality in adults over 30 years	Cardiac hospital admissions (all ages)	Respiratory hospital admissions (all ages)	
Central Otago (21,558)	51	10	10	45,838
Clutha (17,667)	24	4	6	19,232
Dunedin City (126,255)	26	5	7	23,828
Queenstown Lakes (39,153)	8	1	3	17,605
Waitaki (22,308)	63	8	10	34,476
Total	**171**	**28**	**36**	**140,979**

Table 12 **Estimated number of premature deaths, hospital admissions and restricted activity days for Otago districts in 2016. Source: MfE and Stats NZ (2018)**

7.4. Cultural impacts of air pollution

Kāi Tahu whānui are takata whenua of the Otago region, incorporating seven papatipu rūnaka. Three of these rūnaka, Te Rūnanga o Ōtākou, Kāti Huirapa Rūnaka ki Puketeraki, and Te Rūnanga o Moeraki, are located in Otago. A further four, Hokonui Rūnanga, Waihōpai Rūnaka, Awarua Rūnanga, and Ōraka-Aparima Rūnaka, are situated in the Southland district, but with shared authority in the inland parts of Otago.

In Te Ao Māori the concept of whakapapa is integral, as whakapapa connects all people, lifeforms, and the natural world to a common origin. As such, all natural resources such as air, land, water, and indigenous biodiversity are taoka – treasured resources provided by the gods to sustain life. In Kāi Tahu traditions, the air and atmosphere were created after Tāwhirimātea, a child of Rakinui and Papatūānuku, fled with Raki into the sky and took control of wind and weather.

Air pollution has negative impacts on the mauri of air as a taoka, and other taoka such as living things that require clean air. Discharges to air may adversely affect significant places and taoka such as marae, wāhi tapu, mahika kai, water, and indigenous flora. From the Kāi Tahu perspective, the taoka must be passed intact to the next generation and be enhanced where it is degraded.

7.5. Knowledge gaps

There are several monitoring related knowledge gaps in Otago for pollutants $PM_{2.5}$, benzo(a)pyrene and NO_2 and SO_2, as well as the spatial distribution of PM_{10} and port emissions.

$PM_{2.5}$ is the majority component of PM_{10} emitted as wood or coal smoke (MfE and Stats NZ, 2018). In winter, in Otago Air Zone 1 towns it is estimated to be up to 90% of the PM_{10} (ORC, 2019). ORC is in the process of updating the monitoring network to include $PM_{2.5}$, which we are currently only able to estimate based on PM_{10} concentrations, and an understanding of the $PM_{2.5}$ to PM_{10} ratio. Monitoring $PM_{2.5}$ will be a requirement for the forthcoming update to the NESAQ which will include limits for $PM_{2.5}$. If the new standard adopted is the same as the WHO limit of 25 µg/m³ (24-hour average), then greater reductions of emissions will be required to meet this, than is currently required to meet the PM_{10} standard.

It would also be beneficial to establish a baseline of benzo(a)pyrene, which is strongly correlated to woodsmoke and PM_{10}. In addition, monitoring NO_2 and SO_2, would provide up to date data for industry and vehicle related combustion sources in urban areas.

The unexpected relocations of the sites at Alexandra and Arrowtown highlight the need to further study the spatial differences within monitored towns. In the past this has been undertaken every few years, but current technology exists for establishing networks of low-cost sensors to identify spatial patterns within a town.

Another knowledge gap is the emissions from Port Chalmers. Ports within New Zealand are often monitored for $PM_{2.5}$ and/or SO_2, and even though the Port is not covered under the NESAQ or the Otago Air Plan, it is located within an airshed and it would be beneficial to develop an understanding of the pollutants that are emitted there.

Furthering our understanding of emissions and emission sources is important to Otago's air quality programmes. Otago's last source apportionment study was last undertaken in 2011 in Dunedin. Due to the industry improvements the proportion of PM sources will be different now. Undertaking new source apportionment investigations for Dunedin and Mosgiel, the airsheds with the most diverse emission sources, would provide current information on the sources and relative contributions of PM.

More information is needed further our understanding of the relationships between emissions and concentrations in Otago airsheds. A tool to help with this is the emissions inventory, which relies on accurate estimations of emissions factors. A knowledge gap in New Zealand is the performance of ultra-low emission burners (ULEB) in a real-life setting. ULEB are now the only wood burner that can meet Air Zone 1 rules upon installation; with a large proportion of these now being installed it is important to future work to have an emissions factor for ULEBs. This information, in addition to the periodic updating of emission inventories will help improve understanding of the emissions in each town.

Outside of urban air quality, one of the main pollution sources is outdoor burning. The impacts of outdoor burning in Otago is currently unquantified as methods for assessment have not been determined beyond estimations from emission inventories.

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Appendix 1: Airshed and Air Zone boundary maps

Figure 39 **Alexandra: airshed and Air Zone boundaries**

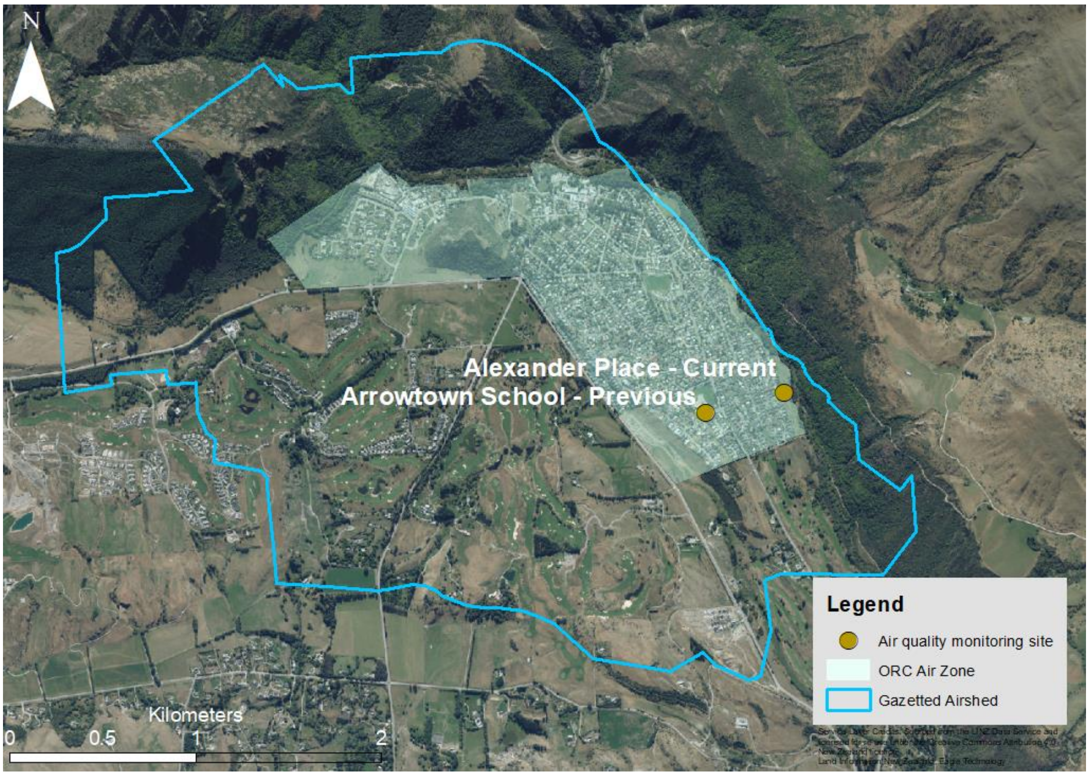

Figure 40 **Arrowtown: airshed and Air Zone boundaries**

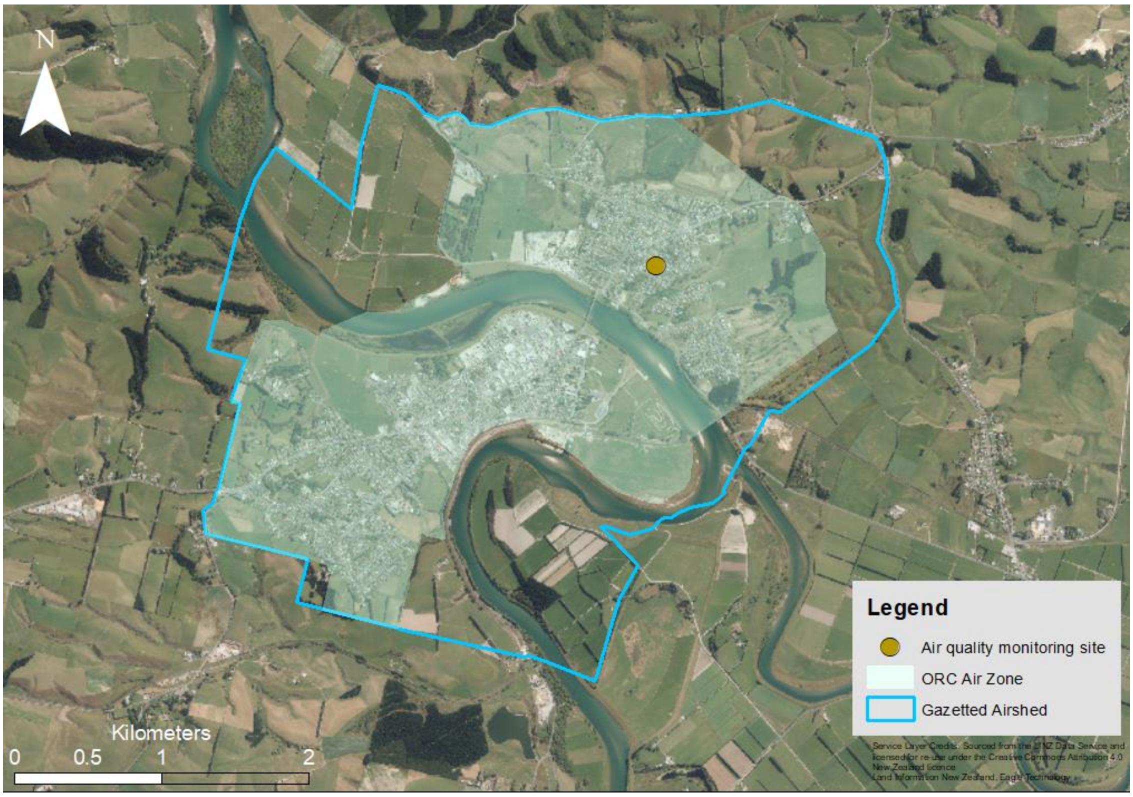

Figure 41 **Balclutha: airshed and Air Zone boundaries**

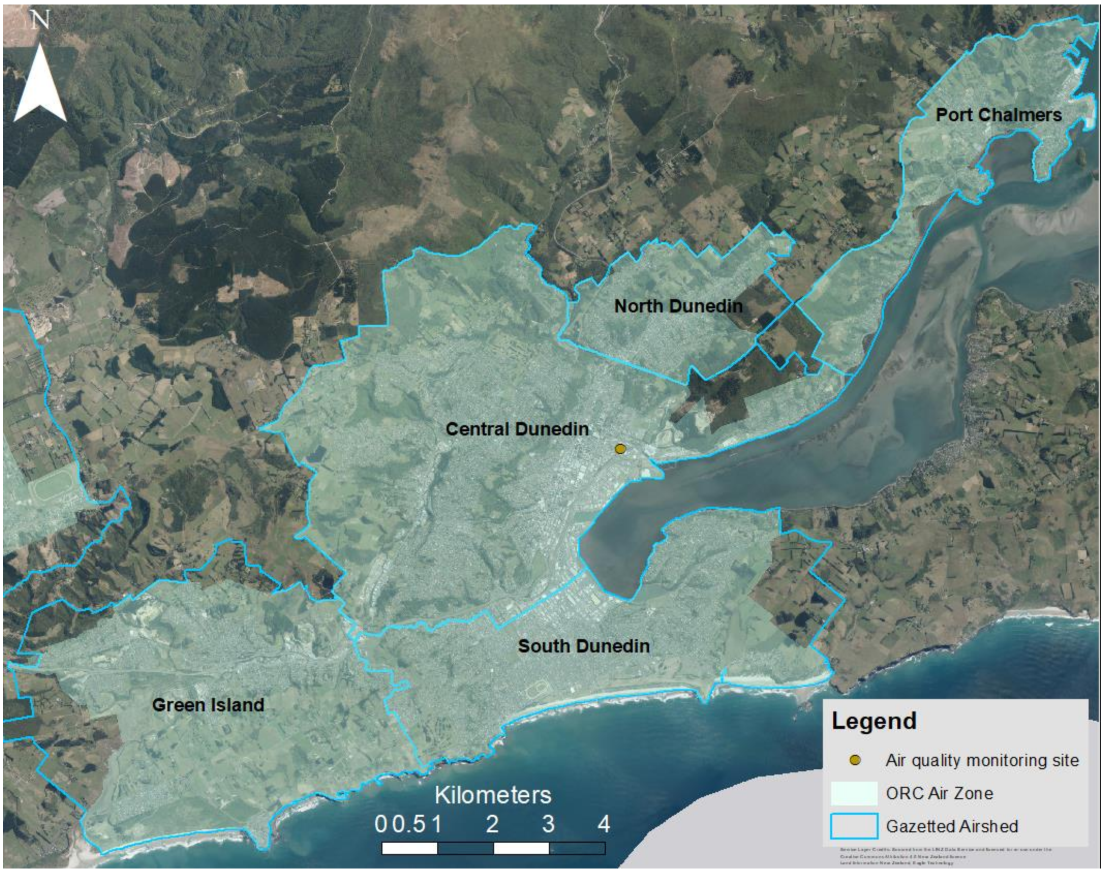

Figure 42 **Dunedin: airshed and Air Zone boundaries**

Figure 43 **Clyde: airshed and Air Zone boundaries**

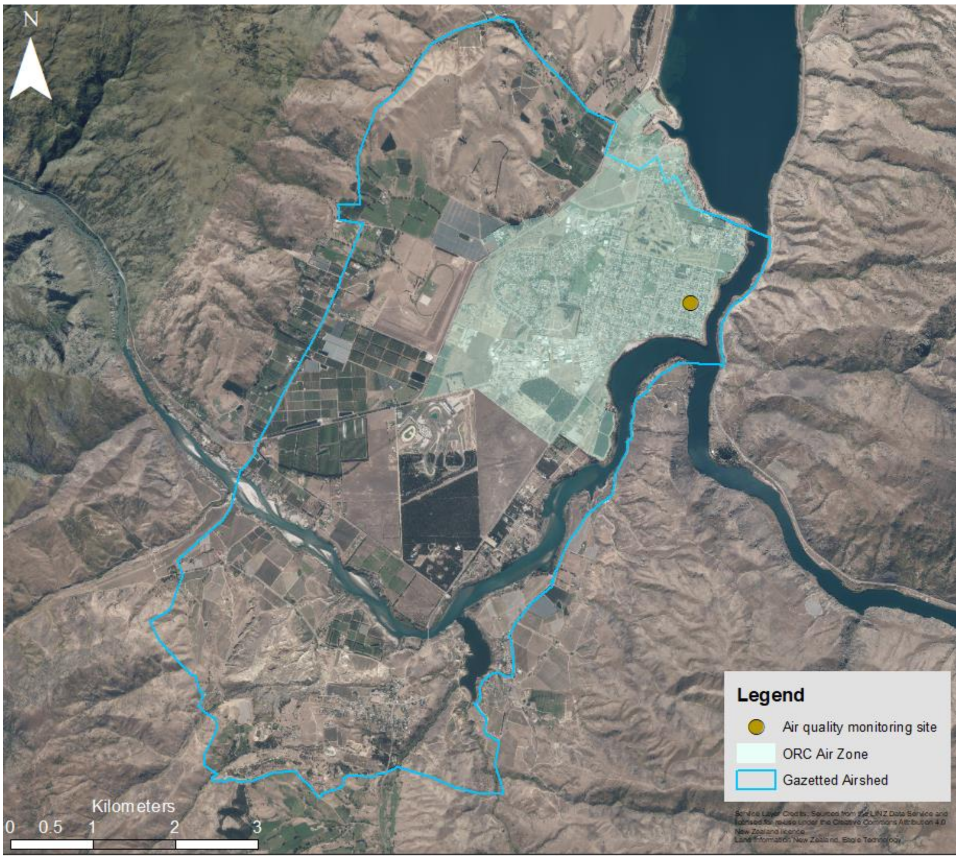

Figure 44 **Cromwell: airshed and Air Zone boundaries**

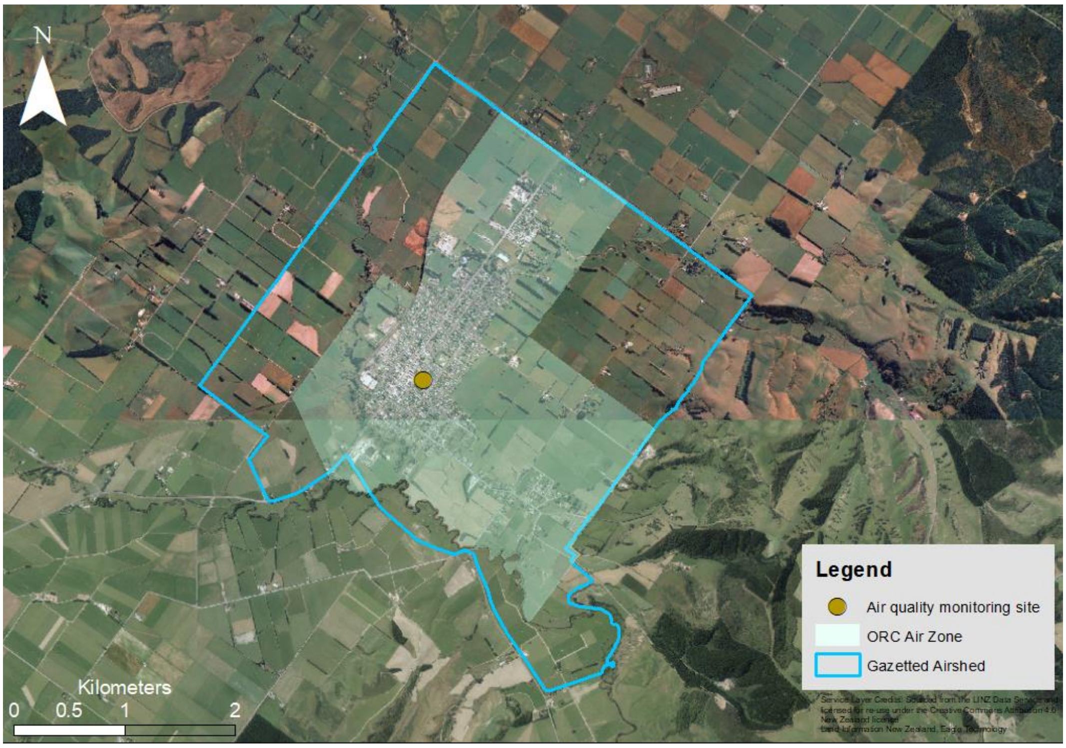

Figure 45 **Milton: airshed and Air Zone boundaries**

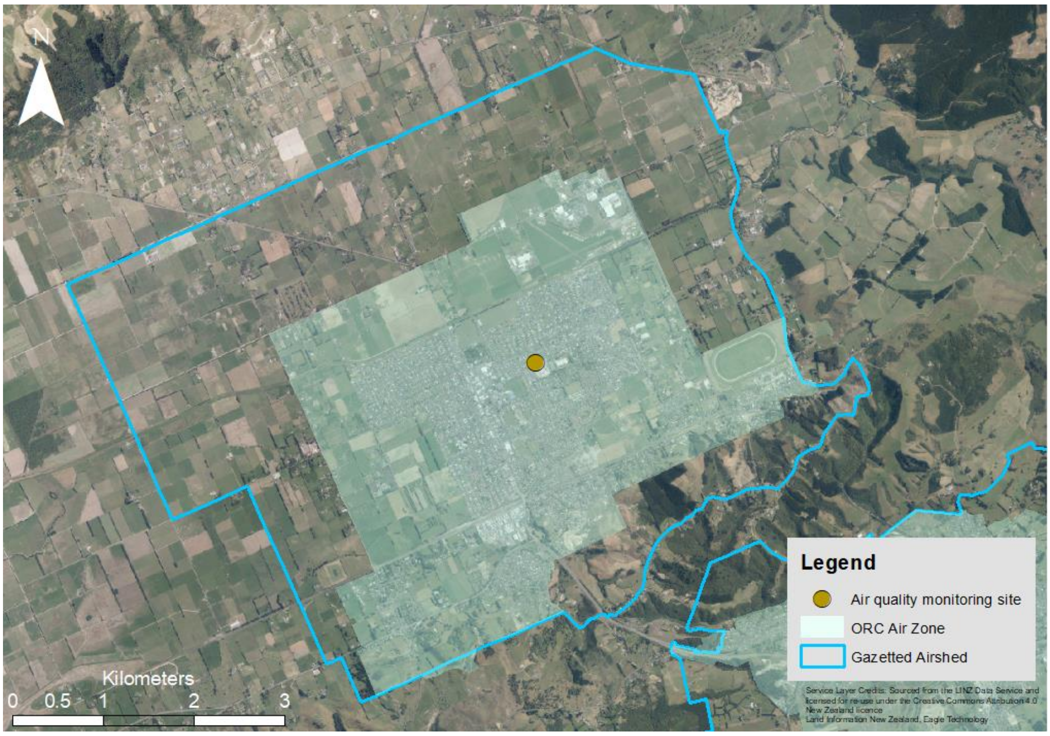

Figure 46 **Mosgiel: airshed and Air Zone boundaries**

Appendix 2: Box plots of winter PM_{10} distribution

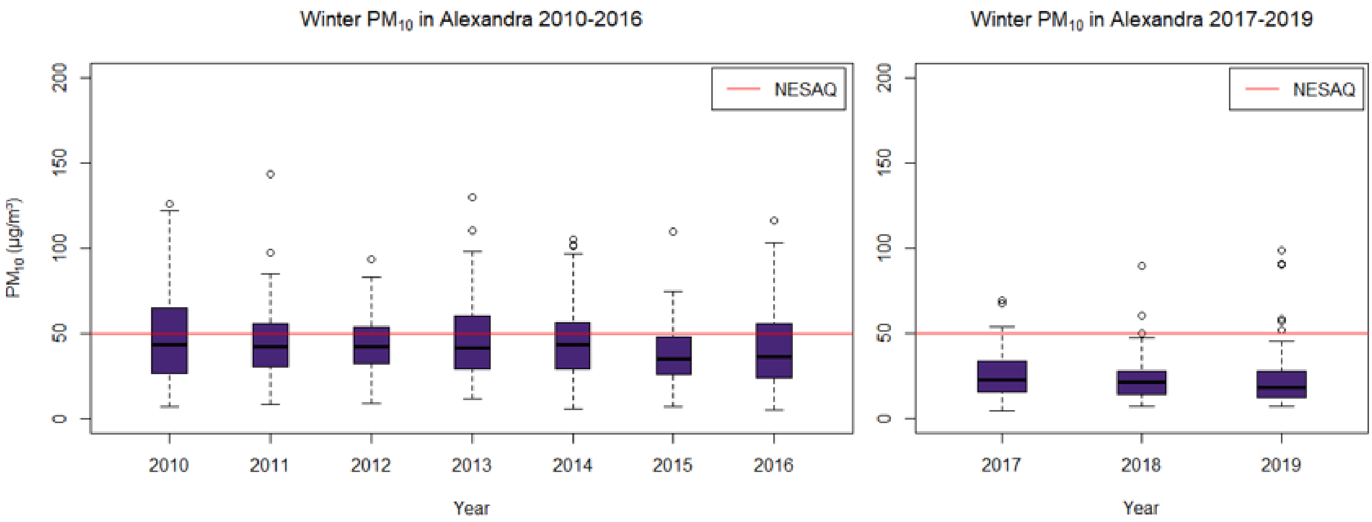

Figure 47 **Alexandra: PM_{10} distribution for winter months (May-August) 24-hour average, different site locations represented by different graphs**

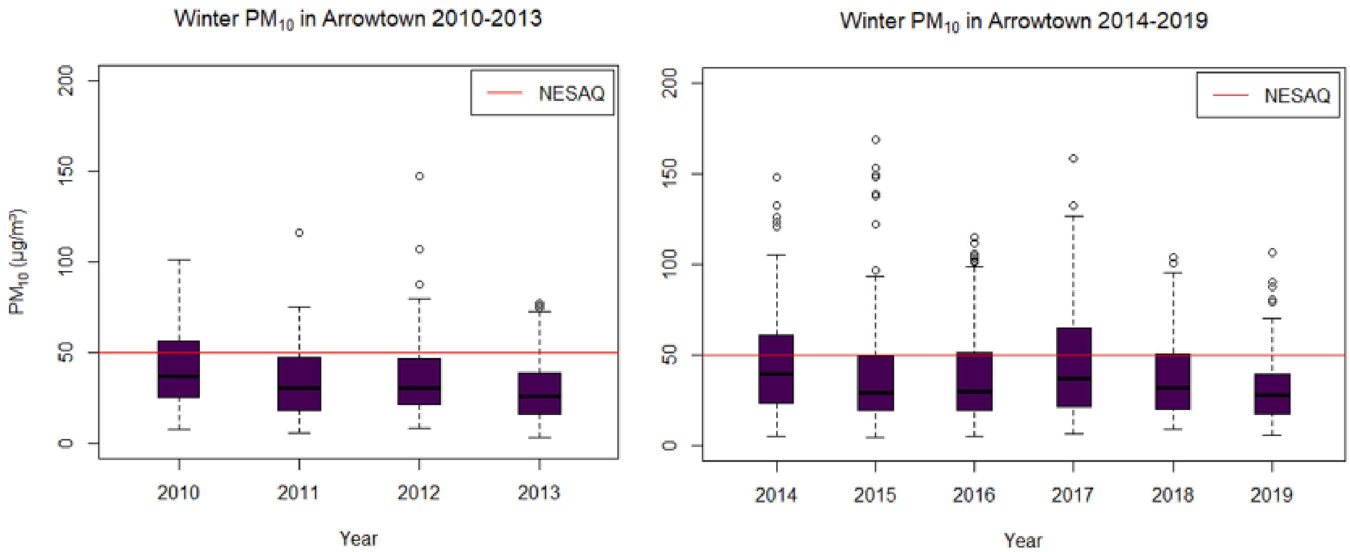

Figure 48 **Arrowtown: PM_{10} distribution for winter months (May-August) 24-hour average, different site locations represented by different graphs**

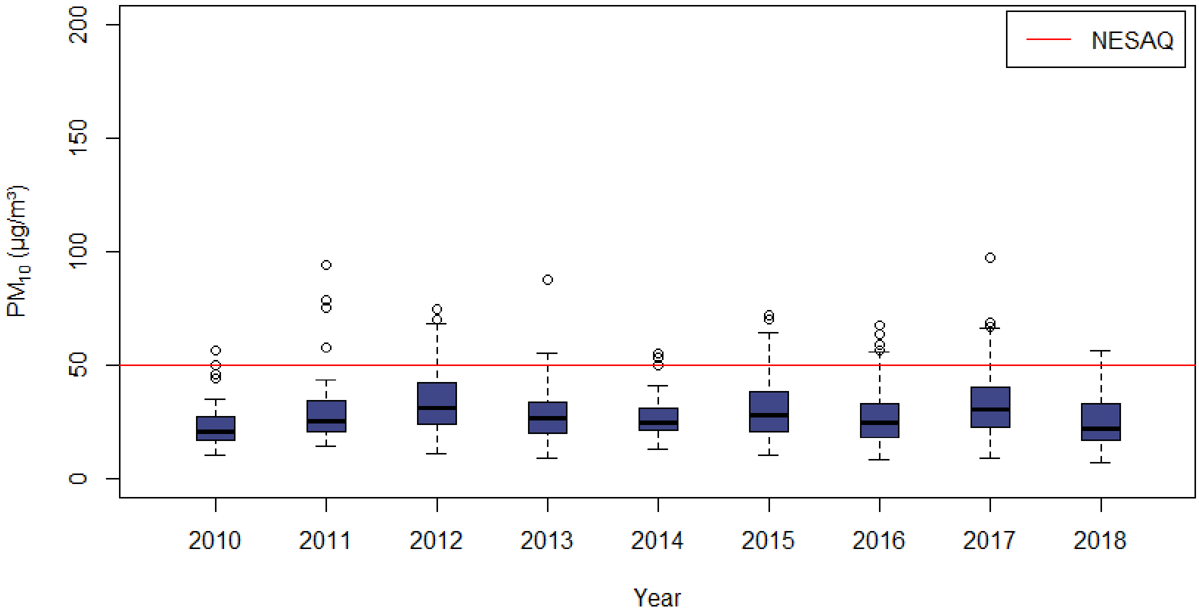

Figure 49 **Balclutha: PM_{10} distribution for winter months (May-August) 24-hour average**

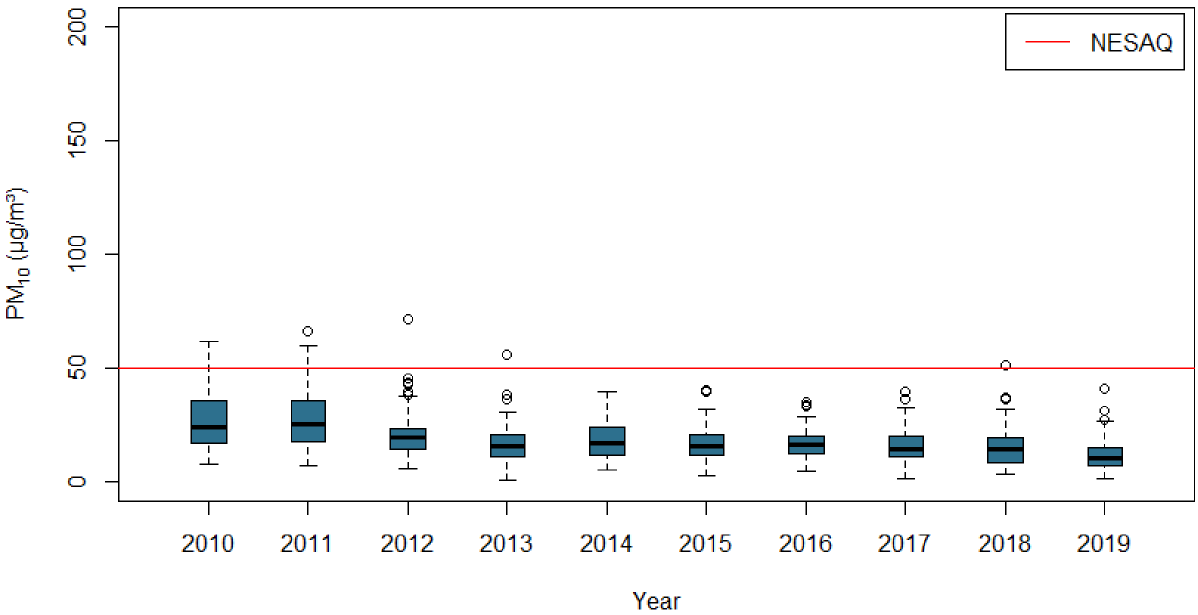

Figure 50 **Central Dunedin: PM_{10} distribution for winter months (May-August) 24-hour average**

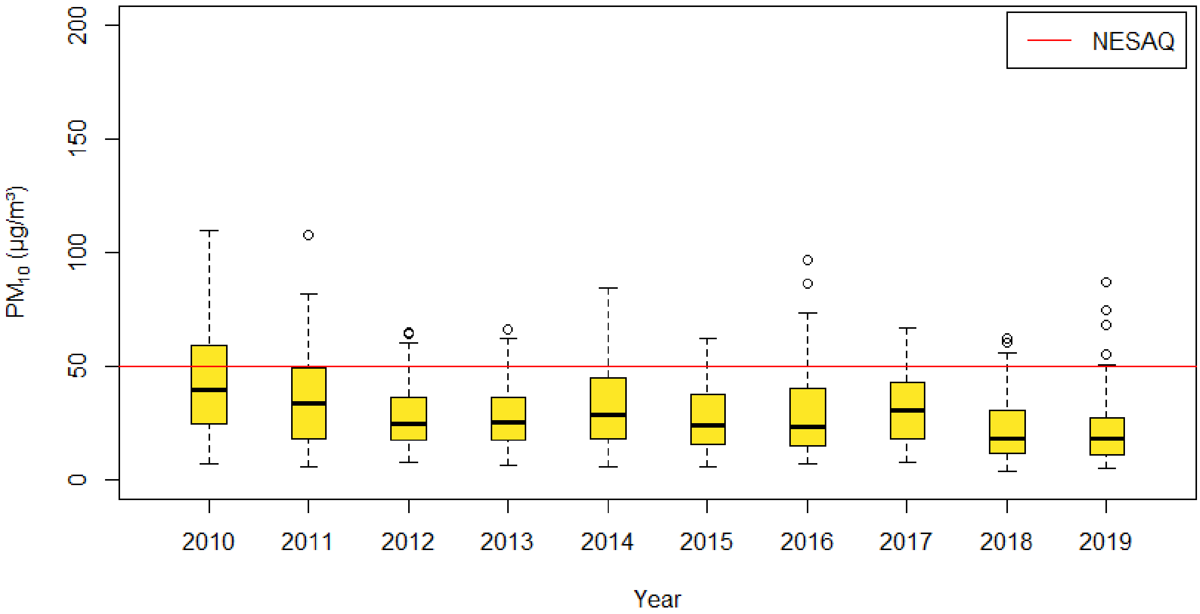

Figure 51 **Clyde: PM_{10} distribution for winter months (May-August) 24-hour average**

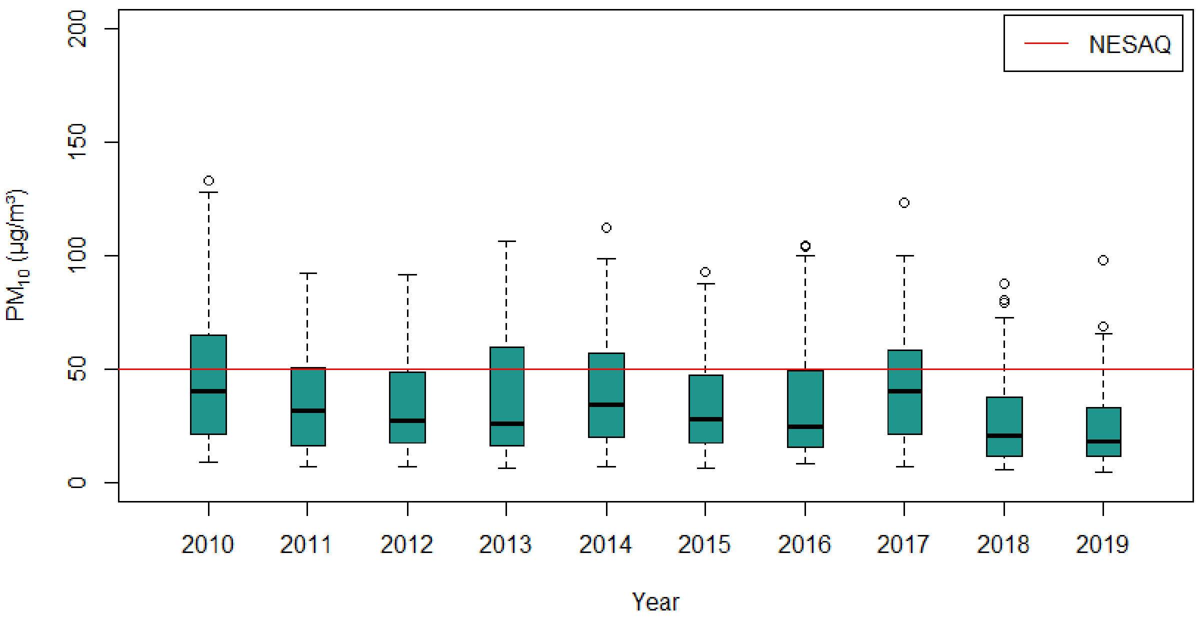

Figure 52 **Cromwell: PM_{10} distribution for winter months (May-August) 24-hour average**

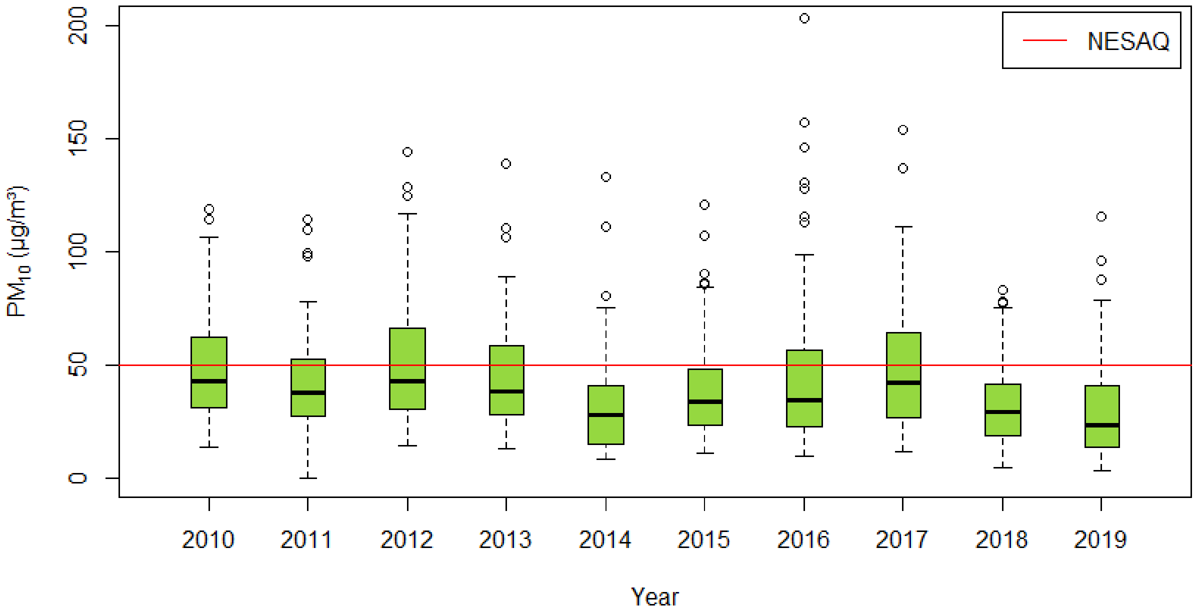

Figure 53 **Milton: PM_{10} distribution for winter months (May-August) 24-hour average**

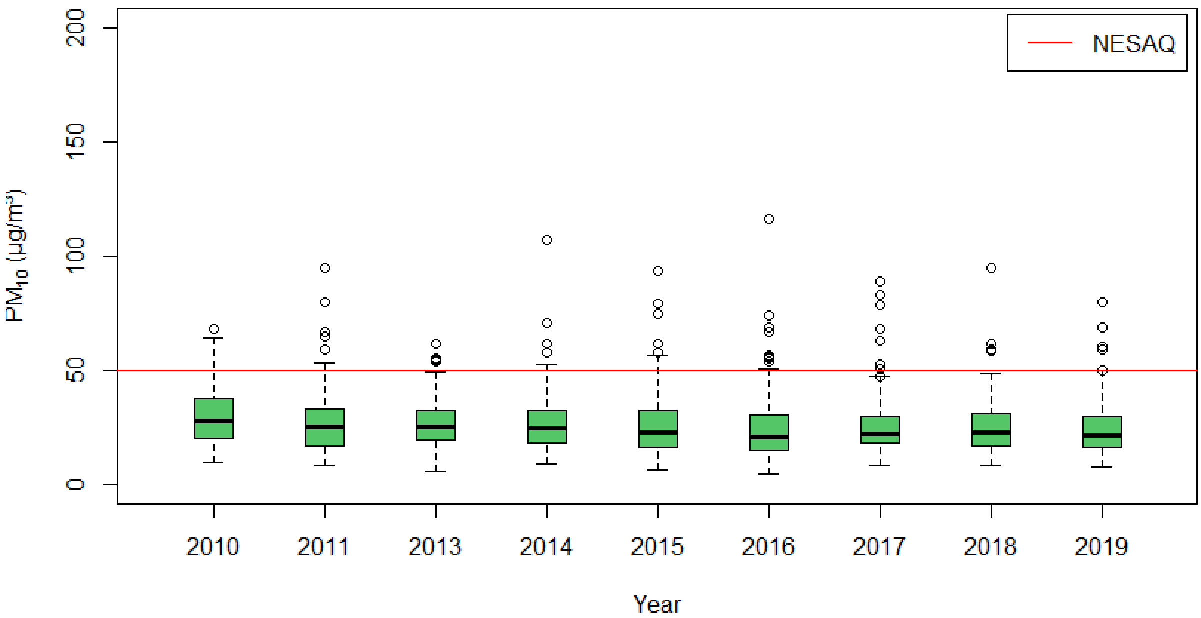

Figure 54 **Mosgiel: PM_{10} distribution for winter months (May-August) 24-hour average**

Appendix 3: Data presentation

R Statistical Software was used to produce the following plots and analyses:

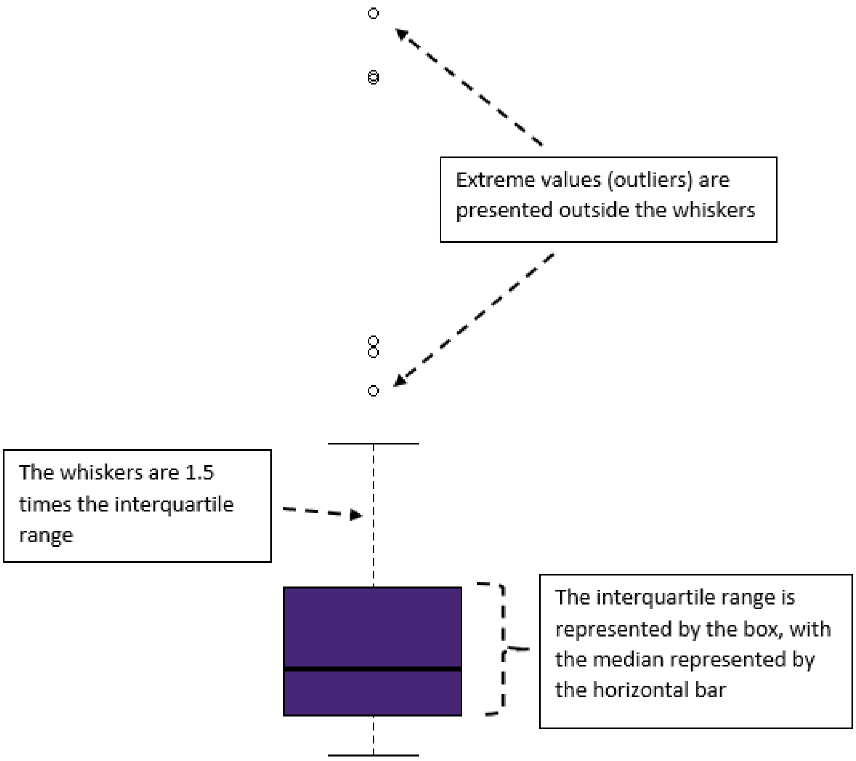

Figure 55 **Box and whisker interpretation**

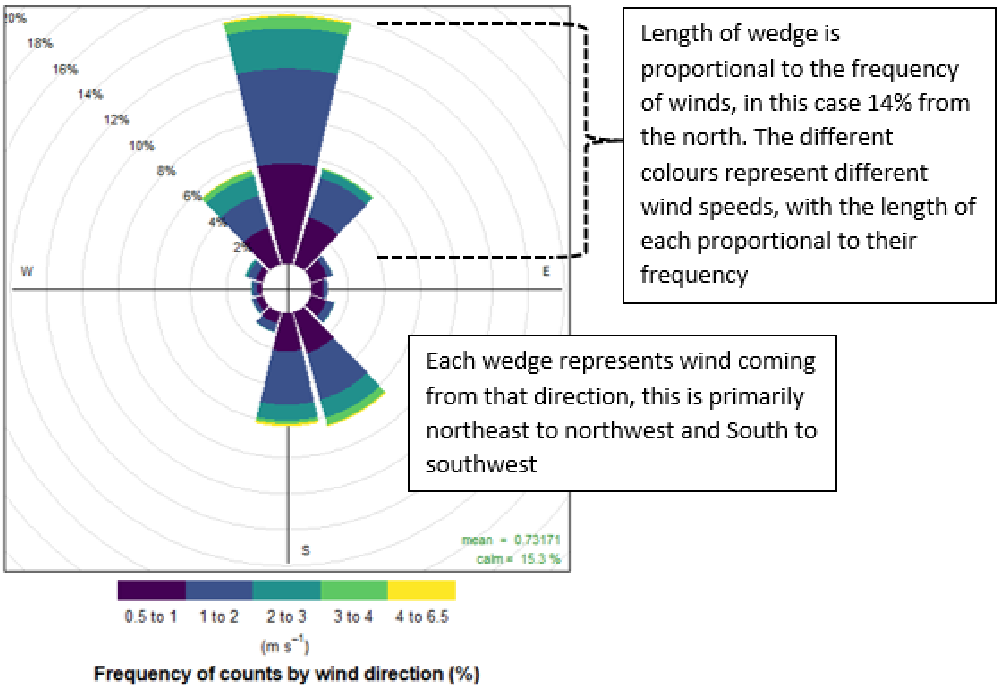

Figure 56 **Wind rose interpretation. These plots show wind speed and wind direction.**

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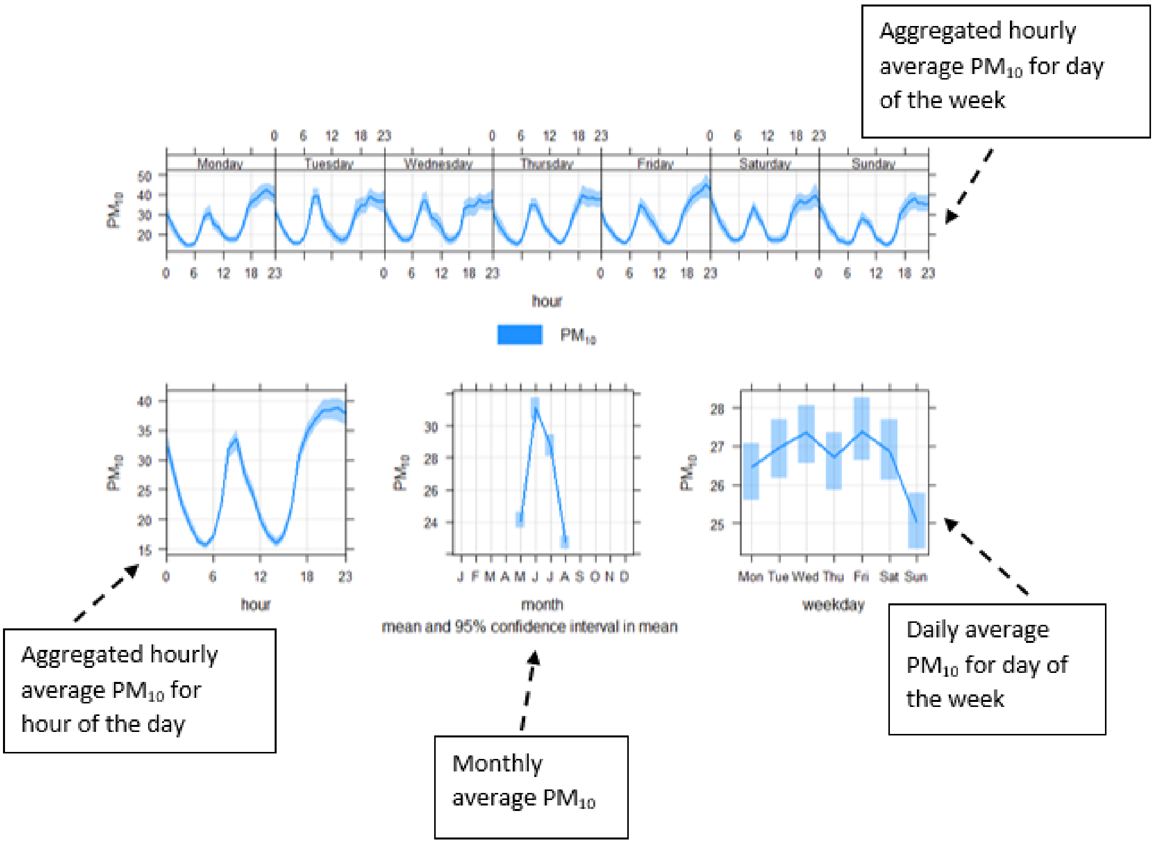

Figure 57 **Time variation plot interpretation. These plots show the mean (line) and 95% confidence intervale of the mean (shaded bars) of a pollutant averaged over different timescales.**

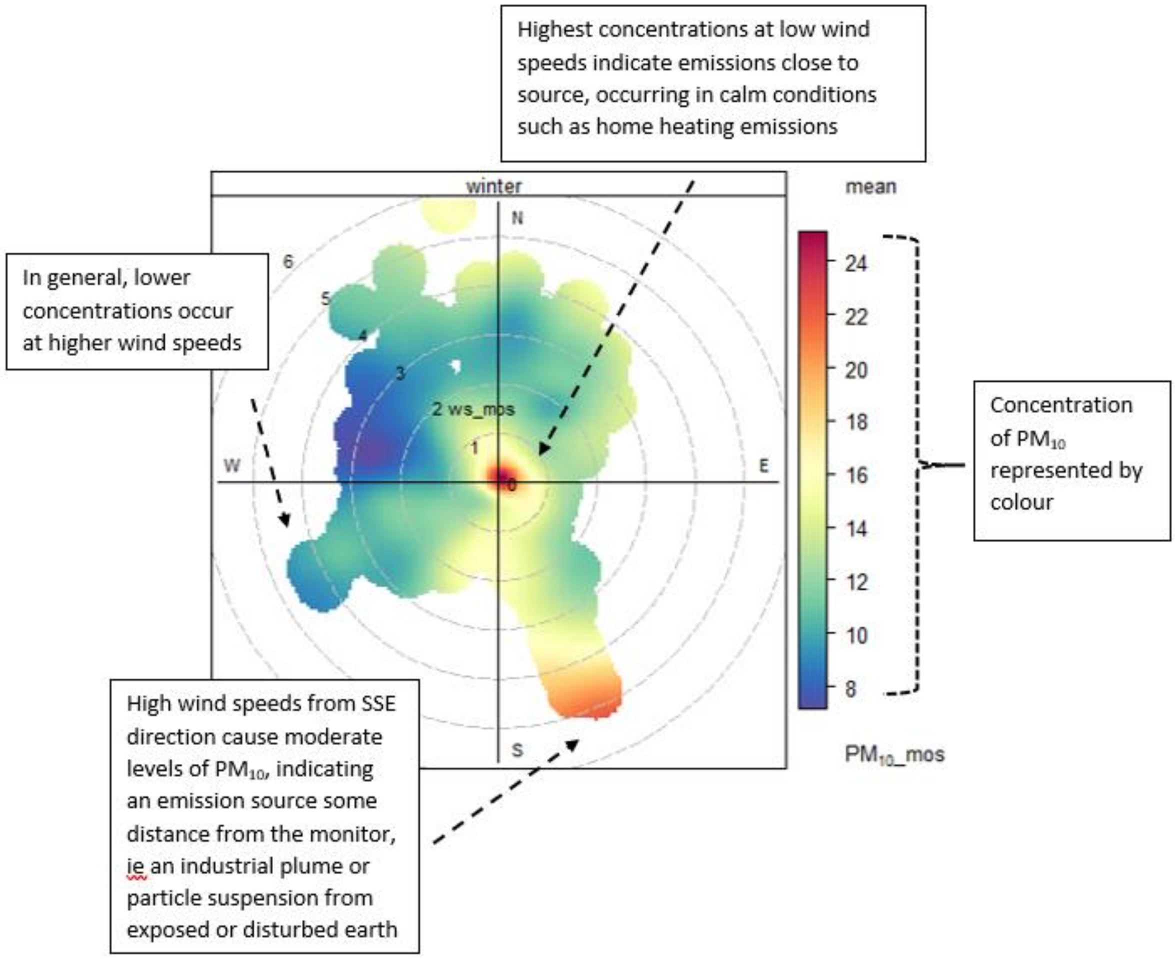

Figure 58 **Bivariate polar plot interpretation. These plots present smoothed PM_{10} concentrations plotted by wind speed (distance to centre of plot) and wind direction (polar co-ordinates), and are used to infer sources of pollution.**

Appendix 4: Summary statistics

PM10 (µg/m³) 24-hour mean	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Site Location	65 Ventry Street							5 Ventry Street		
Minimum	2	3	1	4	3	2	2	4	3	4
25th Percentile	9	9	8	9	8	8	9	9	8	8
Median	13	15	13	16	14	13	16	13	11	10
Mean	24	24	22	25	24	20	25	17	14	14
75th Percentile	29	36	33	35	36	30	35	22	17	15
Maximum	126	143	93	130	105	110	116	70	90	98
NESAQ exceedances	51	40	40	46	51	22	38	3	2	6
% valid	98%	86%	100%	89%	98%	97%	75%	59%	99%	95%

Table 13 **Alexandra: summary statistics for PM_{10}**

PM10 (µg/m³) 24-hour mean	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Site Location	Arrowtown School*				Alexander Place					
Minimum	8	6	9	4	3	2	1	3	2	1
25th Percentile	26	19	22	16	7	7	6	7	6	5
Median	37	30	31	26	16	10	10	11	10	8
Mean	42	34	36	30	28	21	20	22	18	16
75th Percentile	57	47	47	39	41	26	24	25	24	22
Maximum	101	116	147	77	148	169	115	158	104	106
NESAQ exceedances	39	27	24	15	48	30	32	45	29	19
% valid	100%	100%	100%	100%	65%	80%	93%	96%	93%	95%

*Arrowtown was a winter only site during 2010-2013

Table 14 **Arrowtown: summary statistics for PM_{10}**

PM10 (µg/m³) 24-hour mean	2010	2011	2012	2013	2014	2015	2016	2017	2018
Minimum	11	14	11	10	13	10	8	9	7
25th Percentile	17	21	24	20	21	21	19	23	17
Median	21	26	31	27	25	28	25	31	22
Mean	22	30	34	28	27	31	27	34	26
75th Percentile	28	34	42	34	32	38	33	40	33
Maximum	56	94	75	88	55	72	67	98	56
NESAQ exceedances	2	4	13	4	3	9	10	14	5
% valid	100%	50%	92%	100%	64%	98%	98%	86%	93%

Table 15 **Balclutha: summary statistics for PM_{10} (winter only)**

PM_{10} (µg/m³) 24-hour mean	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Minimum	4	7	3	1	5	3	5	2	3	1
25th Percentile	15	17	13	12	13	12	12	10	10	8
Median	23	23	17	17	17	16	16	13	14	11
Mean	25	25	18	18	18	17	16	14	15	12
75th Percentile	31	30	23	22	23	20	18	18	19	15
Maximum	62	70	71	56	40	41	39	40	51	41
NESAQ exceedances	11	14	1	1	0	0	0	0	1	0
% valid	98%	93%	90%	97%	95%	85%	85%	98%	97%	95%

Table 16 Central Dunedin: summary statistics for PM_{10}

PM_{10} (µg/m³) 24-hour mean	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Minimum	8	6	8	6	6	6	7	8	4	2
25th Percentile	25	18	18	18	18	16	15	18	12	11
Median	40	34	25	26	29	24	24	31	18	18
Mean	44	36	28	28	32	27	29	32	22	22
75th Percentile	59	50	36	36	45	38	41	43	30	27
Maximum	110	107	65	66	84	63	97	67	62	87
NESAQ exceedances	40	23	9	10	21	10	18	23	6	4
% valid	100%	72%	100%	98%	100%	100%	98%	98%	100%	100%

Table 17 Clyde: summary statistics for PM_{10} (winter only)

PM_{10} (µg/m³) 24-hour mean	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Minimum	9	7	8	7	7	7	8	7	6	5
25th Percentile	22	17	18	17	20	18	15	22	12	12
Median	40	32	27	26	35	28	25	40	21	18
Mean	48	35	34	37	41	35	36	43	27	26
75th Percentile	65	51	49	60	57	47	50	58	37	33
Maximum	133	92	91	107	112	93	105	123	88	98
NESAQ exceedances	43	27	30	33	49	27	34	41	13	13
% valid	100%	79%	99%	95%	100%	86%	98%	98%	80%	97%

Table 18 Cromwell: summary statistics for PM_{10} (winter only)

PM_{10} (µg/m³) 24-hour mean	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Minimum	14	11	14	13	8	11	10	12	5	3
25th Percentile	31	27	31	28	15	23	23	27	19	14
Median	43	37	43	38	28	34	65	42	30	24
Mean	49	41	50	44	31	38	45	46	32	29
75th Percentile	61	52	66	58	41	48	56	64	42	41
Maximum	119	114	144	139	133	121	203	154	83	115
NESAQ exceedances	46	20	37	44	14	30	36	48	16	20
% valid	98%	61%	81%	100%	81%	100%	94%	99%	95%	97%

Table 19 **Milton: summary statistics for PM_{10} (winter only)**

PM_{10} (µg/m³) 24-hour mean	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Minimum	7	7		6	7	5	4	5	6	5
25th Percentile	15	17		14	15	13	12	13	13	11
Median	20	23		18	19	17	15	16	17	15
Mean	24	26		20	21	20	19	19	19	17
75th Percentile	29	31		24	25	23	22	21	22	20
Maximum	105	95		62	107	93	116	89	94	80
NESAQ exceedances	8	8		5	5	7	9	9	4	4
% valid	68%	46%	28%	95%	98%	92%	70%	95%	90%	92%

Table 20 **Mosgiel: summary statistics for PM_{10}**

Appendix 5: Other ambient pollutants

A5.1 Carbon monoxide

Carbon monoxide (CO) 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. Prominent sources include vehicle exhaust, and the combustion of wood and coal.

A5.2 Nitrogen dioxide

Nitrogen dioxide (NO_2) is a brownish acidic gas and is highly corrosive. It forms from chemical reactions involving nitrogen oxide 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.

A5.3 Sulphur dioxide

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 the combustion of coal in industrial activity or domestic heating.

A5.4 Ozone

Ozone is a secondary pollutant formed from other compounds during photochemical reactions, and it results in smog. Effects of high ozone concentrations 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 and the presence of other pollutants.