Pilot study: air quality monitoring CentrePort, Wellington

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Executive summary

A short-term air monitoring pilot project was carried out between 1 December 2019 and 31 May 2020 to collect data on potential impacts of cumulative shipping emissions and port activities on air quality. COVID-19 movement restrictions from 23 March 2020 disrupted the manual sampling aspects of the project, shortening the data capture for spatial sulphur dioxide (SO_2) monitoring and collection of air particulate samples required for identifying sources of particulate matter (PM_{10}).

The key findings were:

- Peak 24-hour levels of sulphur dioxide (SO_2) and nitrogen dioxide (NO_2) measured by continuous instruments at the port were two times higher than measured at Wellington central air monitoring station, but met national standards and guidelines.

- Levels of PM_{10} were 33% higher at the port compared to Wellington central due to the port having a higher levels of marine aerosol and a local contribution from construction and demolition activities. Peak 24-hour PM_{10} and $PM_{2.5}$ levels at both sites met the national environmental standard.

- The spatial study using passive diffusion tubes found very high SO_2 levels at the non-public access end of the Interislander wharf berth due to proximity of the monitoring site to the ship's exhaust stack. Other monitoring sites detected much lower levels of SO_2, but the results for some sites were inconclusive due to lack of agreement between duplicate samplers deployed.

- The particulate speciation study carried out by GNS Science found that particulate emissions from ship engine exhaust made up 7.5% of PM_{10} levels measured at the port. About a third of PM_{10} measured at Wellington central was composed of secondary sulphate – formed from the conversion of SO_2 gas from combustion and natural sources to particles in the atmosphere.

It was not within the scope of the study to identify impacts from individual vessels, classes of vessels or specific port activities. SO_2 levels at the port did not appear to reduce following the departure of the last international cruise ship on 18 March 2020, suggesting that domestic ferries and other port activities were ongoing SO_2 sources.

Based on the results of this study, regulatory monitoring for SO_2 doesn't appear to be warranted. Future monitoring of SO_2 to measure the effect of MARPOL Annex VI requirements for domestic vessels and to assess air pollutant levels on the western hills above the port area could be considered.

Contents

1. Introduction

1.1 Purpose and scope

This report presents the results of a pilot air monitoring study undertaken to assess the potential impacts of shipping emissions and associated port activities on air quality inside the operational port area and at nearby locations close to the port.

The purpose of the study was to:

- Assess whether there is likely to be any air quality issues that might lead to exceedances of outdoor air quality guidelines and standards.
- Identify any potential air quality impacts from port activities that may be relevant to CentrePort Wellington's environmental and sustainability polices and the wider port regeneration programme.
- Collect baseline data on sulphur dioxide levels around the port before international regulations to reduce emissions from ship engines (MARPOL Annex VI) come into force for domestic vessels.

The project was not designed to link individual vessel movements and specific port activities to impacts on air quality and human health.

The study was planned coincide with summer cruise ship calls and to capture the autumn and early winter period when air pollutant levels from all sources are generally elevated due to reduced atmospheric dispersion. The duration of the monitoring campaign was designed to fit with Greater Wellington's planned relocation of staff and monitoring equipment from Shed 39 at CentrePort to new premises in central Wellington in 2020.

1.2 Air quality monitoring and analysis objectives

Monitoring objectives for this project were to:

- Assess spatial variation of sulphur dioxide (SO_2) within the port operational areas and nearby locations using passive diffusion tubes.
- Measure levels of particulate matter (PM_{10} and $PM_{2.5}$) and black carbon (combustion particles), sulphur dioxide, nitrogen dioxide and NOx within the port area and compare to levels found at the GWRC air reference monitoring station (Wellington central).
- Analyse the elemental composition of particulate matter collected on air filters and use receptor modelling to estimate the relative contributions of different emission sources to measured particulate matter at the port.

2. Background

2.1 Shipping and air quality

Many ports in New Zealand are located close to urban centres and can be important sources of air pollution from shipping emissions and from heavy vehicles loading and unloading ships and moving goods (Ministry for the Environment, 2018). To date, there has been no air quality monitoring of pollutants associated with shipping, such as sulphur dioxide (SO_2), at the port area or in Wellington city.

Shipping is a significant source of sulphur dioxide because most large sea-going vessels use high sulphur-containing fuel and, coupled with large engine capacity, this leads to much higher concentrations of hazardous air pollutants (including heavy metals) than produced by motor vehicles and trucks (Talbot & Reid, 2017). Emissions from ships and associated port activities also include particulate matter, black carbon, nitrogen oxides and carbon monoxide. Studies in Auckland have found that sulphur dioxide concentrations were highest near the waterfront downwind of the direction of the port (Talbot & Reid, 2017) and levels of vanadium and nickel linked to shipping emissions were strongly elevated downwind of the port (Longley et al., 2016). Another long-term Auckland study of particulate matter sources found emissions from ships were detected at many of the regulatory monitoring sites around Auckland, even several kilometres distance from the port (Davy et al., 2017). Levels of shipping-derived particulate have been increasing at Auckland's Queen Street air monitoring site in tandem with increasing freight throughput and cruise ship visits (Davy et al., 2020).

NZ's accession to MARPOL Annex VI (which has regulated emissions of SOx, NOx and particulate matter from shipping since 2005) is due to be completed in 2022. The stated benefits are to reduce local impacts on human health and global climate change through lowering sulphur limit in fuel from 3.5% to 0.5%. From 1 January 2020, all ships visiting CentrePort (flagged to MARPOL signatory countries) needed to comply with the new fuel quality standards or have fitted an exhaust cleaning system ('scrubber') to reduce emissions to a level equivalent to that produced from burning low sulphur fuel. Air monitoring data from the Bay of Plenty Regional Council found a marked reduction in SO_2 measured near the Port of Tauranga from 1 January 2020 onwards that was attributed to visiting international vessels switching to higher grade fuel needed to meet the new MARPOL limit for sulphur content (Iremonger & Mackay, 2020).

The Cook Strait ferries, Interislander (KiwiRail) and Bluebridge (StraitNZ) use Medium Fuel Oil which has approximately 2.5% sulphur content by mass (National Interest Analysis[1]). In contrast, automotive diesel has very low sulphur content, reduced to 10ppm in 2009 (equivalent to 0.001% by mass).

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[1] https://www.transport.govt.nz/assets/Uploads/Report/MARPOL-Annex-VI-National-Interest-Analysis.pdf

Sulphur in petrol also reduced to 10ppm in 2018 (Engine Fuel Specifications Regulations 2011).

2.2 Pollutants

Key indicator pollutants monitored in this study are discussed briefly below.

Particulate matter

Particulate matter concentrations, measured as PM_{10} and $PM_{2.5}$, are pollutants with adverse health impacts from both long-term and short-term exposure (Ministry for the Environment, 2018). Effects range from restricted activity days through to increases in hospital admissions and premature death (Updated health and air pollution in New Zealand study, 2012[2]).

Particles have a variety of shapes and sizes with varying chemical properties depending on their source. The smallest sized particles are largely produced as a by-product of combustion, such as from burning fossil-fuels and biomass (eg, wood). Most of these combustion particles are ultra-fine (ie, smaller than 0.1 µm), with these smallest particles penetrating further into the lungs and even into the bloodstream (Moreno-Ríos et al., 2021). Larger sized particles are derived from brake, tyre and road wear which become re-suspended as road dust from turbulence of moving vehicles. Wind-blown soils and aggregates are also found in the larger or coarse particle size fraction of particulate matter, along with natural sources, such as marine aerosol, especially under high wind conditions (Davy & Trompetter, 2018). Secondary particulate matter can also be formed from chemical reactions in the atmosphere between precursor gases such as sulphur oxides, nitrogen oxides and volatile organic compounds. Most of the secondary particulate is found in the fine fraction ($PM_{2.5}$).

Black carbon

Black carbon or soot is a light-absorbing, carbon-containing constituent of $PM_{2.5}$ formed by the incomplete combustion of fossil fuels, biomass and biofuels (European Environment Agency, 2013). Main sources of black carbon include on-road vehicles, shipping, home-heating (wood or coal burning) and open burning (eg, wildfires or burning of agricultural waste). Diesel-powered vehicles, especially heavy commercial vehicles, are very high emitters of black carbon compared to petrol vehicles (Davy et al., 2011). Although there are no health-based guidelines for black carbon, black carbon is thought to be a universal carrier for other harmful components of traffic-related air pollution (World Health Organization, 2012).

There are also climate concerns regarding black carbon emissions. Black carbon, because of its dark colour is very good at absorbing heat and in the atmosphere it acts as short-term climate warming agent (Ministry for the Environment, 2018). Therefore, reductions in black carbon can more quickly mitigate changes in the climate compared to carbon dioxide which persists for

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[2] https://environment.govt.nz/publications/updated-health-and-air-pollution-in-new-zealand-study-2012-summary-report/

hundreds to thousands of years in the atmosphere (Ramanathan & Carmichael, 2008).

Nitrogen oxides

Nitrogen dioxide (NO_2) is a harmful air pollutant derived from fuel combustion. It causes increased susceptibility to infections and asthma, reduces lung development in children, and is also associated with reduced life expectancy. Recently the World Health Organization has recommended new stricter air quality guidelines for NO_2 based on the latest evidence showing adverse health effects from exposure to relatively low levels of NO_2 (World Health Organization, 2021).

Generally, only a small amount of NO_2 is directly emitted in exhaust emissions. Most NO_2 is formed as a secondary pollutant when nitric oxide (NO) produced during high temperature fuel combustion is rapidly oxidised by ozone (O_3) in outdoor air. The reaction between NO and O_3 continues until either all the available O_3 or NO is depleted. Once formed, NO_2 is then converted back to NO in the presence of strong sunlight. Collectively NO and NO_2 are known as NOx. Although all motor vehicles emit NOx, heavy-duty (diesel) vehicles emit significantly more NOx per vehicle than petrol-powered vehicles.

Sulphur dioxide

Sulphur dioxide (SO_2) is a harmful pollutant produced during the combustion of fossil fuels containing sulphur, such as coal and heavy oil. Natural sources are generated through geothermal activity, usually volcanic eruptions, and from marine plankton during summer. SO_2 is also oxidised in the atmosphere to from sulphate particles which contribute to particulate matter concentrations (Cox & Mulcahy, 1979).

SO_2 can aggravate lung and heart conditions, exacerbate asthma attacks and more recently has been found to be associated with increased death rates (Orellano et al., 2021).

2.3 Meteorology

The Wellington city area is coastal in nature and is the windiest urban area in the region. It has a reduced temperature range due to its windiness and proximity to the sea, and air frosts are very rare (Griffiths, 2011). The lack of very low persistent minimum temperatures usually inhibit the formation of an ‘inversion’ layer which acts to trap pollutants near ground level (Griffiths, 2011).

Local wind speed and direction, temperature, humidity and atmospheric stability are important factors affecting air quality. Wind speed and wind direction are particularly important as elevated pollutant concentrations can occur under low wind speeds or when the monitoring station is downwind of the emission source. Conversely, elevated pollutant concentrations can occur under higher wind speeds due to resuspension of particulates and long-range transport of other particle sources, such as sea salt. Temperature and sunshine also affect atmospheric chemical reactions, such as the formation of NO_2 from precursor gases and gas to particle conversion processes. Rainfall washes out water-soluble pollutants and particulate matter by a process called wet deposition.

2.4 Air quality standards and guidelines

Applicable air quality standards and guidelines are shown in Table 2.1. The primary regulatory standard is the National Environmental Standards for Air Quality Regulations 2004[3] (NES-AQ). Where there is no standard, the national Ambient Air Quality Guidelines (AAQG) (MfE, 2002) are used followed by the most scientifically up-to-date World Health Organization guidelines (WHO, (2021). Reporting categories used for national environmental reporting (LAWA[4]) and the regional annual air quality data report (http://www.gw.govt.nz/Annual-monitoring-reports/) are shown in Table 2.2.

Table 2.1: Air quality standards and guidelines

Pollutant	Standard or Guideline	Threshold concentration	Averaging period	Permissible exceedances per year
PM_{10}	NES-AQ (2004)	50 µg/m^3	24-hour	1
$PM_{2.5}$	WHO (2021)	15 µg/m^3	24-hour	3 - 4
SO_2	NES-AQ (2004)	350 µg/m^3	1-hour	9
	AAQG (2002)	120 µg/m^3	24-hour	0
	WHO (2021)	40 µg/m^3	24-hour	3 - 4
NO_2	NES-AQ (2004)	200 µg/m^3	1-hour	9
	AAQG (2002)	100 µg/m^3	24-hour	0
	WHO (2021)	25 µg/m^3	24-hour	3 - 4

Table 2.2: Air quality reporting categories

Percentage of standard or guideline	Description	Colour coding
Less than 10%	Excellent	🟦
10-33%	Good	🟦
33-66%	Acceptable	🟩
66-100%	Alert	🟨
Above 100%	Non-complying	🟥

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[3] https://environment.govt.nz/acts-and-regulations/regulations/national-environmental-standards-for-air-quality/

[4] https://www.lawa.org.nz/explore-data/air-quality/

3. Monitoring campaign

3.1 Continuous air pollutant measurements

SO_2 (sulphur dioxide), NO_2 (nitrogen dioxide), NOx (nitrogen oxides), PM_{10} and $PM_{2.5}$ were measured at GWRC Shed 39 and at the GWRC Wellington central air reference monitoring site from 1 December 2019 to 31 May 2020 (Figure 3.1). The Shed 39 site was 2.2 km north to northeast of the Wellington central site.

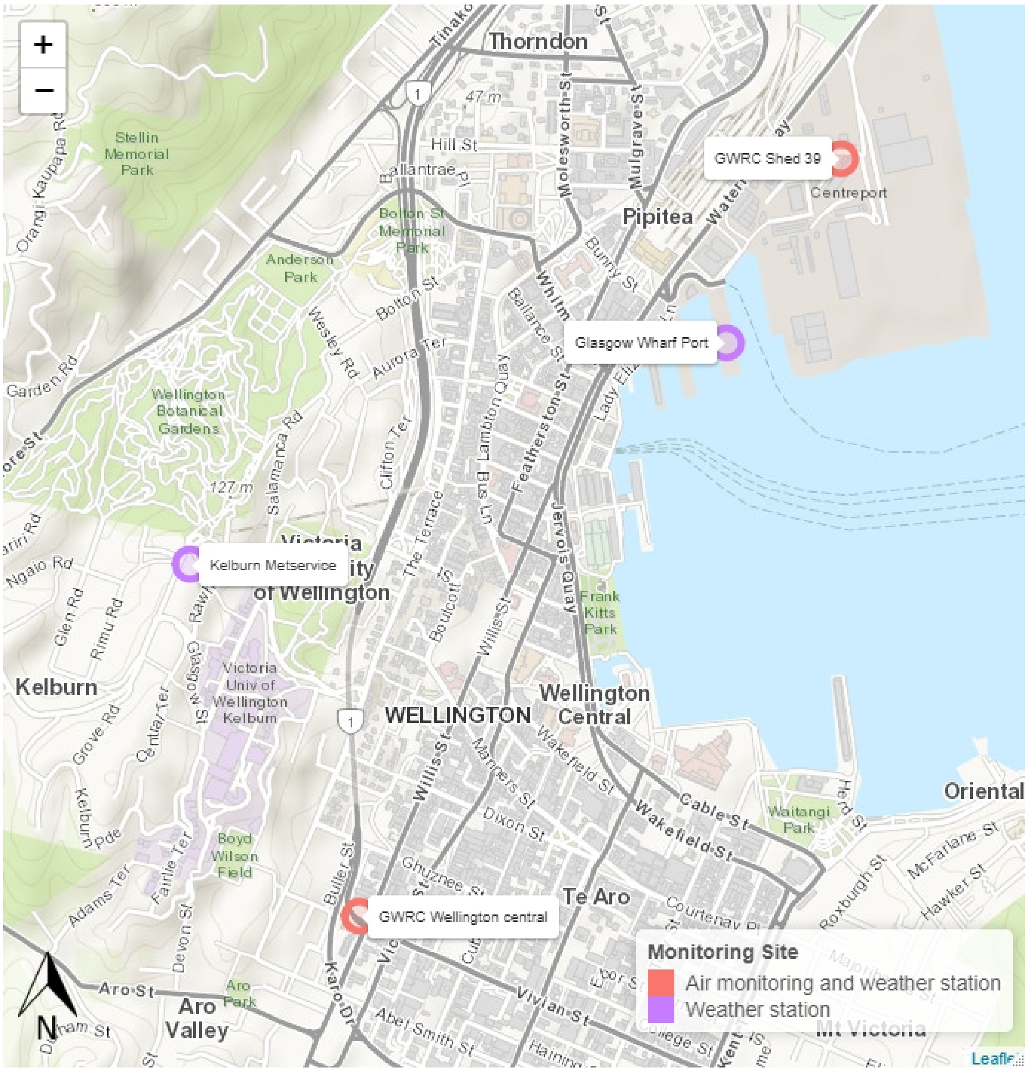


Figure 3.1: Location of air and meteorological monitoring sites

PM_{10} data was not available from Shed 39 until 10 December 2019, and $PM_{2.5}$ was not available until 11 December 2019. The gas and particle concentrations were measured by continuous analysers set to log five-minute averages. The methods and monitoring instruments used are listed in Appendix 1 (Table A1.1).

3.2 Meteorological measurements

Wind speed and direction were used to help interpret the air monitoring results, in particular to characterise how air pollutant levels vary by wind direction and speed as an aid to identify likely emissions sources. Measuring representative wind patterns is challenging in urban built up areas and where there is complex topography, such as Wellington city.

Meteorological measurements were made at the Shed 39 and Wellington central monitoring sites and data were purchased from MetService for Glasgow Wharf and Kelburn sites (Figure 3.1). The Shed 39 monitoring site had a low mast (3.5m) and was subject to local wind flows and channelling from nearby buildings. The Glasgow Wharf monitoring site was reasonably exposed and therefore thought to be more representative of the predominantly northerlies and southerlies that affect the harbour area. The Wellington central monitoring site was next to a tall building which blocks the northerly wind. Local funnelling at this site may mean that northerly winds are recorded as westerlies. Winds recorded at Kelburn weather station are predominately northwesterly, and due to its somewhat sheltered location do not provide a good guide to winds on the harbour (Quayle, 1984).

The meteorological data used in this report is 1-hour average wind speed and vector averaged wind direction.

3.3 Filter collection of particulate matter for elemental analysis

Particulate matter was collected on filters at Shed 39 and at Wellington central air monitoring site from 6 January to 23 March 2020. The air particulate filter holding cassettes needed to be replaced manually every few weeks and so the sampling schedule was interrupted by the COVID-19 alert level restrictions that came into effect from 23 March 2020.

Airborne particulate was collected each day on filters using the GNS particle speciation sampler ("Streaker" sampler) which was set to sample four consecutive 6-hour time periods over each 24-hour period, ie, from 00:00 to 06:00, from 06:00 to 12:00, from 12:00 to 18:00, and from 18:00 to 00:00. The method and sampling instrument are described in Appendix 2.

At Wellington central no valid filter samples were collected from 26 January 2020 to 1 February 2020 due to mechanical problems with the filter collection system. The timing of the sampling periods at Wellington central was inadvertently reset between 5 February and 20 February 2020 so they did not match exactly the time periods monitored at Shed 39 over that period.

3.4 Spatial survey of SO_2 by passive diffusion tubes

SO_2 passive diffusion tubes were deployed at ten locations selected in consultation with CentrePort (Figure 3.2). Photos of the monitoring sites are shown in Appendix 3. In addition, SO_2 was monitored by a continuous analyser at Shed 39 and at Wellington central monitoring site. The SO_2 passive diffusion tube monitoring method is described in Appendix 4. Duplicate passive diffusion tubes were deployed at each monitoring location over five sampling deployments (Table 3.1). The monitoring programme was interrupted by the COVID-19 alert level movement restrictions and consequently tubes deployed in the Port operational area (ie, HEB, FUMO and AQ Emergency Station) were not able to be accessed for the March and April sampling rounds.

Table 3.1: Passive SO_2 tube sampling periods

Month	Start date	End date
December 2019	9/12/2019	6/1/2020
January 2020	6/1/2020	3/2/2020
February 2020	3/2/2020	2/3/2020
March 2020	2/3/2020	23/3/2020
April 2020	23/3/2020	28/4/2020


Interislander
AQ Emergency Station
Thorndon Quay
Wellington Regional Stadium
GWRC Shed 39
Centreport
FUMO
HEB
Marine Store
Clyde Wharf
Westpac Stadium
Thorndon
Pipitea
Wellington Central
WELLINGTON
Tinakori Hill Wellington Town Belt
Bolton St Memorial Park
Frank Kitts Park
Wellington Urban Mtwy
Aotea Quay
Waterloo Quay
Lady Elizabeth Ln
Lambton Quay
Featherston St
Jervois Quay
Whitmore St
Molesworth St
Mulgrave St
Murphy St
Hobson St
Tinakori Rd
Hill St
Bolton St
The Terrace
Willis St
N
Leaflet

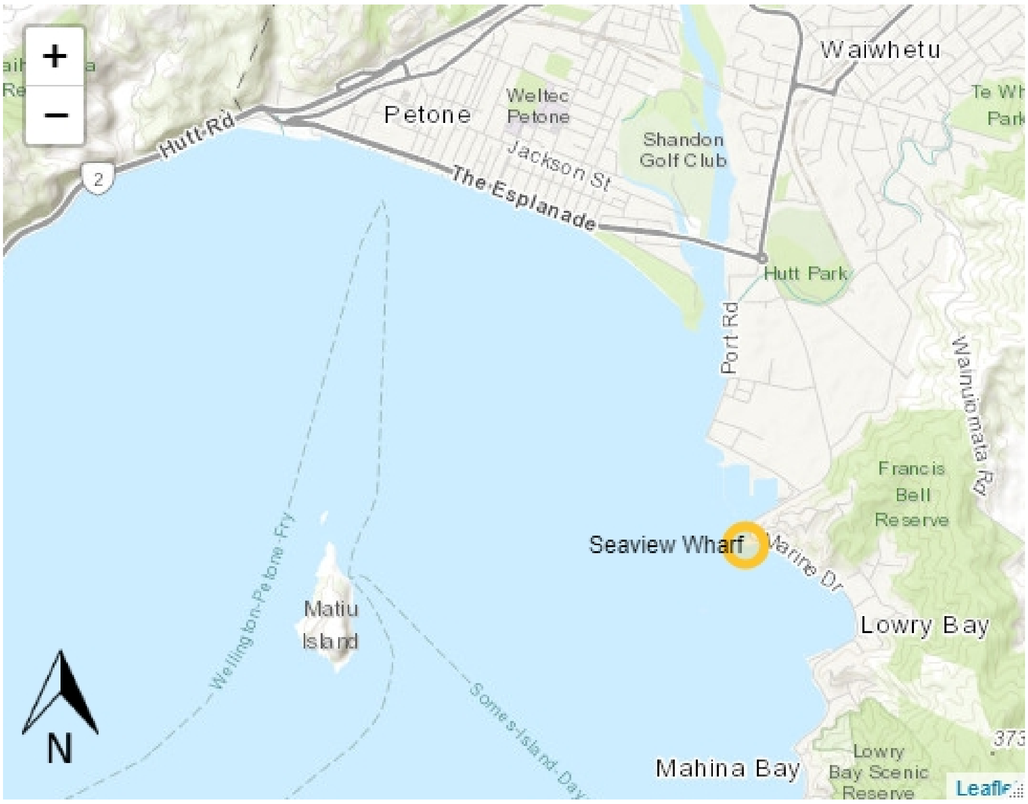


Figure 3.2: Location of SO_2 passive diffusion tube monitoring sites

3.5 Location of port operations

Figure 3.3 shows the general locations of port activities and operations relative to Wellington CBD and state highway 1.

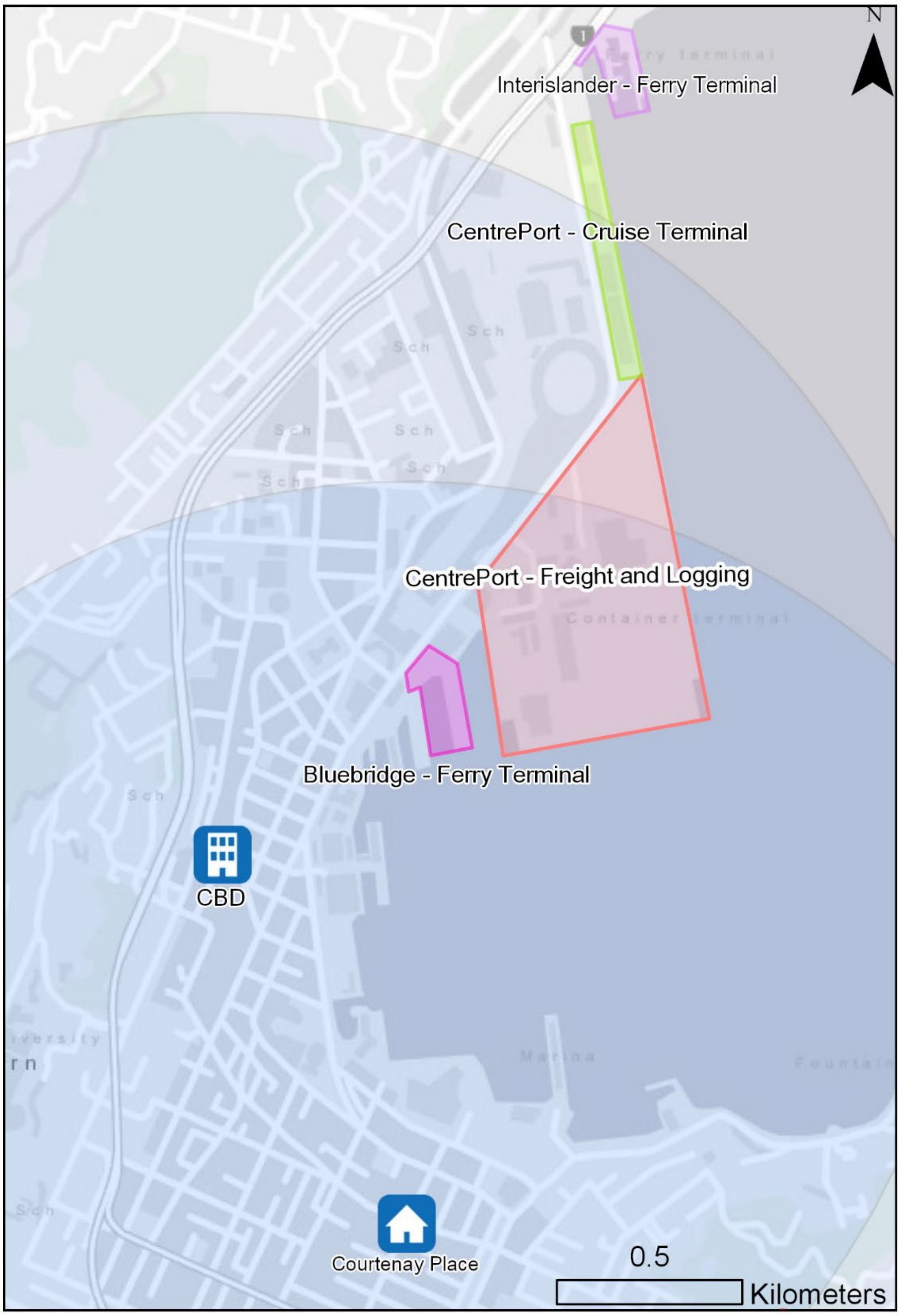


Figure 3.3: Location of port activities and operations. Source: Magnus Williams (ArcGIS 2019)

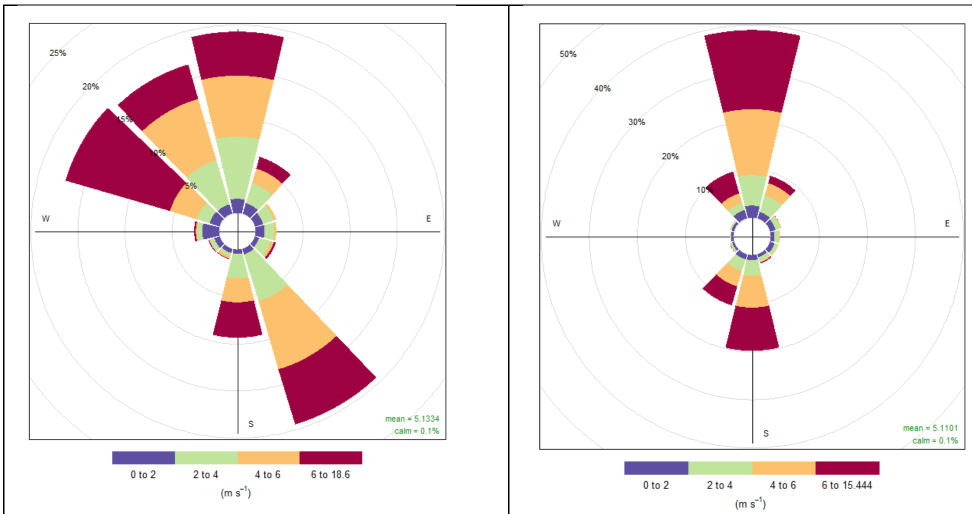
3.6 Data visualisation

Plots and maps were created using R (R Core Team, 2021) packages: openair (Carslaw & Ropkins, 2012), openairmaps (Carslaw, 2021), ggplot2 (Wickham, 2016) and leaflet (Cheng et al., 2021).

4. Continuous meteorology and pollutants

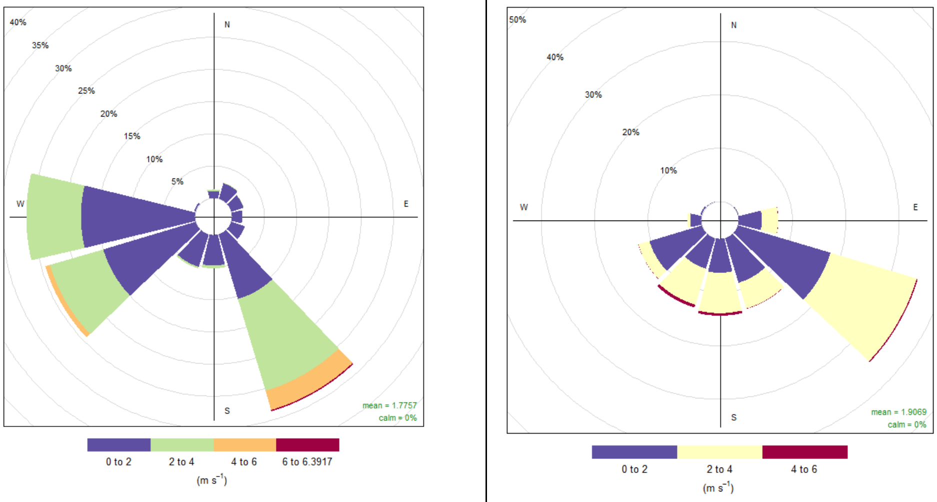
4.1 Meteorology

Pollutant concentrations measured at a particular location vary due to frequency and duration of downwind emission source activity. Wind speed and direction are the key drivers for transport and dilution of emissions from their source. Wind roses for each monitoring period are shown in Figure 4.1 where the points of the compass show the direction the wind was blowing from and the wedges show the proportion of time (represented as a percentage on the grey circles) that the wind is from a certain direction and wind speed band range.



Kelburn (MetService) 10m mast

Glasgow Wharf (MetService) 6m mast



Shed 39 (GWRC) 3.5m mast

Wellington central (GWRC) 6m mast

Figure 4.1: Wind Roses for the period 1 December 2019 to 31 May 2021 for each wind monitoring location

Figure 4.2 shows monthly variation in wind speed and wind direction using measurements from MetService weather station at Glasgow Wharf to represent winds across the harbour and port area. Figure 4.3 shows wind data from Kelburn MetService weather station to represent general wind flows across Wellington city.

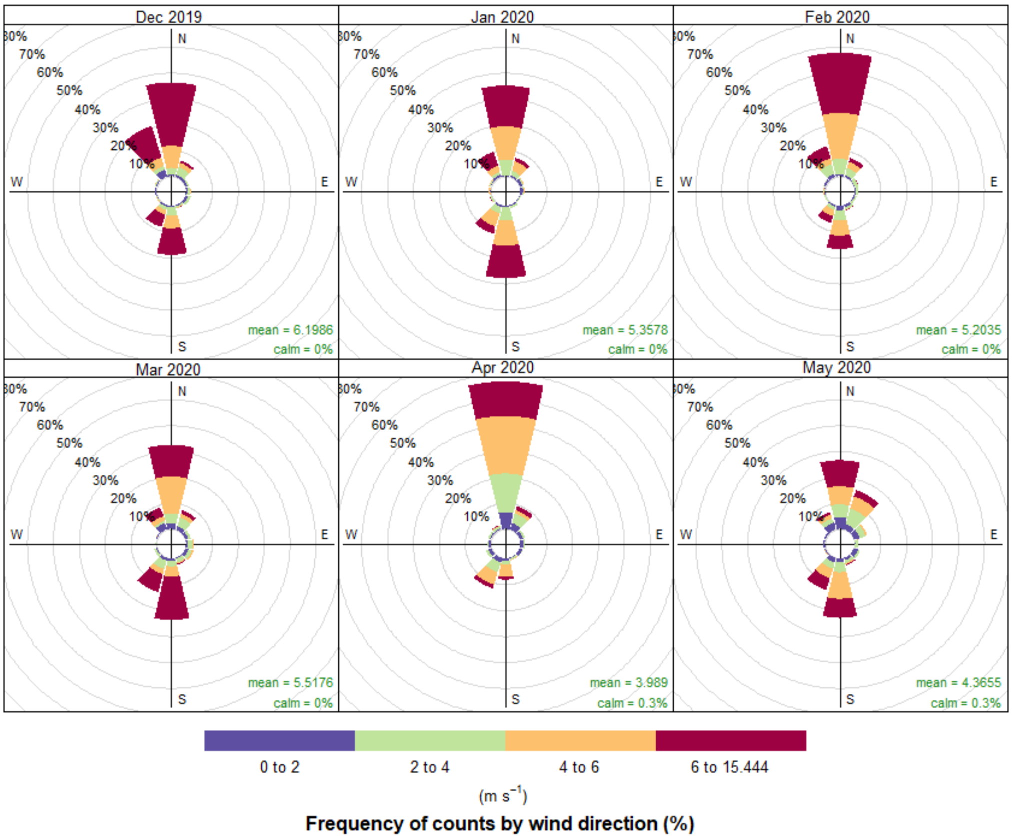


Figure 4.2: Wind Roses for the period 1 December 2019 to 31 May 2021 for MetService's Glasgow Wharf weather station by month

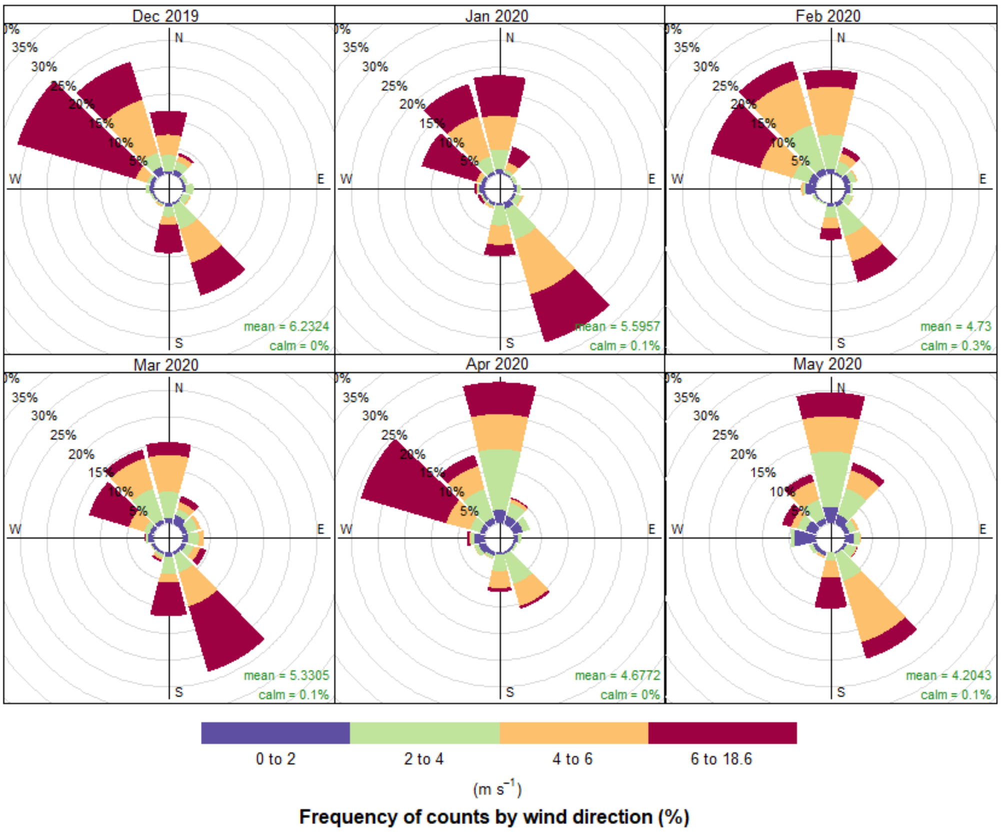


Figure 4.3: Wind Roses for the period 1 December 2019 to 31 May 2021 for MetService's Kelburn weather station by month

Summary statistics for other meteorological variables are shown in Table 4.1. During spring (December to February) Wellington city experienced slightly warmer than usual temperatures and slightly higher than normal wind speeds due to strong westerly flows. December 2019 was much wetter than normal, with January and February 2020 rainfall being well below average[5]. During autumn (March to May) temperatures remained warmer than average and wind speeds were below average due to a blocking high pressure to the east of New Zealand and low pressure south of Australia. March 2020 was much wetter than normal, with most of rain falling between 27-29 March. April was drier than usual and conditions returned to near normal in May 2020[6].

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[5] GWRC, Climate and water resources summary for the Wellington region, April 2020. http://www.gw.govt.nz/past-seasonal-climate-and-water-resource-summaries/#2020

[6] GWRC, Climate and water resources summary for the Wellington region, June 2020.

Table 4.1: Meteorological summary derived from Kelburn weather station (Metservice)

Month	Temp mean	Temp min (1 hour)	Temp max (1-hr)	Rain total (mm)	Number rain days (> 1 mm)	Number heavy rain days (> 25 mm)
Dec 2019	15.2	8.6	21.4	133	7	2
Jan 2020	16.0	9.4	24	26	5	0
Feb 2020	17.4	9.7	24.1	41.8	7	0
Mar 2020	15.0	7	23.4	121	6	2
Apr 2020	13.6	6.6	19.2	22	6	0
May 2020	11.9	3.7	18	136.4	5	3
Jun 2020	10.3	5.2	15.6	177.2	15	2

4.2 Continuous pollutant measurements

4.2.1 Summary statistics and time series

Summary statistics for monitored pollutants are shown in Table 4.2. During the monitoring period all pollutants met current national air quality standards and guidelines. The updated 2021 World Health Organization (WHO) 24-hour guidelines for NO_2 and SO_2 are much stricter than the existing national ambient air quality guidelines (MfE 2002). Comparison to the updated 24-hour WHO guidelines, moves SO_2 measured at Shed 39 from ‘good’ to ‘acceptable’. There were 12 days where daily NO_2 measured at Shed 39 exceeded the WHO daily guideline. The peak 24-hour and 1-hour concentration of SO_2 measured at Shed 39 was very similar to that found at the Ports of Auckland monitoring site at Gladstone Park, Parnell in January 2019 to February 2019[7].

It is noted that the monitoring period did not include all the winter months when levels of NO_2 measured across the region are highest due to colder and calmer weather, which restricts the dispersion of air pollutants. Peak PM levels at both sites were at the ‘alert’ level which is greater than 66% of the relevant standard or guideline.

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[7] Tonkin & Taylor 2020 Ambient air quality monitoring for the Ports of Auckland.

Table 4.2: Summary statistics for pollutant concentrations measured at Shed 39 and Wellington central from 1 December 2019 to 31 May 2020. The colour banding denotes air quality reporting category as shown in Table 2.2.

Pollutants (µg/m^3)	**SO_2**	**NO_2**	**PM_{10}**	**$PM_{2.5}$**
Shed 39				
24-hour mean and standard deviation in brackets	5.1 (2.5)	11.3 (7.4)	17.8* (6.4)	5.7* (2.0)
24-hour max	19.4	51.4	41.2*	17.6*
1-hour max	79.4	96.8	231.7	36.9
data capture	93%	81%	88%	87%
Wellington central				
24-hour mean and standard deviation in brackets	4.3 (1.6)	8.4 (4.6)	13.3 (5.7)	5.8 (2.6)
24-hour max	8.7	29.0	38.5	18.4
1-hour max	32.8	50.5	46.9	25.0
data capture	83%	93%	98%	97%

*Adjusted to be equivalent to the NES-AQ compliant monitoring method used at Wellington central (Appendix 1)

Figure 4.4 shows the time series of 24-hour measurements for continuous pollutant measurements at both sites.

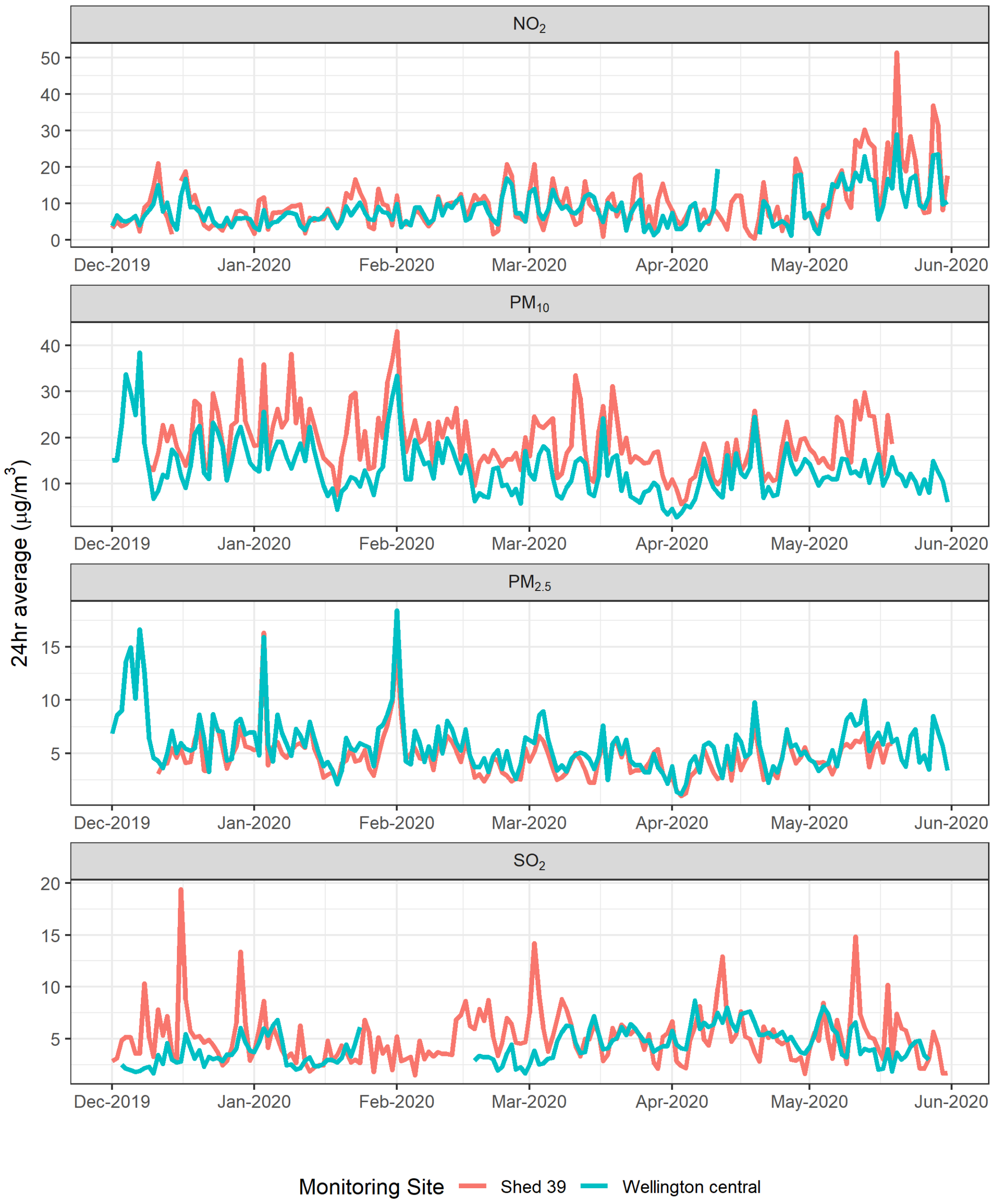

Figure 4.4: Time series of 24-hour average pollutant concentrations measured at Shed 39 and Wellington central from 1 December 2019 to 31 May 2020

4.2.2 Sulphur dioxide

The continuous measurements of SO_2 at Shed 39 and at Wellington central monitoring station showed a similar temporal pattern, but with short term elevated concentrations being measured at Shed 39 (Figure 4.4). This was most likely due to the port area being closer to a source of SO_2 emissions which were then dispersed and diluted before being measured at Wellington central under certain wind conditions.

The diurnal variation in average hourly SO_2 by day of the week measured at both sites is shown in Figure 4.5. This plot highlights the influence of local SO_2 sources measured at Shed 39.

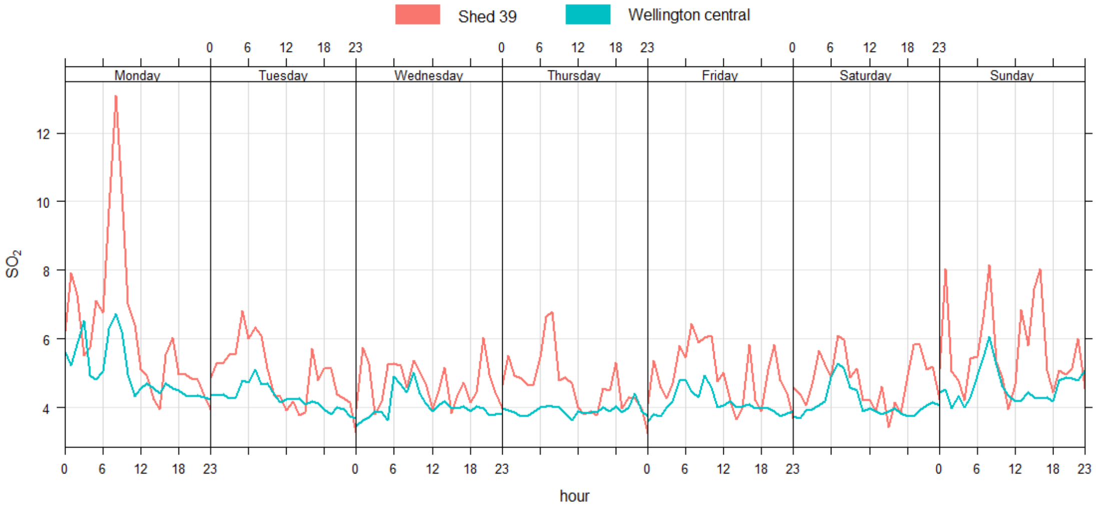

Figure 4.5: Time variation[8] in average 1-hour SO_2 concentrations by hour of day by weekday from December 2019 to May 2020 for the two monitoring sites

Polar plots show how SO_2 varied by wind speed and wind direction intervals using a smoothed concentration surface (Carslaw & Ropkins, 2012). The concentration of SO_2 is shown on a ‘heat’ colour scale, with the cooler blue hues representing the lowest concentrations and the dark red colour showing the highest concentrations. The points of the compass show the direction the wind was blowing from, and the radial scale shows wind speed in 5 m/s increments.

The polar plots show elevated SO_2 concentrations were measured at Shed 39 (Figure 4.6) under predominantly northerly winds suggesting that the source of this SO_2 is from the direction of the cruise ship berth area and Interislander terminal. The picture is less clear at Wellington central, where there was an SO_2 influence to the north as well as westerly component (Figure 4.7). It is speculated that some SO_2 measured at Wellington central may be associated with peak emissions from heavy duty vehicles using the Terrace Tunnel.

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[8] Plots created using R package openair **(Carslaw & Ropkins, 2012).**

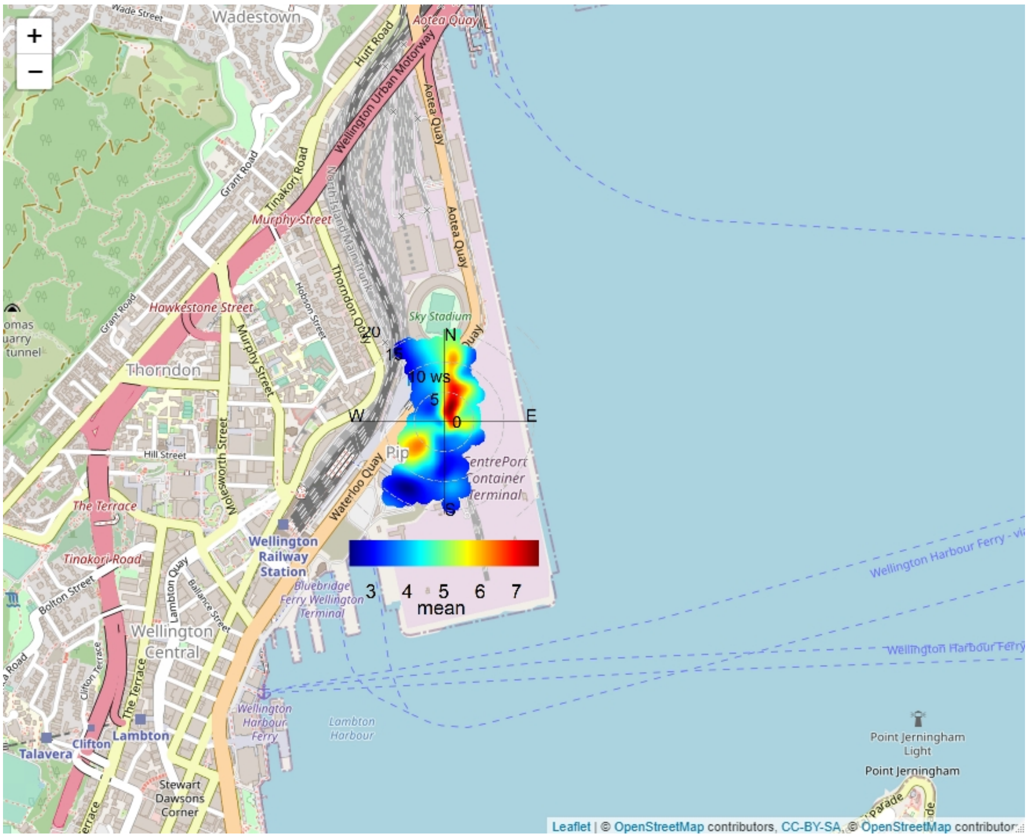


Figure 4.6: Polar plots of average 1-hour SO_2 measured at Shed 39 from 1 December 2019 to 31 May 2020 using wind data from Glasgow Wharf (MetService)

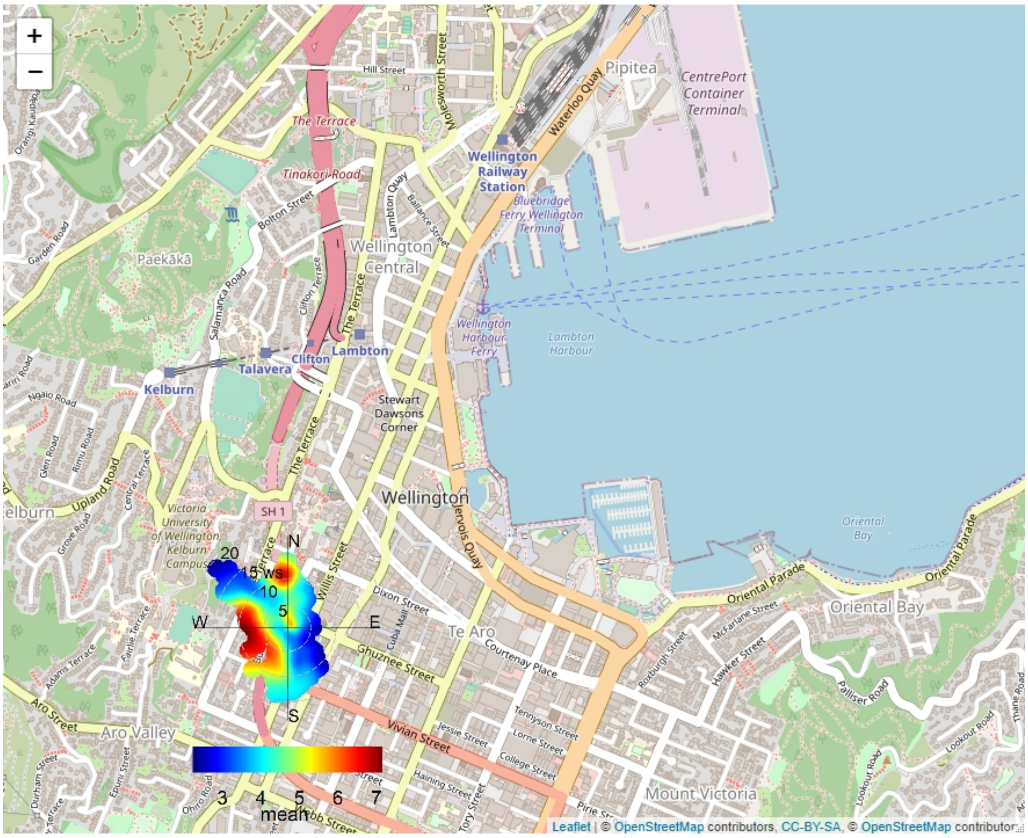


Figure 4.7: Polar plots of average 1-hour SO_2 measured at Wellington central from 1 December 2019 to 31 May 2020 using wind data from Kelburn (MetService)

Due to COVID-19 disruptions the last international cruise ship departed from Wellington on 18 March 2020. A polar plot showing average SO_2 concentration by wind direction before and after this date (Figure 4.8) shows elevated SO_2 levels in the absence of cruise ships suggesting that SO_2 emissions from other vessels or land-based sources operating after this date were being measured at Shed 39.

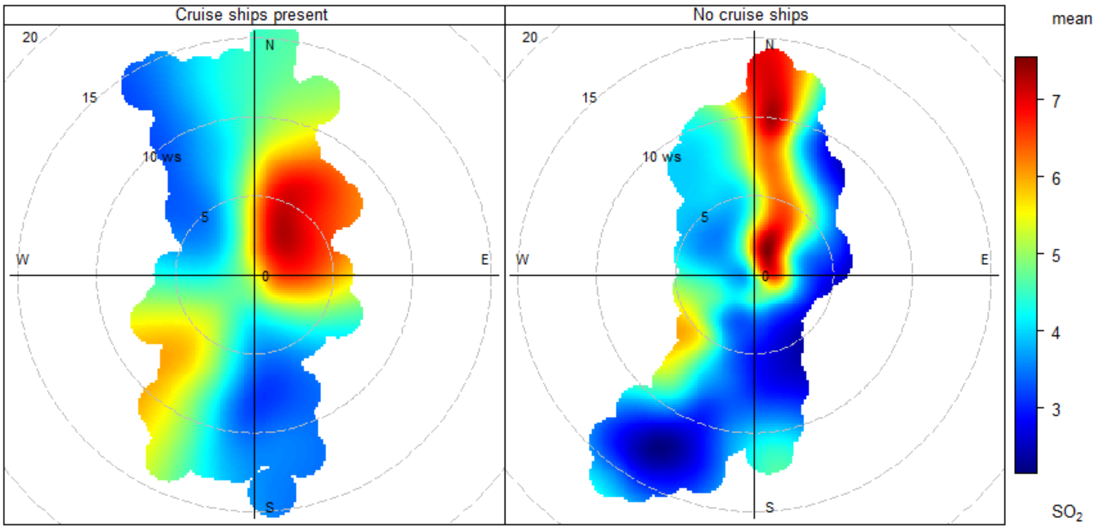


Figure 4.8: SO_2 polar plots for the period before (left) and after (right) the last international cruise ship departed on 18 March 2020

Figure 4.9 shows the daily variation in SO_2 concentrations measured at Shed 39 annotated with wind direction and wind speed arrows. Plots of 10 minute SO2 readings for peak SO_2 concentration days (ie, 16/12/2029, 29/12/2019, 2/3/2020, 12/4/2020 and 11/5/2020) are shown in Appendix 7. A common pattern was observed with high SO_2 days measured at Shed 39 coinciding with northerly winds.

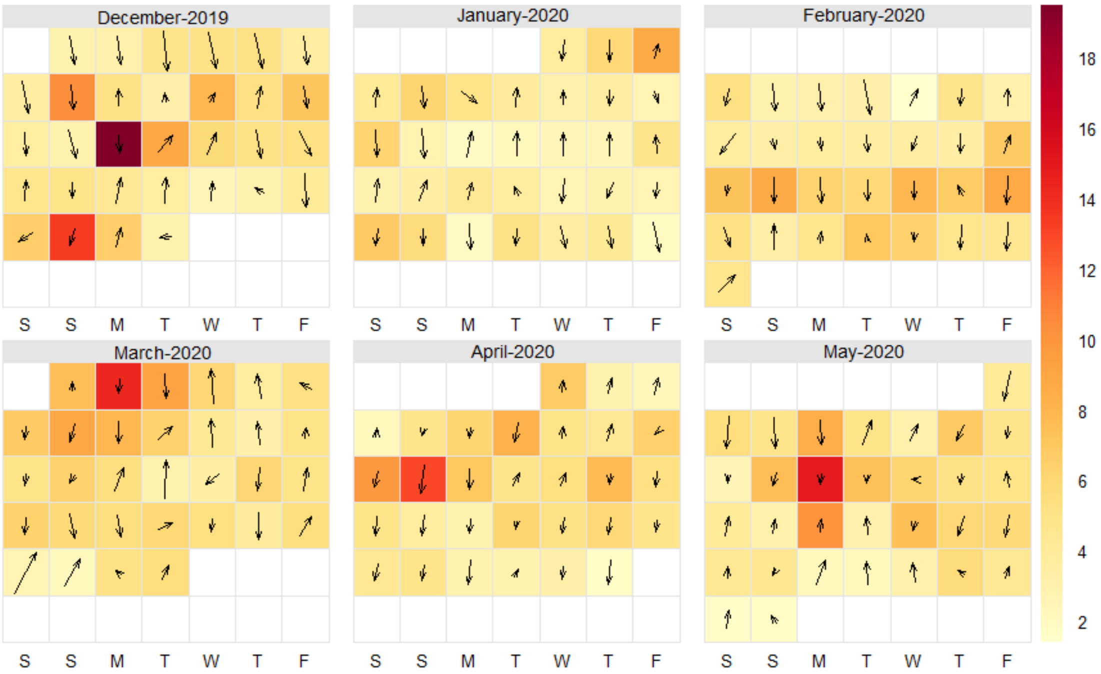


Figure 4.9: Calendar plot showing 24-hour average SO_2 concentrations by calendar day. The arrow points towards direction the wind was blowing from and the length of the arrow is proportional to wind speed (measured at Glasgow Wharf by MetService.

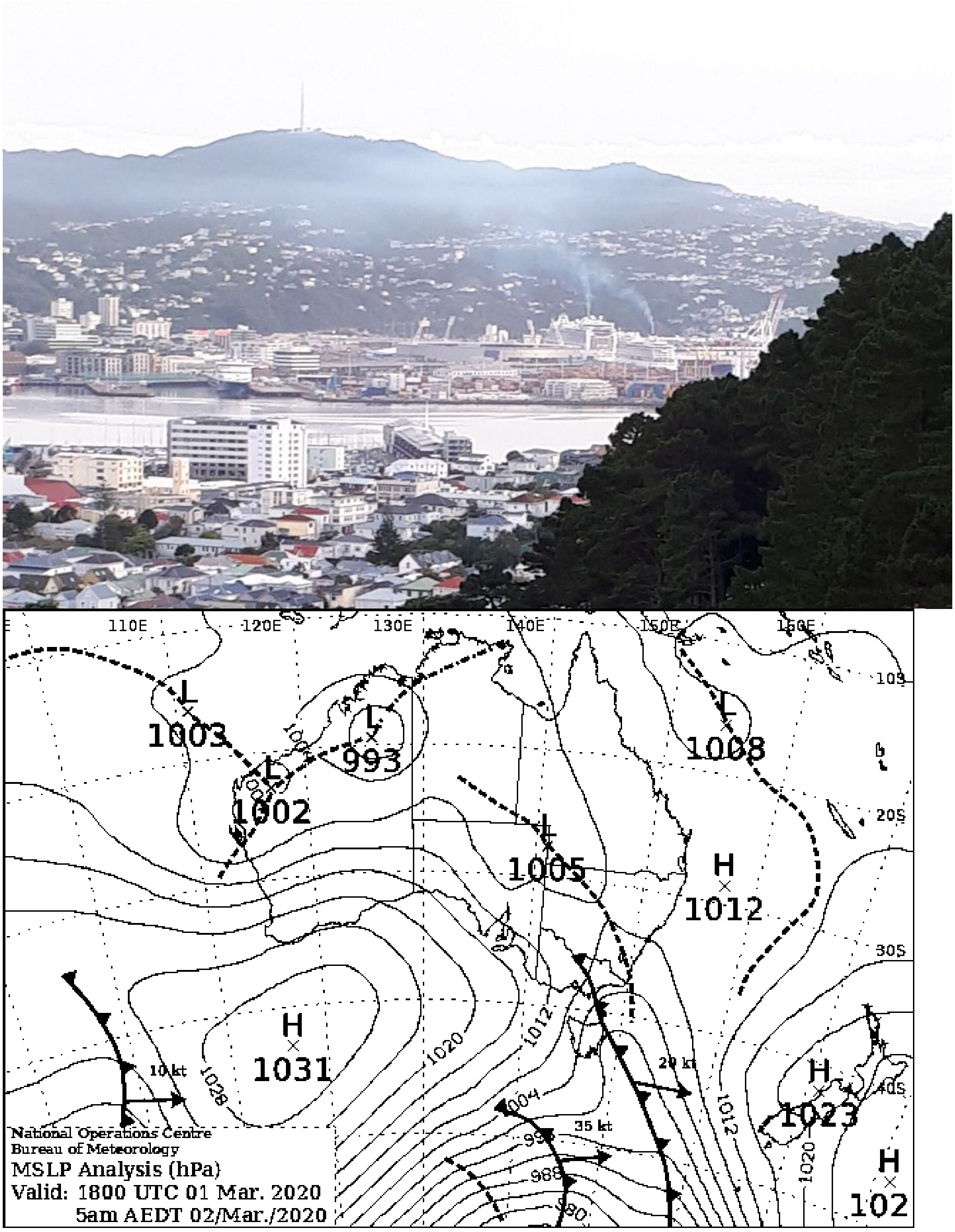


Figure 4.10: Photo showing emissions from two cruise ships at berth on 2 March 2020 at 07:47 coinciding with calm wind conditions and a high pressure system over central New Zealand (Australian Bureau of Meteorology)

4.2.3 Oxides of nitrogen (NO_2 and NOx)

The increase in NO_2 during May 2020 (Figure 4.4 and 4.11) shows the start of the winter meteorological influence, in which more stable atmospheric conditions allow air pollutants to accumulate. NO_2 levels at both sites showed a similar morning peak typically associated with week day rush hour traffic (Figure 4.11). Overall, NO_2 levels measured at Shed 39 were higher than Wellington central and also differed in having a second peak later in the evening that did not drop to the same low overnight levels seen at Wellington central. It's likely that the difference between the sites was due to the high NOx emissions from heavy duty vehicles (trucks) that travelled past Shed 39 between Fryatt Quay and Hinemoa Street during the day and the afterhours ferry and freight traffic.

During Level 4 COVID-19 movement restrictions (26/3/2020 to 27/4/2020) there was an estimated reduction in average NO_2 of 58% and in NOx of 71% accounting for the effect of meteorology at Wellington central (Mitchell, 2021). It was not possible to calculate the impact of L4 restrictions on NO_2 and NOx measured at Shed 39 as there was no historical baseline data for comparison at that monitoring site.

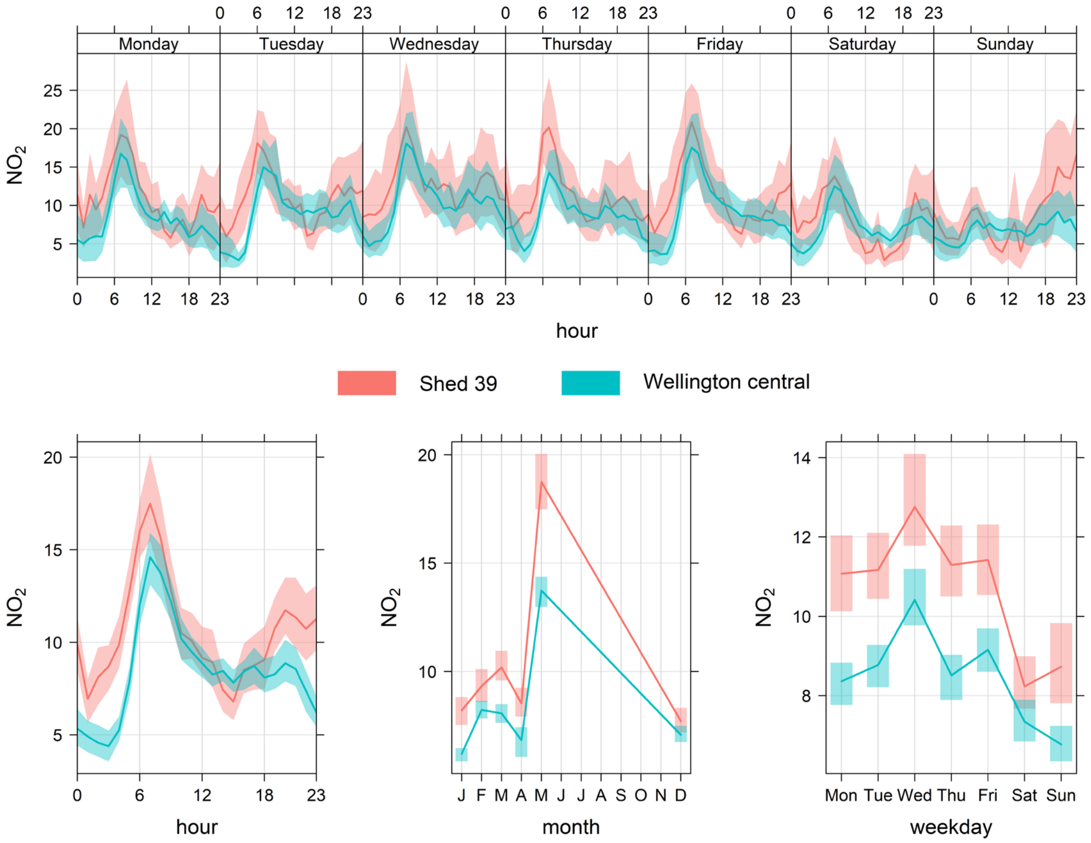


Figure 4.11: Time variation in average 1-hour NO_2 concentrations by hour of day by weekday from December 2019 to May 2020 for the two monitoring sites. The shaded area shows the 95% confidence interval for the average.

4.2.4 Particulate matter (PM_{10} and $PM_{2.5}$)

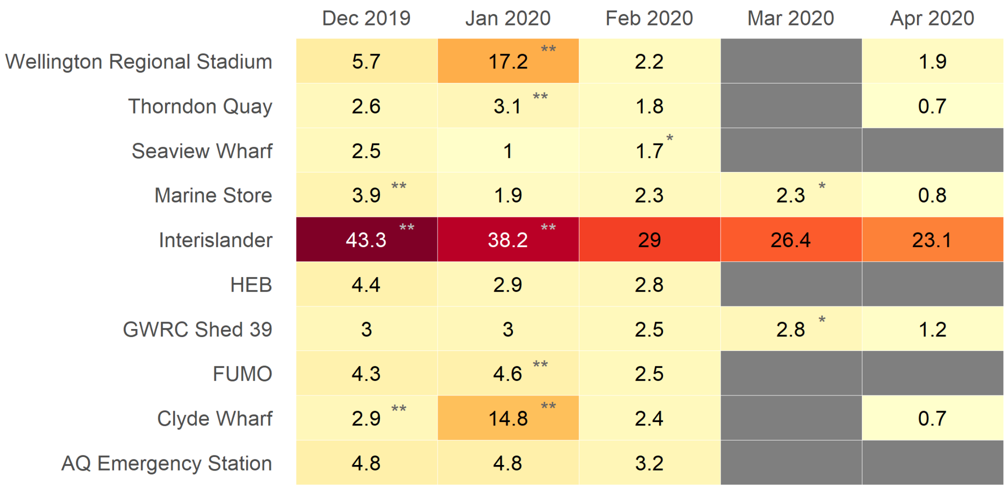
Average concentrations of fine particles ($PM_{2.5}$) were similar at both sites. PM_{10} was higher at Shed 39 than at Wellington central reflecting the contribution of local sources of 'coarse' particulate from marine aerosol, wind-blown soils, and construction and demolition activities nearby. The contributions of different particle sources to observed PM_{10} and $PM_{2.5}$ concentrations is discussed in Section 6.

The peak 24-hour average PM_{10} concentration at Wellington central measured on 7 December 2019 was due to long range transport of desert dust together with fine smoke particles from the Australian bush fires (Davy, 2021). PM_{10} measurements were not available from Shed 39 until 10 December 2019 so this event was not monitored. High particle episodes observed on 3 January 2020 and 1 February 2020 were also measured at GWRC's monitoring sites in Upper Hutt, Wainuiomata, Lower Hutt and Masterton, showing it was a region-wide event.

5. Sulphur dioxide passive tube spatial survey

5.1 SO_2 concentrations by monitoring locations

Sulphur dioxide (SO_2) concentration by monitoring period and by site are shown in Figure 5.1 with the results presented in full in Appendix 4 (Table A1.1). Duplicate tubes were deployed at all sites for quality control of the sampling and analysis method. The SO_2 concentration reported for each location is based on the average of the pair of tubes at that location. Results, where the relative percentage difference between paired tubes at a monitoring location was greater than 30% and the absolute difference was greater than 1 µg/m^3, were considered questionable but are included for completeness. It was noted by the analytical laboratory that some of the tubes were 'dirty' and therefore results may be compromised. Source of the particulate deposited on the tubes is not known, but may be from natural sources, such as, wind-blown soils and dust from paved areas. During March 2020, SO_2 concentrations at Seaview Wharf, Thorndon Quay and Wellington Regional Stadium were below the laboratory reporting limit.



	Dec 2019	Jan 2020	Feb 2020	Mar 2020	Apr 2020
Wellington Regional Stadium	5.7	17.2 **	2.2		1.9
Thorndon Quay	2.6	3.1 **	1.8		0.7
Seaview Wharf	2.5	1	1.7 *		
Marine Store	3.9 **	1.9	2.3	2.3 *	0.8
Interislander	43.3 **	38.2 **	29	26.4	23.1
HEB	4.4	2.9	2.8		
GWRC Shed 39	3	3	2.5	2.8 *	1.2
FUMO	4.3	4.6 **	2.5		
Clyde Wharf	2.9 **	14.8 **	2.4		0.7
AQ Emergency Station	4.8	4.8	3.2		

*One of the paired tubes was below the laboratory reporting limit
**Duplicate tubes with a relative percent difference > 30% and absolute difference > 1 µg/m^3

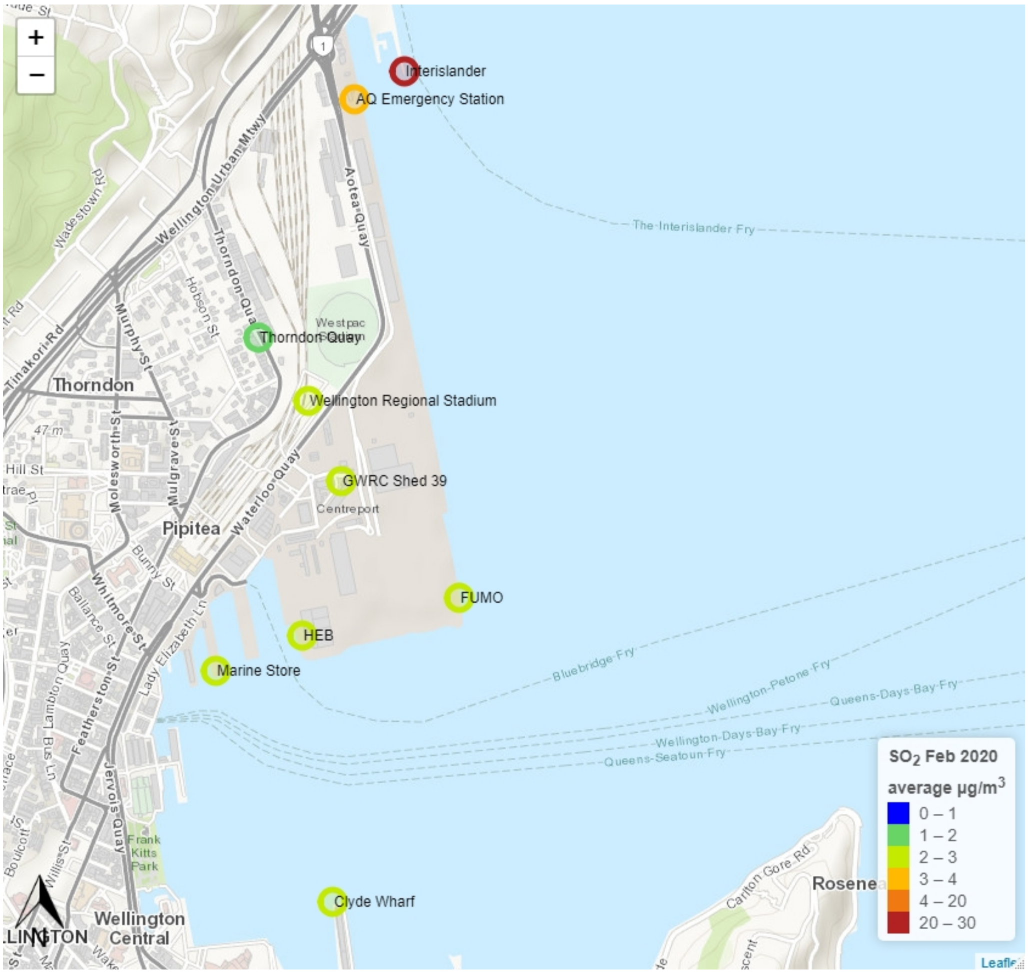
Figure 5.1: Heat plot showing monthly SO_2 passive diffusion tube concentration (µg/m^3) by monitoring location. Grey cells show no data available as tube sites could not be accessed or both duplicate tubes were below the laboratory reporting limit.

Maximum SO_2 concentrations were consistently recorded at the Interislander wharf monitoring site. This high concentration is probably due to the monitoring site being influenced by ship stack downwash, where the plume touches down in the lee of the ship under certain meteorological conditions. Although this area is not accessible to the public, it shows the potential for high SO_2 concentrations near ship berths where the ship uses high sulphur fuel.

Elevated SO_2 concentrations were also recorded by one of each of the paired tubes at Wellington Regional Stadium and Clyde Wharf in the January 2020 sampling round. These paired results were unusual (ie, Wellington Regional Stadium: 29.6 µg/m^3 and 4.8 µg/m^3; Clyde Wharf: 28.1 µg/m^3 and 1.6 µg/m^3) and based on the overall pattern of duplicate tube results (Figure A4.1) it is possible that there was a tube labelling error and the results for each site have been erroneously combined. The Wellington Regional Stadium monitoring site was located on the elevated overhead walkway so potentially could be more impacted by ships plumes which are released at a similar height.

5.2 Spatial variation in SO_2

All measurements from the February 2020 deployment round were within the quality assurance limits and therefore can be taken to represent spatial variation between monitoring sites for that month (Figure 5.2). During February 2020, the port operational sites plus GWRC Shed 39, Wellington Regional Stadium and Clyde Wharf had on average, SO_2 levels 1.4 times higher than Thorndon Quay and Seaview Wharf. The relative contribution of local recreation and fishing vessels using Clyde Wharf and Kings Wharf (Marine Store site) to SO_2 measurements is unknown, but not thought to be significant.



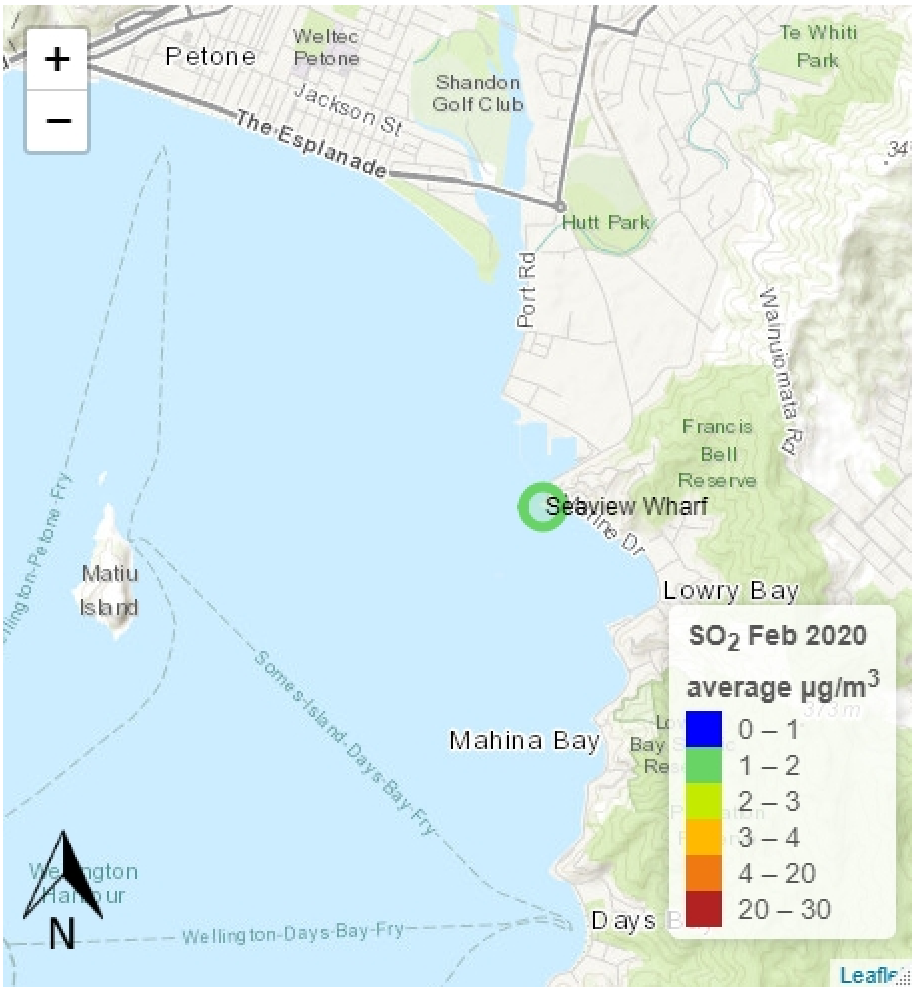


Figure 5.2: February 2020 SO_2 passive tube monitoring results

6. Source analysis of particulate matter

6.1 Elemental concentrations in particulate matter

Particulate matter samples were collected on air filters at Shed 39 and at Wellington central monitoring sites from 6 January to 23 March 2020. The concentrations of elements in the air filter samples from each site were determined by ion beam analysis at the New Zealand Ion Beam Analysis Research Laboratory operated by GNS Science in Lower Hutt. Summary data for concentrations of elements determined from the fine ($PM_{2.5}$) and coarse ($PM_{10-2.5}$) filters are presented in Appendix 6 (Tables A6.1 to A6.4).

6.2 Particle source identification

Receptor modelling was undertaken by GNS Science to identify and apportion sources of particulate matter measured during the monitoring campaign. The receptor modelling method is described in Appendix 2. The elemental profiles determined for each source factor and the percentage contribution by total mass of each element to each source factor are presented in Appendix 6 (Tables A6.5 and A6.6). The source factors derived from the receptor modelling were identified based on the elemental fingerprint of each source as follows:

Particulate sources found at Shed 39 and Wellington central

- **Coarse soil** derived from the mechanical abrasion and weathering of the Earth’s crust. Sources include unsealed yards and open areas where soil particles are disturbed by wind action. The soil source was associated with the PM coarse size fraction and was primarily composed of aluminosilicate minerals, mainly aluminium (Al) and silicate (Si), together with magnesium (Mg), potassium (K) iron (Fe) and titanium (Ti).

- **Marine aerosol or sea salt** was characterised by high levels of its two major constituents, sodium (Na) and chlorine (Cl), along with the more minor components of sea salt, potassium (K), calcium (Ca), manganese and sulphur (S). This source is ubiquitous throughout the region, even in inland areas. Fine marine aerosol arises from long-range transport from the Tasman Sea and the coarse marine aerosol is mainly composed of sea spray from Wellington harbour.

- **Motor vehicles** source was identified due to the presence of copper (Cu) from the widespread use of this metal in motor vehicle brake pads and iron (Fe) from car bodies.

- **Secondary sulphate** derived from the gas-to-particle conversion in the atmosphere of sulphur containing gases from combustion of fuels (with a high sulphur content) and from natural sources, such as volcanic activity or marine algae. These particles are formed particularly during the summer months when atmospheric reactions are enhanced by sunlight and warmer temperatures. The natural source contributions to secondary sulphate, such as volcanic activity, can occur over long distances and therefore generally impact the whole Wellington region.

Particulate sources specific to Shed 39

- **Construction and demolition activity** was a mixed source representing a combination of fine windblown soil, dust generated by earthworks, construction, roadworks and associated vehicle movements. Over the monitoring period the port area was affected by nearby building demolitions and various on-site road construction projects.

- **Ship emissions** were characterised by presence of fine vanadium (V), nickel (Ni), sulphur and black carbon. These components are specific to primary particle emissions from ship engines that use fuels that are high in sulphur and heavy metals, such as heavy and medium fuel oil.

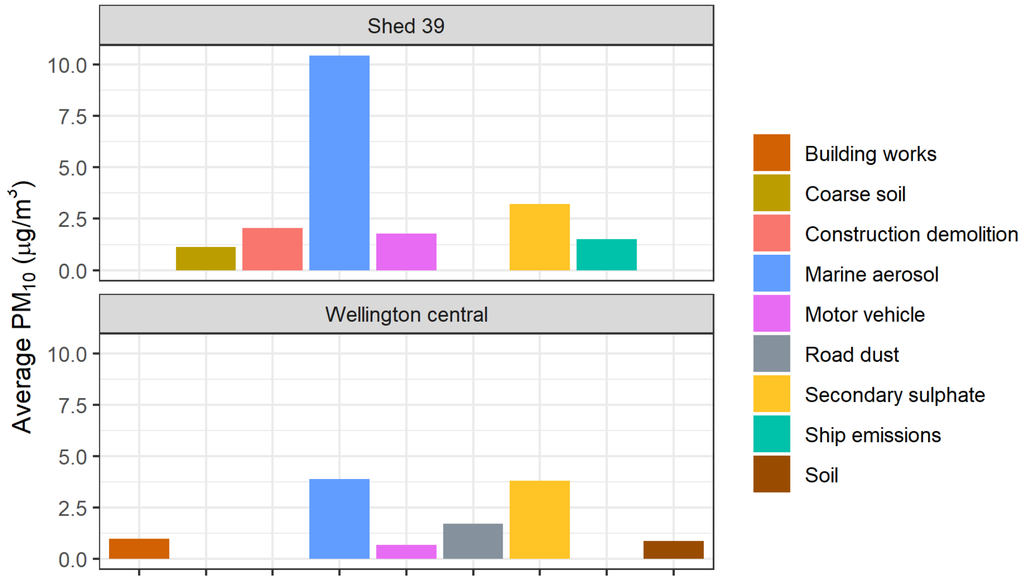
Particulate sources specific to Wellington central

- **Road dust** arises from re-suspended dust from road surfaces due to the turbulence created by the passage of vehicles. Road dust contains elements associated with break and tyre wear, such as copper (Cu) and zinc (Zn).

- **Building refurbishment works** were being carried out on the apartment block close to the Wellington central monitoring station. These works included replacing windows in the multi-storey building. This resulted in an unusual elemental signature of high fine silicate (Si) in the particulate matter samples.

6.3 Contributions of sources to PM_{10} mass

The contribution of each source to average PM_{10} levels measured at Shed 39 and Wellington central during the monitoring period is presented in Figure 6.1. Table 6.1 lists the source concentrations and their percent contributions to total modelled mass. The total PM mass estimated by the receptor modelling is slightly lower than what was measured by the co-located PM by continuous monitoring instruments as some compounds that contribute to PM mass (eg, nitrates) are not accounted for by the element measurements alone.



Data source: GNS Science

Figure 6.1: Average source contributions to PM_{10} at Shed 39 and at Wellington central from 6 January 2020 to 23 March 2020

Table 6.1: Average source contributions and their relative percentages of receptor modelled PM_{10} at Shed 39 and at Wellington central from 6 January 2020 to 23 March 2020

Source	**Shed 39**		**Wellington central**	
	Concentration	Percent	Concentration	Percent
Building works			1.0 $\mu g/m^3$	8.0 %
Coarse soil	1.1 $\mu g/m^3$	5.5 %		
Construction demolition	2.1 $\mu g/m^3$	10.4 %		
Marine aerosol	10.4 $\mu g/m^3$	51.7 %	3.9 $\mu g/m^3$	32.6 %
Motor vehicles	1.8 $\mu g/m^3$	9.0 %	0.7 $\mu g/m^3$	5.7 %
Road dust			1.7 $\mu g/m^3$	14.4 %
Secondary sulphate	3.2 $\mu g/m^3$	15.9 %	3.8 $\mu g/m^3$	32.0 %
Ship emissions	1.5 $\mu g/m^3$	7.5 %		
Soil			0.8 $\mu g/m^3$	7.2 %
Average modelled sources	20.1 $\mu g/m^3$		11.9 $\mu g/m^3$	
Average continuous measurement method	22.0 (18.7*) $\mu g/m^3$		12.8 $\mu g/m^3$	

* Corrected to be equivalent to the monitoring method used at Wellington central (Appendix 1)

At Shed 39, marine aerosol made up just over half of all PM_{10}. The increased loading of marine aerosol compared to the Wellington central monitoring site is most likely due to the Shed 39 monitoring site being much closer to the harbour and therefore measuring proportionally more of the ‘coarse-sized’ particles from local sea spray, compared to the regional fine aerosol source from long range transport from the Southern Ocean.

The next largest contributor to PM measured at Shed 39 was secondary sulphate, which is a mix of natural and combustion sources. Interestingly, secondary sulphate concentrations were slightly higher at Wellington central than at Shed 39. The reasons for this are not clear, but may be due to high regional background from natural sources plus some contribution from upwind combustion sources containing sulphur that have undergone gas-to-particle conversion.

At Shed 39, ship emissions accounted for 7.3% of measured PM_{10}. This was slightly above the contribution of ship emissions from the Auckland port area (from 2006 to 2013) to PM_{10} concentrations measured at the Queen Street (Auckland) air monitoring site, which was 0.73 $\mu g/m^3$ (4%) (Davy et al., 2017).

6.4 Daily variation in source contributions to PM_{10}

The daily variation in source contributions of PM_{10} measured at Shed 39 is shown in Figure 6.2 and at Wellington central in Figure 6.3. On any given day the concentration of a source measured at the monitoring site will vary depending on the emission source activity and wind speed and direction with respect to the monitoring site. Elevated particulate levels due to a high loading of secondary sulphate were measured on 1 February 2020 at both sites. Based on regulatory monitoring data from elsewhere in the region (section 4.2.4) this appears to be a high particulate region-wide event possibly from sulphates originating from a spike in offshore marine phytoplankton activity. A satellite study showed widespread phytoplankton blooms from December 2019 to March 2020 in the Southern Ocean triggered by aerosols released from the intense Australian bushfires (Tang et al., 2021).

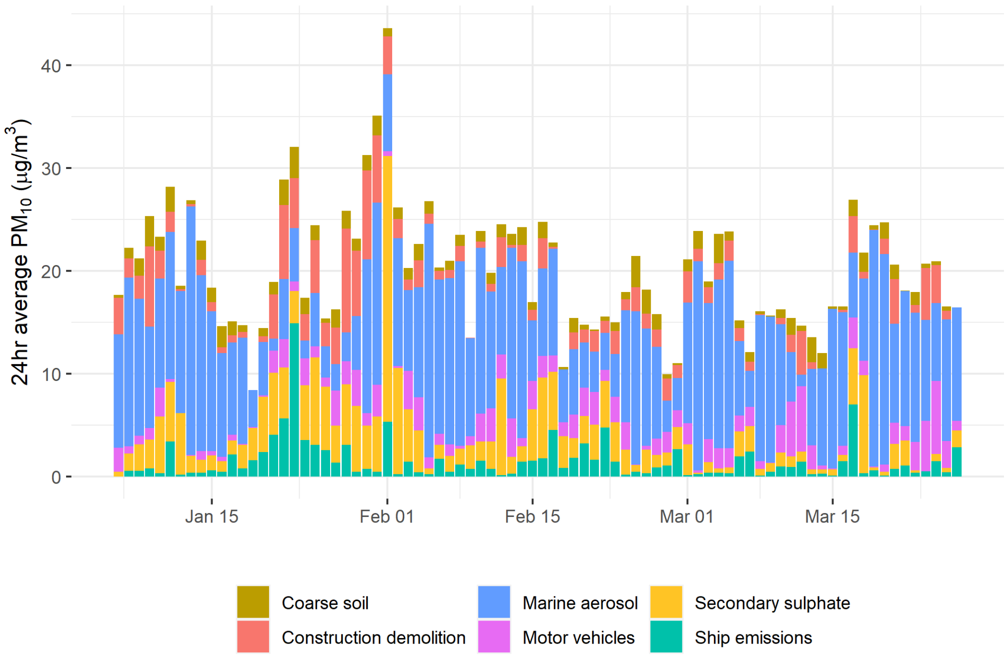


Figure 6.2: Daily source contributions to PM_{10} measured at Shed 39 from 6 January 2020 to 23 March 2020

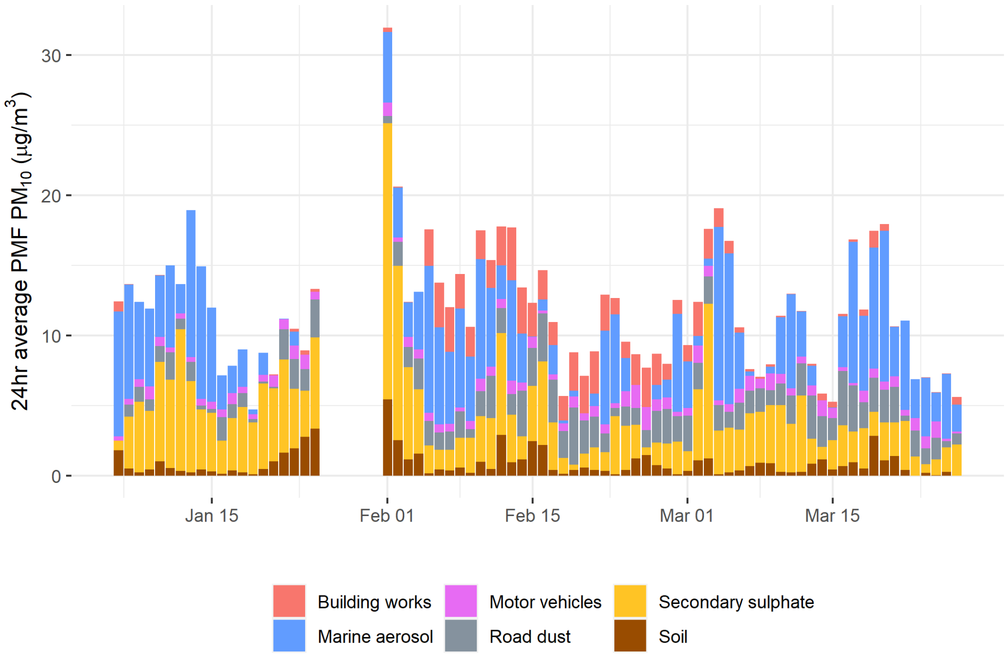


Figure 6.3: Daily source contributions to PM_{10} measured at Wellington central from 6 January 2020 to 23 March 2020

Black carbon filter measurements, an indicator of combustion emissions, were higher at Shed 39 compared to Wellington central (Figure 6.4). This is most likely due to heavy duty vehicles (trucks) travelling past the monitoring site at Shed 39. Trucks accelerating after stopping at the nearby intersection in Hinemoa Street is a possible explanation for locally elevated black carbon levels. There may have also been other combustion-related activities occurring nearby.

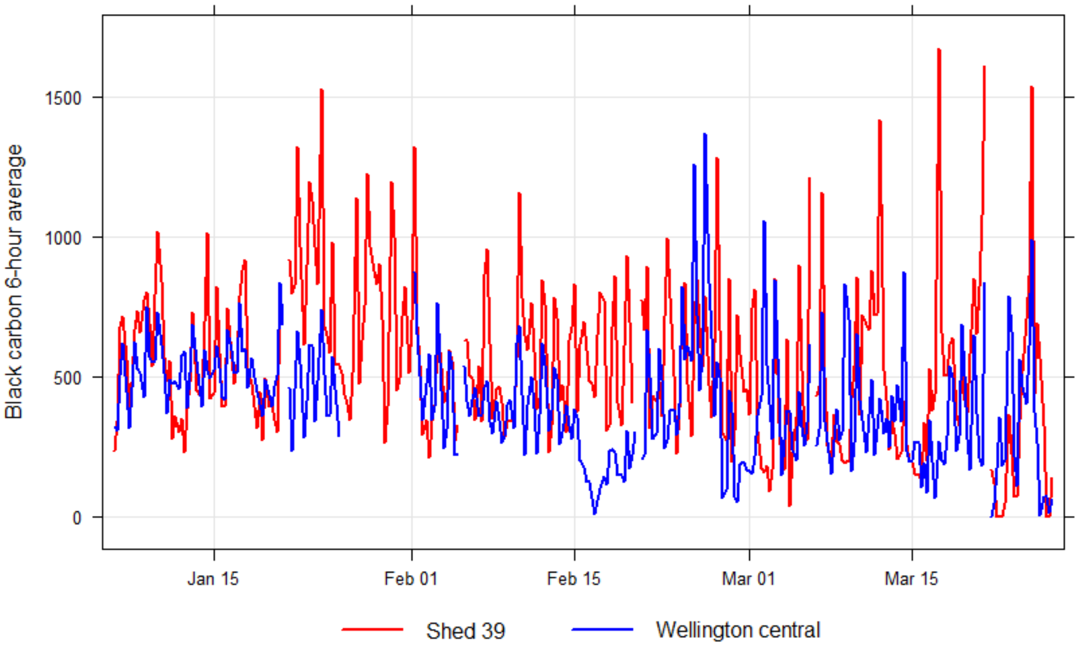
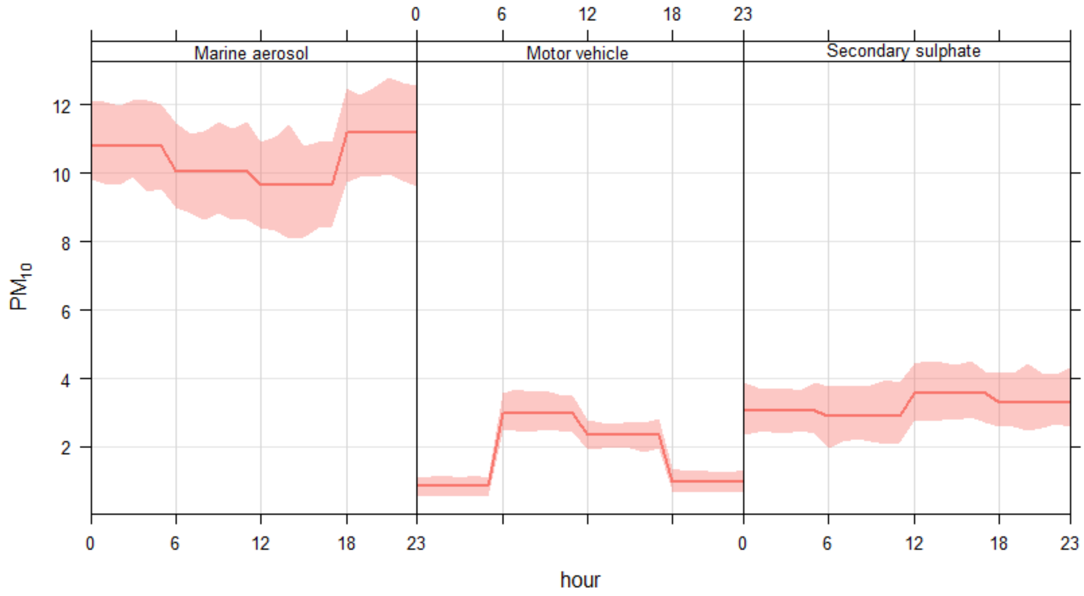


Figure 6.4: Black carbon filter concentrations (ng/m^3) measured on air filter samples at Shed 39 and at Wellington central from 6 January 2020 to 23 March 2020

6.5 Diurnal and weekday variation in PM$_{10}$ sources at Shed 39

Diurnal plots (Figure 6.5) were constructed to show average daily variation in the 6-hour concentrations starting at midnight, 6am, 12pm and 7pm. Average source contributions are also shown by day of the week (Figure 6.6). As the monitoring period was short, there is some random variation due to meteorological effects as well as one or two high particulate source days having an undue effect on the overall patterns. The coarse soil and construction sources were lower on a Sunday and Monday (two public holidays were observed on Mondays during the monitoring period) suggesting likely to be a combination of wind-blown soil and dust generated by earthworks, construction, road works and the demolition of nearby buildings. Ship emissions and secondary sulphate did not show a consistent pattern, but it is noted that very high levels of secondary sulphate were measured on Saturday (1 February 2020) which makes this day of the week appear much higher than other week days.



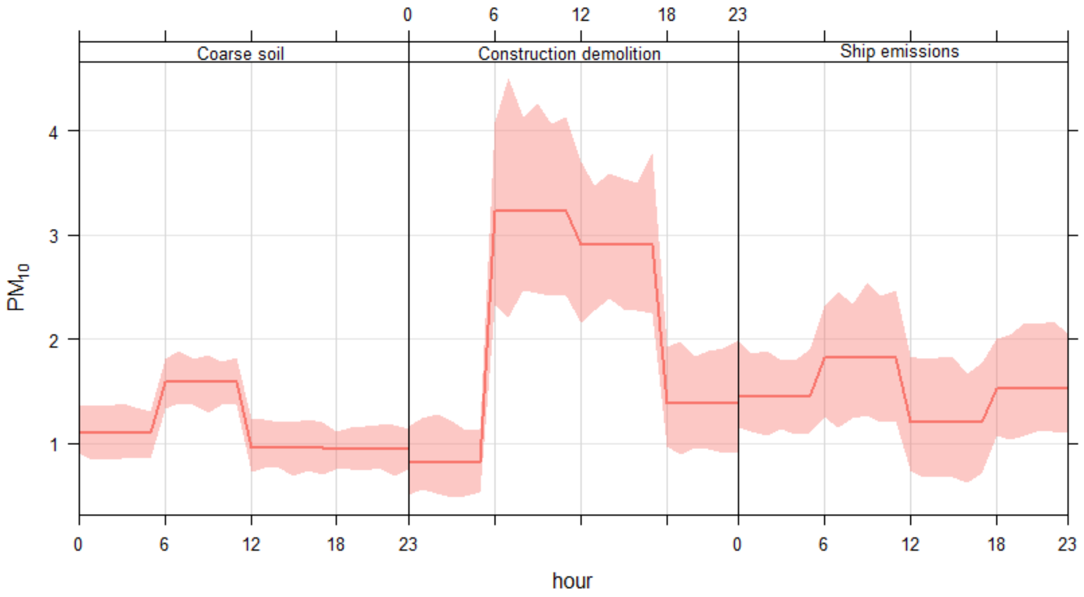


Figure 6.5: Diurnal plots showing variation in average 6-hour PM_{10} source contributions at Shed 39

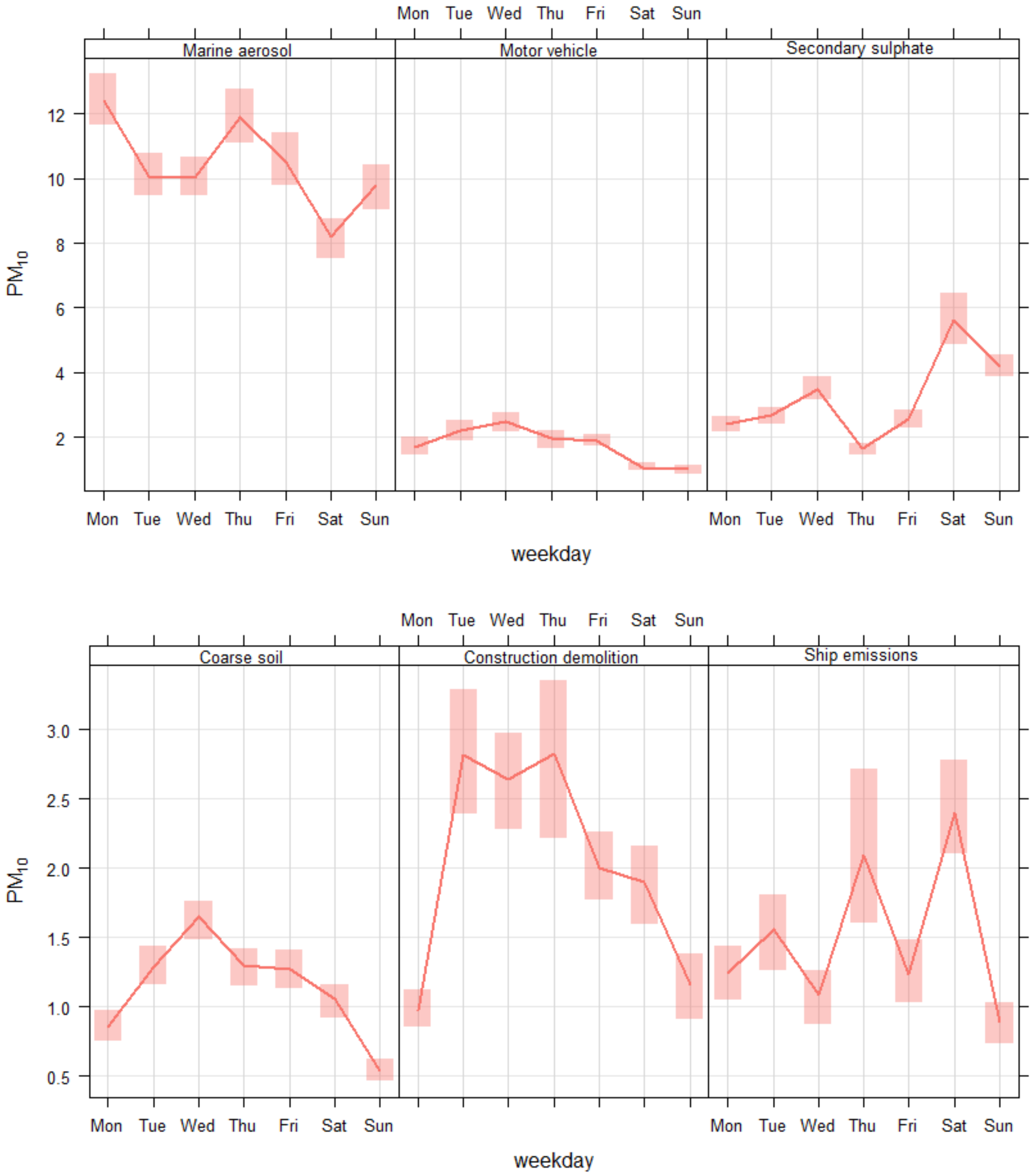


Figure 6.6: Day of week plots showing variation in average week day PM_{10} source contributions at Shed 39

6.6 Source transport and identification

Figure 6.7 shows the windrose for the monitoring period from 1 January to 23 March 2020. Local wind flows at the port are highly variable, with exposure to very strong winds in places as well as disturbances to local wind flows due to buildings and other structures.

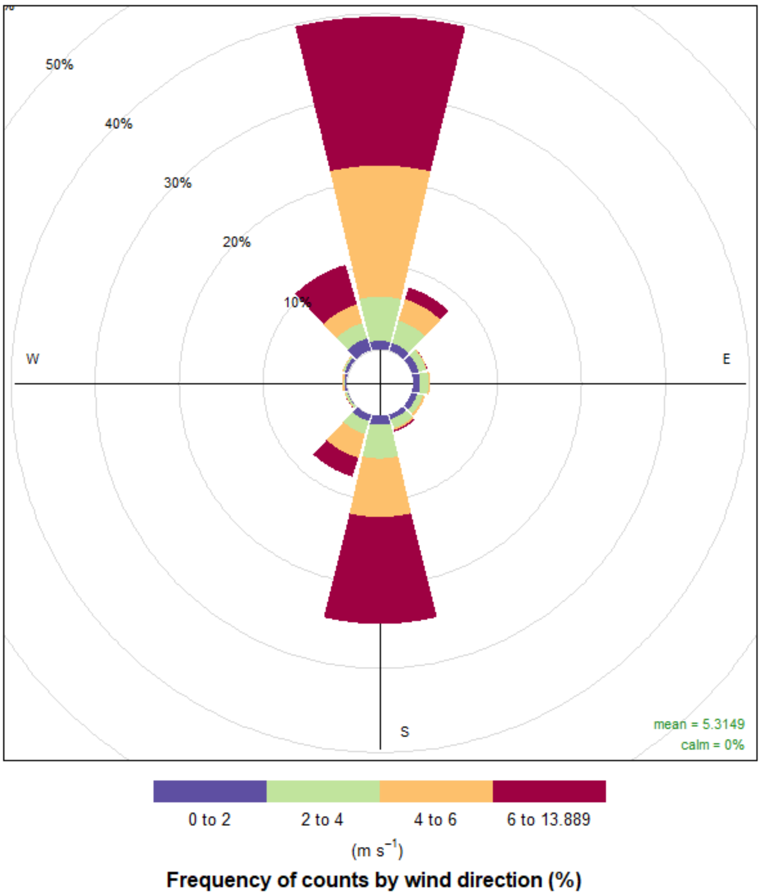


Figure 6.7: Windrose from Glasgow Wharf (MetService) 6 January to 23 March 2020

Polar plots (Figures 6.8 to 6.13) illustrate how the different sources of PM_{10} varied by wind speed and wind direction. These plots are useful for inferring the origins of particle emission sources measured at the monitoring site. The concentration of the particle source is shown on a ‘heat’ colour scale, with the cooler blue hues representing the lowest concentrations and the dark red colour showing the highest concentrations. The points of the compass show the direction the wind was blowing from, and the radial scale shows wind speed in 5 m/s increments. The relatively short monitoring period means there was a lower probability of detecting intermittent sources or those downwind of infrequent wind directions.

Ship emissions (Figure 6.8) were associated with two potential sources - one to the north-east direction aligned with cruise ship berths and the Interislander Ferry terminal and a second source from the south to southwest direction in line with the inner harbour shipping lane, including that used by BlueBridge ferries.

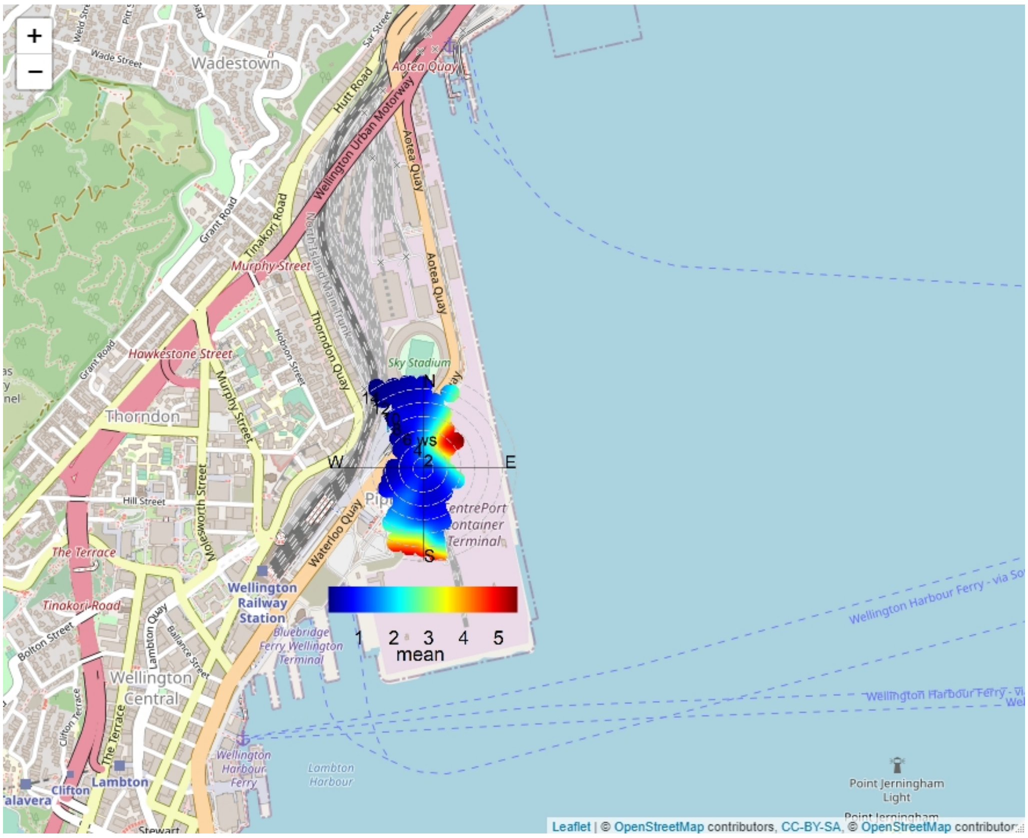


Figure 6.8: Polar plot for 6-hour average PM_{10} apportioned to shipping emissions from 6 January to 23 March 2020

Motor vehicle emissions (Figure 6.9) were associated with the vehicle lanes used by trucks passing immediately adjacent the north-west of the monitoring site. The influence from the south to southeast may be due to vehicles accessing the port area and vehicles used to move container cargo.

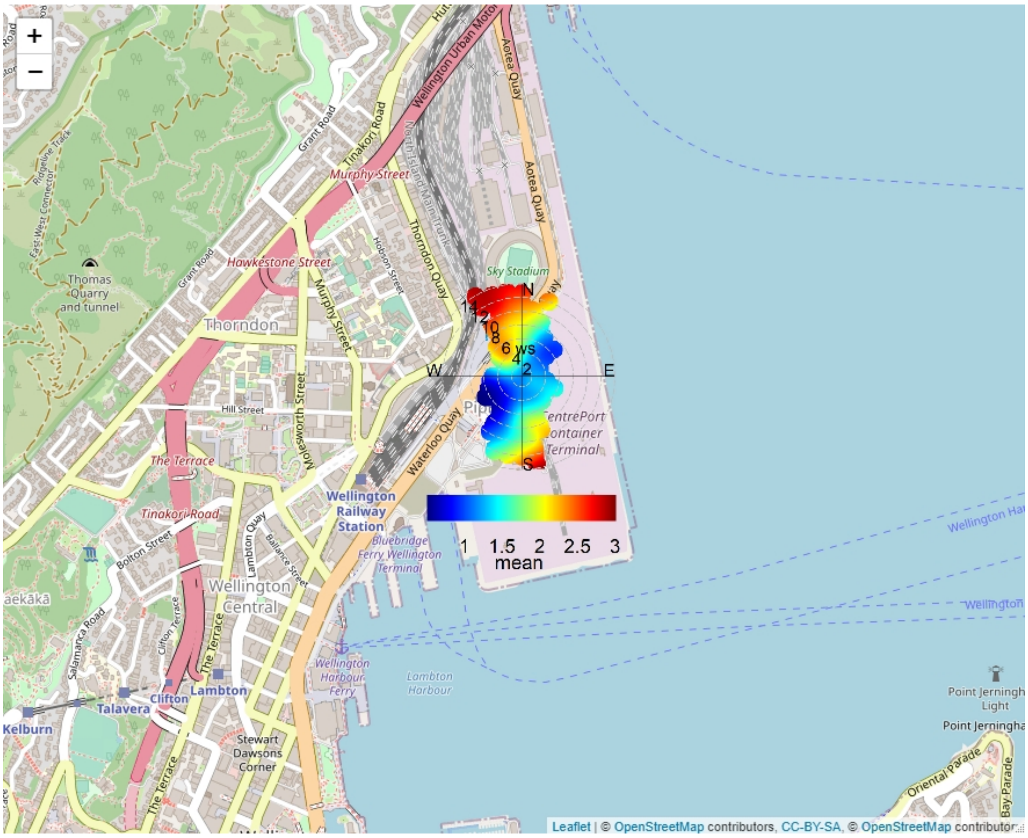


Figure 6.9: Polar plot for 6-hour average PM_{10} apportioned to motor vehicle associated emissions from 6 January to 23 March 2020

Secondary sulphate emissions (Figure 6.10) measured at Shed 39 were mostly from the north-to-north-east wind direction At Wellington central, secondary sulphate concentrations were also elevated under north-east wind direction and also from north-west (not shown). Secondary sulphate concentrations were correlated between the two sites (r=0.64) indicating a common influence. The average concentration of secondary sulphate measured at Wellington central was slightly higher at Shed 39 during the monitoring period. The atmospheric reactions that lead to sulphur-containing gases forming sulphate particles can take hours to days depending on the reaction pathways. Therefore, levels of secondary sulphate particles can be highest at some distance downwind from the sulphur-containing gas source.

In this study it was not possible to differentiate secondary sulphate from natural sources from that derived from oxidation of sulphur dioxide from combustion sources. However, other receptor modelling studies of particulate composition from around New Zealand show a consistent pattern of secondary sulphate associated with emissions of precursor gases from ship's engines (Davy & Trompetter, 2020). A study of sources of sulphate aerosols found that 21-27% of secondary sulphate measured at Baring Head was from shipping sources (Li et al., 2018).

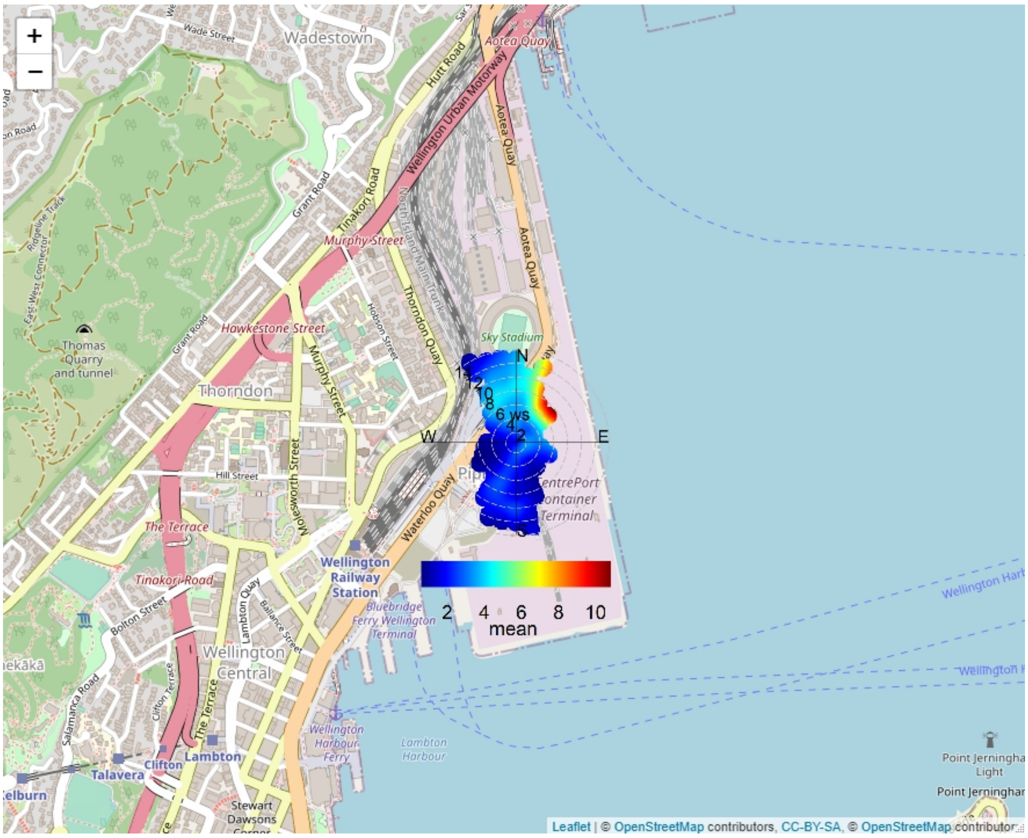


Figure 6.10: Polar plot for 6-hour average PM_{10} apportioned to secondary sulphate from 6 January to 23 March 2020

Construction and demolition emissions reflected the multiple activity sites on and near the port. The top 25% of concentrations shown in the conditional probability function polar plot (Figure 6.11) were associated with the less frequent north to west direction which aligns with the demolition of the BNZ building on Waterloo Quay.

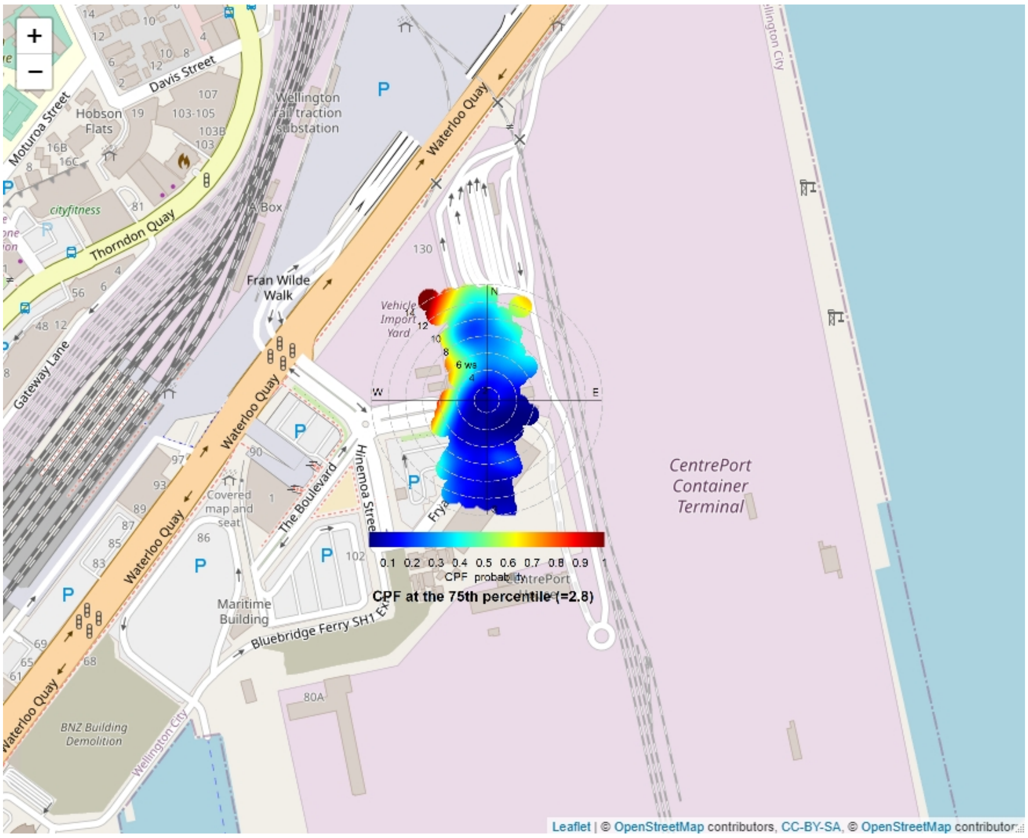


Figure 6.11: Conditional probability function polar plot for 6-hour average PM$_{10}$ apportioned to construction and demolition activities from 6 January to 23 March 2020

Coarse soil sources (Figure 6.12) were likely to come from local re-suspension of dust particles from paved surfaces as well as from stockpiles, exposed soil surfaces etc. The top 25% of concentrations were associated with strong northerly winds. There may be a contribution from the log storage area.

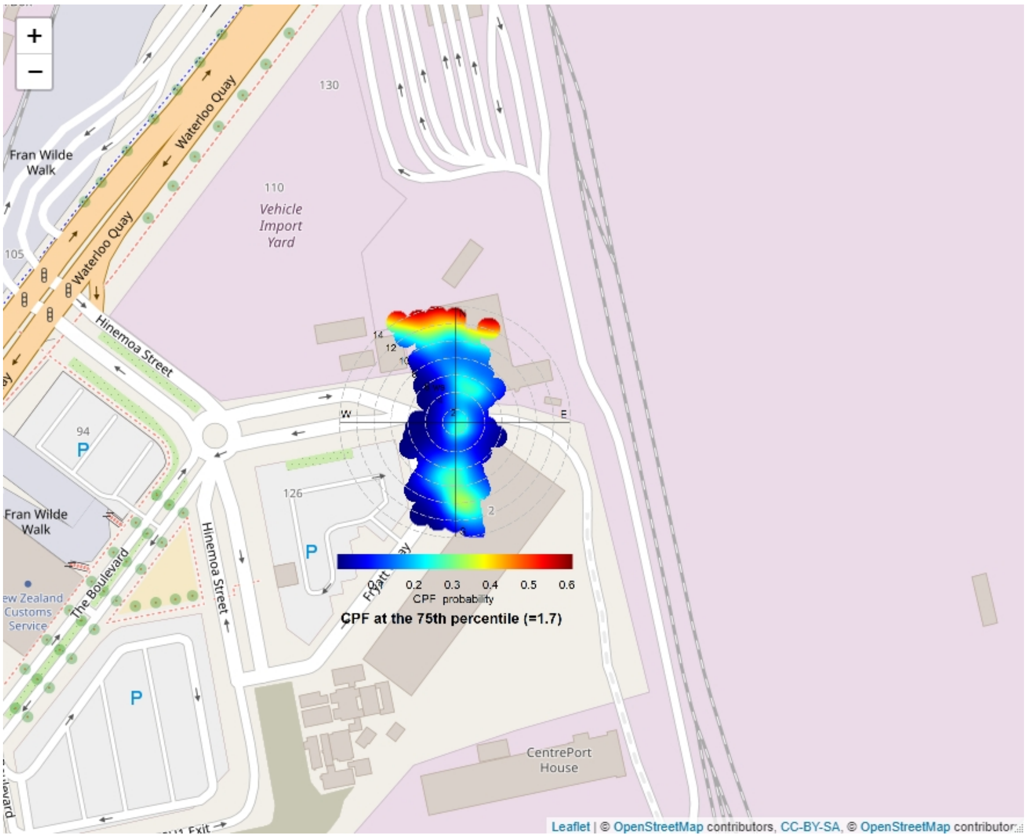


Figure 6.12: Conditional probability function polar plot for 6-hour average PM_{10} apportioned to a coarse soil source from 6 January to 23 March 2020

Marine aerosol emissions (Figure 6.13) were highest from the north-west likely originating from long-range transport from the southern ocean under high wind speeds. Locally generated marine aerosol from the harbour, mainly from the south-east, also influenced the monitoring site. Marine aerosol at Shed 39 was moderately correlated with that measured at Wellington central (r=0.47) indicating a common regional source.

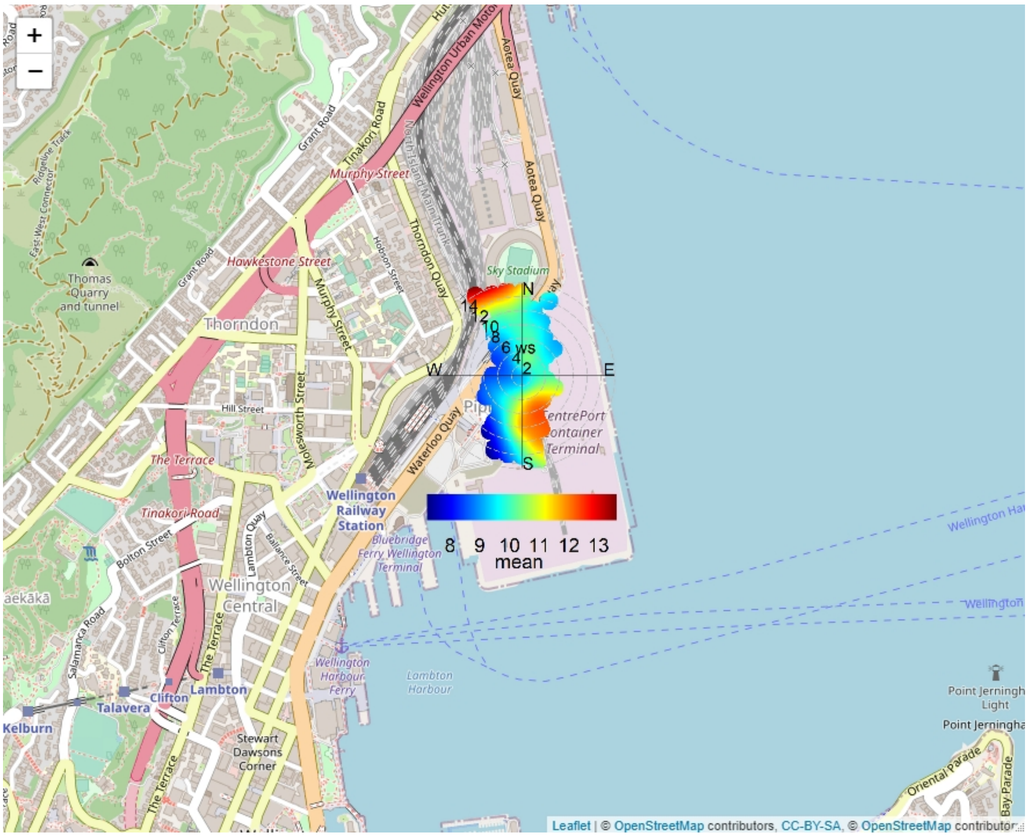


Figure 6.13: Polar plot for 6-hour average PM_{10} apportioned to marine aerosol from 6 January to 23 March 2020

7. Conclusions

This study provides preliminary air quality measurements within and close to the port area prior to New Zealand's accession to MARPOL Annex VI. It is not clear how representative the results are due to the disruption caused by COVID-19 travel restrictions, which led to an early end to the cruise ship season. There were also regional impacts on air quality resulting from the severe 2019-2020 Australian wildfires and desert dust.

Results suggest it is likely that non-operational areas within the port would comply with relevant air quality standards and guidelines for regulated pollutants during the summer to autumn months. Further monitoring is needed to make a determination for the winter period, when air quality is generally worse due to more stable atmospheric conditions leading to reduced dispersion of emissions.

Pollutants were elevated inside the port when compared to the Wellington central air monitoring site. Increased NOx, NO_2 and black carbon levels inside the port were mostly likely due to the greater frequency of stop/start truck movements, which are high emitters of these pollutants, as well as combustion emissions from road construction activities being undertaken at CentrePort during the monitoring period. PM_{10} concentrations were also elevated at the port due to a higher quantity of coarse particles from sea-salt, construction and demolition activities, re-suspended dust from paved surfaces, traffic and exposed soil. Average $PM_{2.5}$ levels were similar at both sites. Ship engine particulate emissions were detected at the Shed 39 monitoring site correlated with the presence of nickel and vanadium, which are contaminants associated with burning of heavy fuel oil.

Very high sulphur dioxide concentrations were found at the Interislander Cook Strait Ferry berth. It appears possible that domestic ferries are the main source of sulphur dioxide measured at the port as impacts continued after the end of the cruise ship season. Therefore, further sulphur dioxide monitoring could be useful to detect impacts domestic ferries switching to lower sulphur fuels following the implementation of MARPOL Annex VI. There appeared to be some local enhancement of SO_2 around the operational port area, but the off-site areas that were monitored, and where there is public access, were likely to comply with the relevant standards and guidelines. Further investigation is required to confirm SO_2 levels on the Wellington Regional Stadium concourse as the results were inconclusive. A limitation of the SO_2 tube spatial monitoring was that there were no tubes situated at height on the western hills overlooking the port. Under very stable atmospheric conditions, emissions from multi-storey ships accumulate and disperse more slowly (Figure 4.10). However, these meteorological conditions are infrequent in Wellington city.

It is challenging to appropriately site monitoring equipment as ship emissions are intermittent and the location of the ship's exhaust plume touch down at ground level will vary with wind speed and direction. The feasibility of using sophisticated monitoring technologies, such as MAX DOAS (multi-axis Differential Optical Absorption Spectroscopy) which can measure multiple gases (including, SO_2 NO_2 and ozone) over long horizontal paths, could be investigated for future studies.

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- CentrePort for financial contribution and assistance with monitoring site selection and access to port operational areas.
- Interislander, Wellington Regional Stadium Trust and Wellington Waterfront for permission to use structures for monitoring sites.
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- Nick Talbot ((independent consultant and Auckland University researcher) for peer review and useful recommendations.

References

Carslaw, D. C. and K. Ropkins, (2012) openair --- an R package for air quality data analysis. Environmental Modelling & Software. Volume 27-28, 52-61.

Carslaw, D.C.l (2021). openairmaps: Package to Plot Openair Outputs on Static and Leaflet Maps. R package version 0.1.2.

Cheng, J., Karambelkar, B., and Xie, Y. (2021). leaflet: Create Interactive Web Maps with the JavaScript 'Leaflet' Library. R package version 2.0.4.1. https://CRAN.R-project.org/package=leaflet

Cox, R. A., & Mulcahy, M. F. R. (1979). Photochemical Oxidation of Atmospheric Sulphur Dioxide [and Discussion]. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, *290*(1376), 543–550. http://www.jstor.org/stable/75089

Davy, P. K., Ancelet, T., Trompetter, W. J and Markwitz, A (2017). Source apportionment and trend analysis of air particulate matter in the Auckland region. Prepared by the Institute of Geological and Nuclear Sciences Ltd, GNS Science for Auckland Council. Auckland Council technical report, TR2017/001

Davy, P. K. and Trompetter, W.J. (2020). Composition, sources and long-term trends for Auckland air particulate matter: Summary Report. GNS Science Consultancy Report 2019/151. Lower Hutt, NZ.

Davy, P. K. and Trompetter, W.J. (2018). Heavy metals, black carbon and natural sources of particulate matter in New Zealand. GNS Science Consultancy Report 2018/328. July 2018. Lower Hutt, NZ.

Davy, P. K., Trompetter, W. J., Markwitz, A. (2011). Concentration, composition and sources of particulate matter in Johnstone Hills Tunnel, Auckland. GNS Science consultancy report; 2010/296. Lower Hutt.

European Environment Agency (2013). Status of black carbon monitoring in ambient air in Europe. Technical Report No 18/2013. Luxembourg. https://www.eea.europa.eu/publications/status-of-black-carbon-monitoring

Griffiths, G. (2011). An updated climatology of the Wellington region for air quality purposes. Report prepared for GWRC by NIWA. Report AKL-2011-025, Auckland.

Iremonger, S. and Mackay, M. (2020). Ambient air quality data update 2020. Bay of Plenty Regional Council. Environmental Publication 2020/03. https://www.boprc.govt.nz/your-council/documents-and-publications/publications

Li, J., Michalski, G., Davy, P., Harvey, M., Katzman, T., & Wilkins, B. (2018). Investigating Source Contributions of Size-Aggregated Aerosols Collected in Southern Ocean and Baring Head, New Zealand Using Sulfur Isotopes. *Geophysical Research Letters*, *45*. https://doi.org/10.1002/2018GL077353

Longley, I., Clougherty, J. and Tunno, B. (2016). SpaRTANZ Auckland Pilot Study. Spatially resolved technique for source apportionment in New Zealand. NIWA, Auckland.

Orellano, P., Reynoso, J. & Quaranta, N. (2021). Short-term exposure to sulphur dioxide (SO_2) and all-cause and respiratory mortality: A systematic review and meta-analysis. Environment International Volume 150, May 2021, 106434

Ramanathan, V, & Carmichael, G (2008). Global and regional climate changes due to black carbon. Nature Geoscience, 1, 221–227. https://doi.org/10.1038/ngeo156.

Ministry for the Environment (2018). Our air 2018. Data to 2017. ME 1384, Wellington. https://environment.govt.nz/publications/our-air-2018/

Ministry for the Environment (2002). Ambient air quality guidelines: 2002 update. ME 438, Wellington.https://environment.govt.nz/publications/ambient-air-quality-guidelines-2002-update/

Mitchell, T.A. (2021). An analysis of the impact of COVID-19 restrictions on air quality in the Wellington region. GWRC publication no. GW/ESCI-T-21/3.

Moreno-Ríos, A. L., Tejeda-Benítez, L. P., & Bustillo-Lecompte, C. F. (2021). Sources, characteristics, toxicity, and control of ultrafine particles: An overview. *Geoscience Frontiers*, 101147. https://doi.org/10.1016/j.gsf.2021.101147

R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Talbot, N. and Reid, N (2017). A review of research into the effects of shipping on air quality in Auckland: 2006-2016. Auckland Council Technical Report 2017/005.

Tang, W., Llort, J., Weis, J., Perron, M. M. G., Basart, S., Li, Z., Sathyendranath, S., Jackson, T., Sanz Rodriguez, E., Proemse, B. C., Bowie, A. R., Schallenberg, C., Strutton, P. G., Matear, R., & Cassar, N. (2021). Widespread phytoplankton blooms triggered by 2019–2020 Australian wildfires. *Nature*, *597*(7876), 370–375. https://doi.org/10.1038/s41586-021-03805-8

Wickham, H. (2016). ggplot2 Elegant Graphics for Data Analysis. Springer-Verlag New York, 2016.

World Health Organization (2021). WHO global air quality guidelines. Particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva: World Health Organization.

World Health Organization (2012). Health effects of black carbon. Regional Office for Europe. Retrieved from: https://www.euro.who.int/en/publications/abstracts/health-effects-of-black-carbon-2012

Appendix 1: Methods - continuous pollutant measurements

Table A1.1: Monitoring methods and instruments

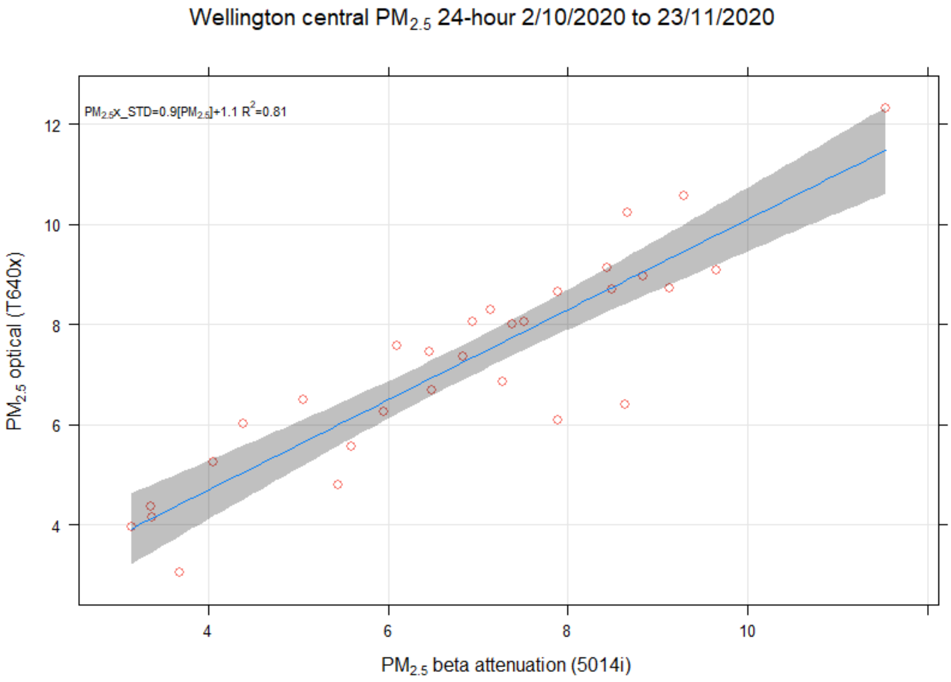
Pollutant	Instrument	Method	Site
Black carbon	Aethalometer AE33 - Magee Scientific	In accordance with manufacturer's instructions	Wellington central
NOx	Chemiluminsecence M200E - Teledyne API	AS 3580.5.1:2011 Method 5.1: Determination of oxides of nitrogen – Direct-reading instrumental method	Wellington central Shed 39
SO_2	UV fluroescence M100E - Teledyne API		Wellington central Shed 39
PM_{10} and $PM_{2.5}$	Optical T640x - Teledyne API	In accordance with manufacturer's instructions	Shed 39
PM_{10} and $PM_{2.5}$	Beta Attenuation 5014i - Thermo Scientific	EQPM-1102-150 Method 9.11: Determination of suspended particulate matter – PM_{10} beta attenuation monitors in accordance with AS/NZS 3580.9.11:2008 EQPM-0609-183 Method 9.12: Determination of suspended particulate matter – $PM_{2.5}$ beta attenuation monitors in accordance with AS/NZS 3580.9.12:2013	Wellington central

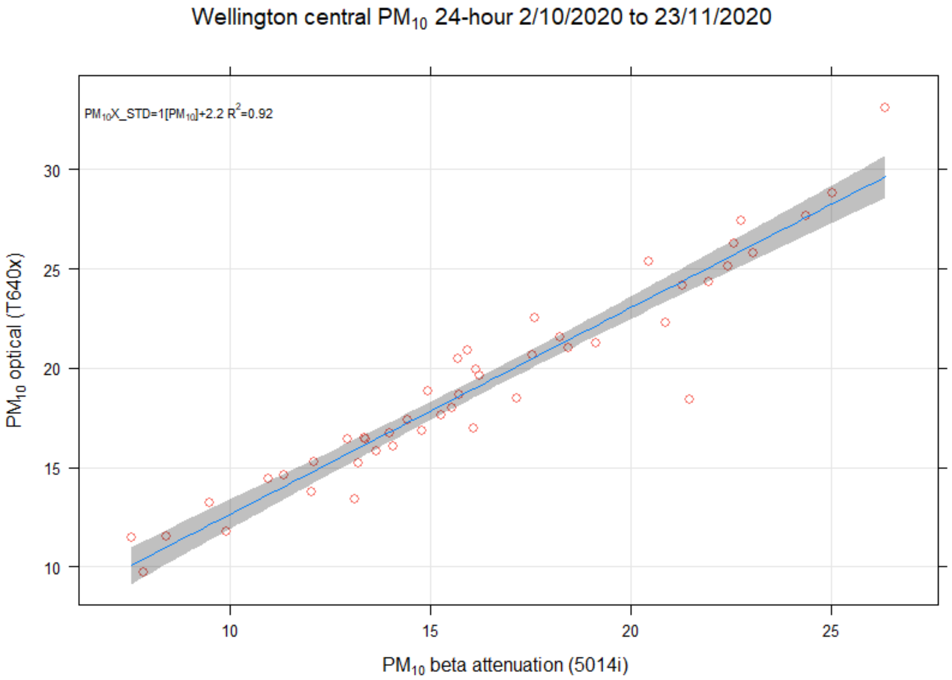
Particulate matter monitoring is method-dependent, therefore concentrations using optical and beta attenuation methods are not necessarily comparable. The optical method (T640x) underwent a short period of co-location with the beta attenuation method (5014i) at Wellington central prior to the study. This co-location found that the 24-hour average T640x and the 5014i PM measurements were linearly correlated, but the T640x produced higher concentrations for $PM_{2.5}$ and PM_{10}. The tendency for the T640x to over measure relative to the 5014i was more pronounced for PM_{10} than for $PM_{2.5}$.

The equations used to correct the T640x PM measurements at Shed 39 to equivalence to the 5014i method used at Wellington central were:

1) $PM_{2.5} = 0.9 * T640x + 0.28$

2) $PM_{10} = 0.88 * T640x – 0.63$




Wellington central PM_{10} 24-hour 2/10/2020 to 23/11/2020
$PM_{10}X\_STD=1[PM_{10}]+2.2\ R^2=0.92$
PM_{10} optical (T640x)
10
15
20
25
30
PM_{10} beta attenuation (5014i)
10
15
20
25

Appendix 2: Methods – Particulate matter source apportionment

P Davy, GNS Science

A2.1: Particulate filter measurements

The Shed 39 and Wellington central quality monitoring sites were equipped with a Streaker sampler (PIXE International Corporation, USA). The instrument consists of a pre-impactor that removes particles larger than PM_{10} from the incoming air flow, a thin Kapton foil that collects coarse particles ($PM_{10–2.5}$) through impaction and a Nucleopore filter (0.4 µm pore size) that collects fine particles ($PM_{2.5}$) with discrete spacing between each deposit to ensure that each only consisted of particulate matter collected during the intended sample period. Because each discrete particulate matter sample was collected on a single filter, gravimetric determination of the particulate matter mass for each sample was not possible. Instead, the particulate matter data from the continuous samplers operated by GWRC alongside was used for the data analysis process and assignment of source mass contributions to ambient particulate matter concentrations.

IBA was used to measure the concentrations of elements with atomic numbers above neon in the particulate matter samples. The IBA was performed using a 3 MeV accelerator proton beam with standards (SrF_2, NaCl, Cr, Ni, SiO, KCl, Al) run before and after each analytical cycle. Spectral X-ray peak deconvolution was performed using GUPIX software. The number of pulses (counts) in each peak for a given element is used by the GUPIX software to calculate the concentration of that element. The background and neighbouring elements determine the statistical error and the limit of detection. Note that GUPIX provides a specific statistical error and limit of detection for each element in each particulate matter sample, and these have been used to provide the uncertainty matrix used in the Positive Matrix Factorisation (PMF) analysis. IBA measurements were carried out at the New Zealand National Isotope Centre operated by the Institute of Geological & Nuclear Sciences (GNS Science) at Gracefield, Lower Hutt, New Zealand. Black carbon was measured using a M43D Digital Smoke Stain Reflectometer.

A2.2: Receptor modelling

Receptor modelling and apportionment of particulate matter mass by PMF was performed using the EPAPMF version 5.0.14 program in accordance with the User's Guide (Norris et al., 2014). With PMF, sources are constrained to have non-negative species concentrations, no sample can have a negative source contribution and error estimates for each observed point are used as point-by-point weights. This is a distinct advantage of PMF, as it can accommodate missing or below-detection-limit data that is a common feature of environmental monitoring (Song et al., 2001). Another advantage of PMF is that particulate matter mass concentrations can be included in the model as another variable and the results are directly interpretable as the covariant particulate matter mass contributions associated with each factor (source). Prior to the PMF analyses, data and uncertainty matrices were prepared in the same manner as previous studies (Polissar et al., 1998; Song et al., 2001). Data screening and the source apportionment were performed in accordance to the protocols and recommendations set out by Paatero et al. (2014) and Brown et al. (2015). Due to the effect that random analytical noise can have on the receptor modelling process, variables with low signal-to-noise ratios were examined by alternate inclusion and exclusion in a modelling run, and only those variables that could be explained in association with source emissions were included in the final results (Paatero and Hopke 2003).

The multivariate analysis of air particulate matter sample composition (also known as receptor modelling) provides groupings (or factors) of elements that vary together over time. This technique effectively ‘fingerprints’ the sources that are contributing to airborne particulate matter and the mass of each element (and the PM mass) attributed to that source. In this study the primary source contributors were determined using results from the Positive Matrix Factorisation (PMF analysis) of the particulate matter elemental composition.

A critical point for understanding the receptor modelling process is that the PMF model can produce any number of solutions, all of which may be mathematically correct (Paatero, Hopke et al., 2002). The “best” solution (eg, number of factors, etc.) is generally determined by the practitioner after taking into account the model diagnostics and a review of the available factor profiles and contributions (to check physical interpretability). Most commonly used receptor models are based on conservation of mass from the point of emission to the point of sampling and measurement (Hopke 1999). Their mathematical formulations express ambient chemical concentrations as the sum of products of species abundances in source emissions and source contributions. In other words, the chemical profile measured at a monitoring station is resolved mathematically to be the sum of a number of different factors or sources. As with most modelling approaches, receptor models based on the conservation of mass are simplifications of reality and have the following general assumptions:

1. compositions of source emissions are constant over the period of ambient and source sampling;
2. chemical species do not react with each other (i.e., they add linearly);
3. all sources with a potential for contributing to the receptor have been identified and have had their emissions characterised;
4. the number of sources or source categories is less than or equal to the number of species measured;
5. the source profiles are linearly independent of each other; and
6. measurement uncertainties are random, uncorrelated, and normally distributed.

The effects of deviations from these assumptions are testable and therefore allow the accuracy of source quantification to be evaluated. Uncertainties in input data can also be propagated to evaluate the uncertainty of source contribution estimates. There are a number of natural physical restraints that must be considered when developing a model for identifying and apportioning sources of airborne particles, these are (Hopke 2003):

- the model must explain the observations;
- the predicted source compositions must be non-negative;
- the predicted source contributions must be non-negative;
- the sum of predicted elemental mass contributions from each source must be less than or equal to measured mass for each element.

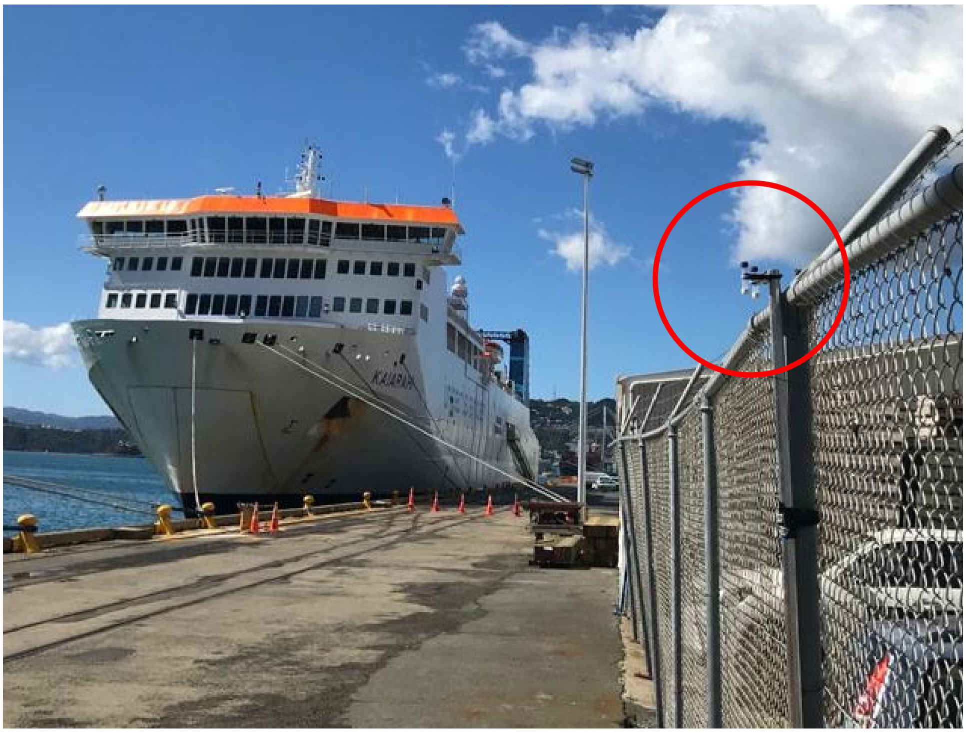
These constraints need to be kept in mind when conducting and interpreting any receptor modelling approach, particularly since a receptor model is still an approximation of the real-world system. A number of factors also affect the nature of a sources' particle composition and its contributions to ambient loadings (Brimblecombe 1986, Hopke 1999, Seinfeld and Pandis 2006):

1. the composition of particles emitted from a source may vary over time;
2. the composition of particles is modified in the atmosphere through a multitude of processes and interactions, for example;
    - adsorption of other species onto particle surfaces;
    - gas to particle conversions forming secondary particulate matter, for example the conversion of SO_2 gas to SO_4^{2-};
    - volatilisation of particle components such as organic compounds or volatilisation of Cl through reaction with acidic species;
    - interaction with and transformation by, solar radiation and free radicals in the atmosphere such as the OH and NO_3 species

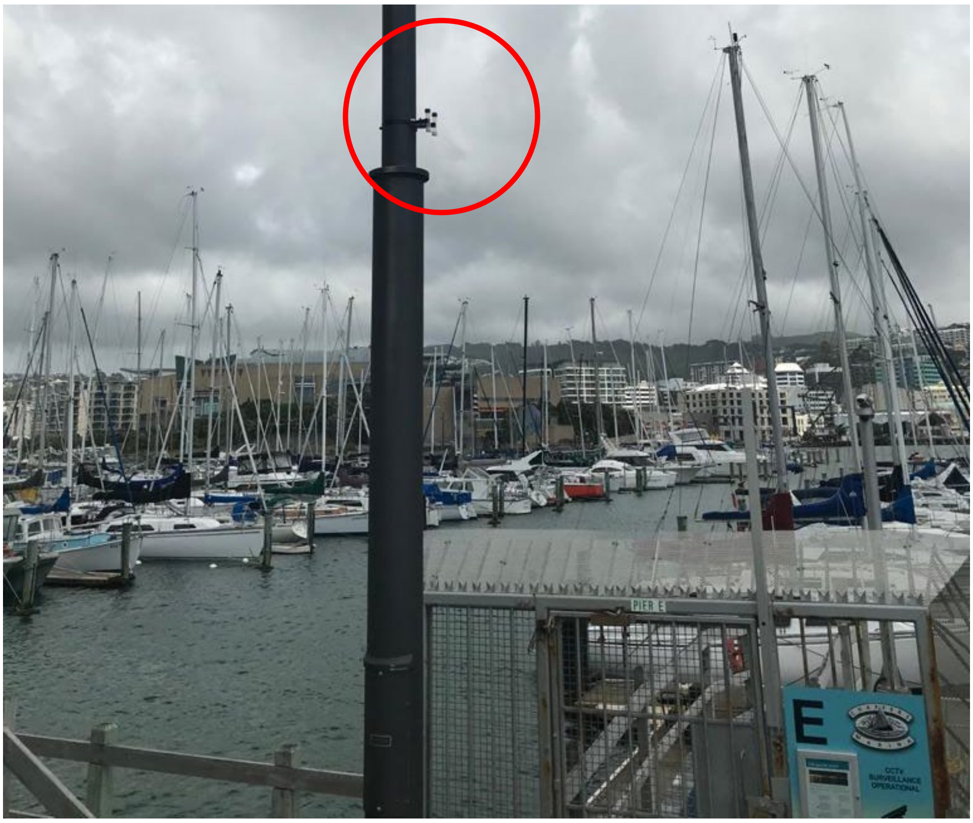
Appendix 3: Site photos – SO_2 by passive diffusion tubes

Shed 39 (CentrePort)

Wellington Regional Stadium



AQ Emergency (CentrePort)



Clyde Wharf (Wellington Waterfront)

Marine Store (CentrePort)

HEB (CenterPort)

FUMO (CentrePort)

Interislander (KiwiRail)

Seaview Wharf (CentrePort)

Thorndon Quay (WCC)

Appendix 4: Methods – SO_2 by passive diffusion tubes

A4.1: Description

Levels of sulphur dioxide gas were measured using Palmes-type diffusion tubes (Palmes, 1981). The tubes were purchased pre-prepared from Gradko International Ltd (UK)[9]. The tubes are plastic (florinated ethylene polymer), 71 mm long with an internal diameter of 11 mm. The tubes are fitted with purple and white thermoplastic rubber caps at each end. The tube is mounted vertically with the purple cap on top and the while cap on the bottom. The purple cap contains an absorbent and the white cap contains a 1 micron porosity filter to prevent ingress of particulates loaded with sulphur, ie, diesel fumes. The tubes passively absorb pollutants by molecular diffusion directly from the surrounding air. The molecular compounds in air collect on the absorbent at the top of the tube under the purple cap.

Tubes were attached to street lights and fences at a height of 2.5 to 3 m above ground level. After the sampling period exposed tubes were couriered back to Gradko International Ltd (UK) where they were analysed to determine the concentration of sulphate ions (SO_4^{2-}) by Ion Chromatography. The final concentration of SO_2 measured by each tube is calculated from the molecular diffusion uptake rate, the exposure time and the conversion factor for converting sulphate ions to sulphur dioxide. The Gradko laboratory reporting limit for SO_4^{2-} in the extracted filtrate is 0.09µg/ml which equates to and SO_2 concentration of 0.78 µg/m^3. Samples below the laboratory reporting level were not included in the analysis. Results provided by Gradko of blank corrected SO_2 (ppb) were converted to µg/m^3, corrected to standard temperature 0^{o}C in accordance with NZ conversion factors gaseous pollutants (Ministry for the Environment, 2009).

Quality control included deploying duplicate tubes at each site. Each sampling deployment included a field blank located at the Shed 39 site and a travel blank which was not deployed. The field blank was mounted alongside the exposed tubes but was kept within its plastic case so was not exposed to outdoor air. Tubes when not in use were kept refrigerated.

A4.2: Data quality and coverage limitations

Gradko Laboratory noted that some of the tubes received for analysis were 'dirty' and therefore results may be compromised. The Wellington City coastal environment, at times, has high levels of sea salt and wind-blown dust from paved surfaces and roads as well as soils. The SO_2 tubes were all impacted during the December 2019 deployment and some other sites during other months.

The tubes have a shelf life of 12-weeks which was exceeded on the April 2020 sampling round which may have compromised the monitoring results for this deployment. During March and April 2020, COVID-19 restrictions meant access to sites at Centre Port (Port 01, Port 03, and Port 04) was not permitted so the tubes were unable to be retrieved or exchanged. There were also delays with airfreight during March to April 2020 to the UK meaning the tubes were unable to be analysed in a timely manner.

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[9] https://www.gradko.com/environmental/environmental-products/sulphur-dioxide-diffusion-tubes.shtml

Appendix 5: Laboratory results – SO_2 passive diffusion tubes

Table A5.1

Passive SO2 tube sampling results

Month	AQ Emergency	Interislander	HEB	FUMO	Marine store	Seaview wharf	Thorndon Quay	Clyde Wharf	WRS	Shed 39
Dec 2019	4.49	33.03	5.01	4.30	5.61	2.56	3.24	1.55	6.14	2.79
Dec 2019	5.07	53.50	3.71	4.27	2.22	2.38	1.93	4.25	5.34	3.32
Jan 2020	4.74	22.34	3.40	7.16	1.82	0.78	4.37	28.12	29.58	3.66
Jan 2020	4.94	54.02	2.46	2.02	1.91	1.30	1.77	1.55	4.75	2.23
Feb 2020	3.57	29.13	2.37	2.09	2.69	1.73	1.70	1.60	2.58	2.54
Feb 2020	2.75	28.80	3.28	2.96	1.90	NA	1.80	3.10	1.90	2.45
Mar 2020	NA	27.88	NA	NA	2.29	NA	NA	NA	NA	2.80
Mar 2020	NA	24.83	NA	NA	NA	NA	NA	NA	NA	NA
Apr 2020	NA	20.92	NA	NA	0.93	NA	0.89	0.45	2.21	1.59
Apr 2020	NA	25.34	NA	NA	0.76	NA	0.53	1.03	1.62	0.87

The closeness of agreement between the duplicate measurements at each monitoring site vary, with some sites showing large differences, outside of the Gradko reported measurement uncertainty of +/- 9.6%. The most extreme differences were for Port 01 (Interislander) for December 2019 and January 2020 deployments, and for GWRC 02 (Clyde Wharf) and GWRC 03 (Regional Stadium) for January 2020. A plausible explanation for the large duplicate differences for GWRC 02 and GWRC 03 is that the tubes were placed in the wrong sample bag after the original labelled zip lock for GWRC 03 bag blew away in a high wind gust during the tube exchange at Clyde Wharf on 3 February 2020.

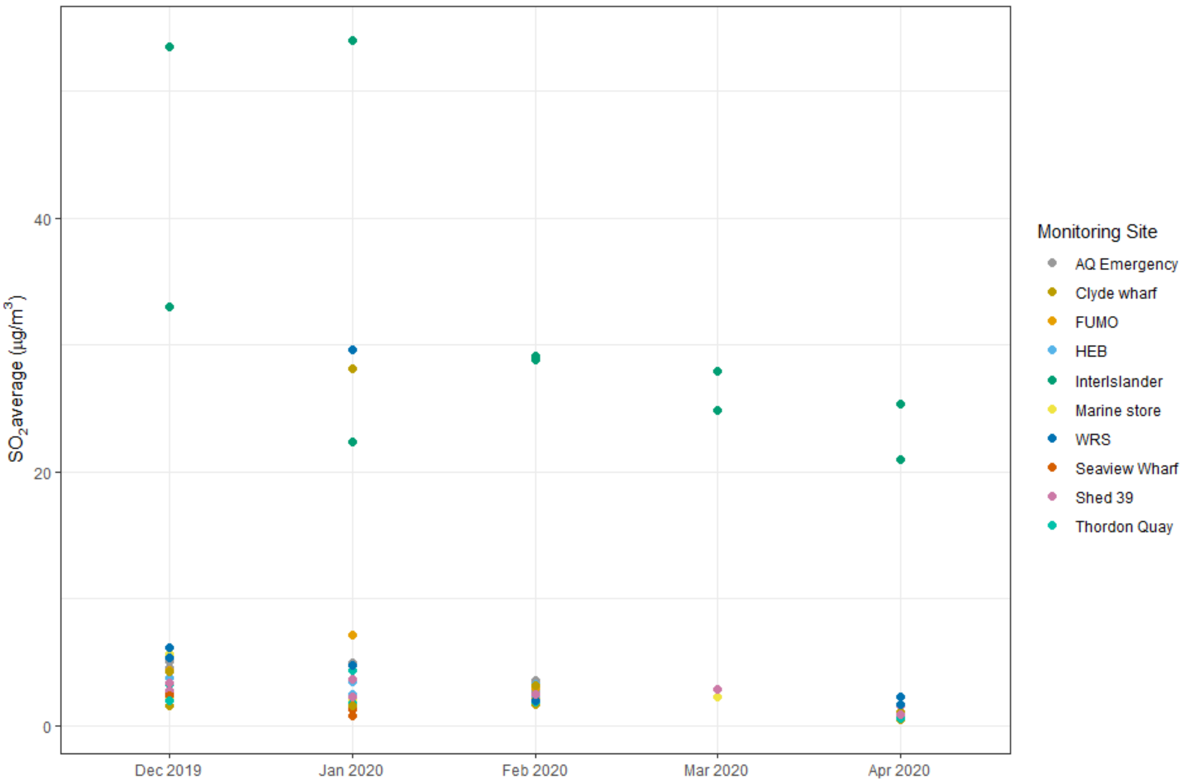


Figure A5.1: Duplicate measurements at monitoring locations by deployment month

Appendix 6: Results – elemental analysis of particulate filters

A6.1: Shed 39 element concentrations in $PM_{2.5}$ particulate matter samples

Shed 39 elemental concentrations PM2.5 filters (n = 317)

Species	Average	Max	Min	Median	SD	Ave LOD	n > LOD	% > LOD
PM2.5	6.0	20.5	0.0	5.7	2.5	0.6	316	99.7
BC	550.8	1,675.1	0.0	501.6	293.0	155.7	305	96.2
F Gam	16.6	188.6	0.0	0.0	30.2	166.1	0	0.0
Na Gam	178.0	814.9	0.0	167.0	143.5	229.0	119	37.5
Na	199.9	967.8	0.0	172.3	146.1	35.9	305	96.2
Mg	26.9	124.8	0.0	23.7	19.0	7.8	286	90.2
Al	20.0	161.6	0.0	12.9	22.2	5.1	275	86.8
Si	44.7	404.9	0.0	26.0	58.6	6.5	250	78.9
P	0.5	8.7	0.0	0.0	1.2	1.9	18	5.7
S	134.7	652.0	0.1	104.7	98.8	14.9	313	98.7
Cl	260.4	1,418.0	0.0	180.3	268.4	27.2	286	90.2
K	21.0	184.5	0.0	17.5	17.2	3.3	308	97.2
Ca	16.4	117.0	0.0	14.2	13.0	2.8	298	94.0
Sc	0.3	3.0	0.0	0.0	0.5	1.5	11	3.5
Ti	1.1	10.6	0.0	0.6	1.6	1.3	102	32.2
V	1.8	50.8	0.0	0.8	4.6	1.2	122	38.5
Cr	0.3	8.0	0.0	0.0	0.6	0.6	38	12.0
Mn	1.0	36.3	0.0	0.2	3.8	0.7	77	24.3
Fe	23.9	536.8	0.0	10.9	53.8	2.8	302	95.3
Co	0.4	2.4	0.0	0.4	0.5	1.0	45	14.2
Ni	1.1	10.1	0.0	0.6	1.5	0.7	171	53.9
Cu	0.7	17.8	0.0	0.3	1.7	0.8	88	27.8
Zn	1.0	162.1	0.0	0.0	9.3	0.9	39	12.3
Ga	0.1	1.5	0.0	0.0	0.3	1.1	3	0.9
Ge	0.2	2.1	0.0	0.0	0.5	1.6	6	1.9
As	0.2	3.5	0.0	0.0	0.6	2.0	7	2.2
Se	0.3	2.9	0.0	0.0	0.8	2.6	4	1.3
Br	0.8	9.8	0.0	0.0	1.5	3.9	14	4.4
Rb	0.8	11.2	0.0	0.0	2.1	6.5	7	2.2
Sr	1.2	14.1	0.0	0.0	2.8	9.1	2	0.6
Mo	4.4	58.3	0.0	0.0	11.7	33.6	10	3.2
I	0.5	7.3	0.0	0.0	1.3	4.8	3	0.9
Ba	0.9	8.5	0.0	0.0	1.6	4.5	10	3.2
Hg	0.5	6.3	0.0	0.0	1.2	4.2	0	0.0
Pb	0.4	11.6	0.0	0.0	1.2	5.0	1	0.3

A6.2: Shed 39 element concentrations in PM$_{10\text{-}2.5}$ particulate matter samples

Shed 39 elemental concentrations PM10-2.5 filters (n = 317)

Species	Average	Max	Min	Median	SD	Ave LOD	n > LOD	% > LOD
PM10-2.5	16.0	81.0	0.0	13.8	8.6	1.6	316	99.7
F Gam	13.8	184.2	0.0	0.0	28.2	163.7	0	0.0
Na Gam	980.0	2,948.1	0.0	882.0	599.4	272.2	287	90.5
Na	650.7	1,871.2	51.3	600.5	278.0	96.1	317	100.0
Mg	133.3	329.4	13.1	127.6	57.9	18.5	317	100.0
Al	147.8	744.3	5.4	115.4	115.0	17.5	317	100.0
Si	413.9	1,861.1	7.3	330.7	318.7	43.2	317	100.0
P	1.6	13.8	0.0	0.0	2.5	2.3	71	22.4
S	126.2	299.6	14.9	121.4	53.2	14.9	317	100.0
Cl	1,836.7	5,339.9	63.7	1,745.1	962.1	184.2	317	100.0
K	98.7	305.4	11.9	89.3	49.4	10.6	317	100.0
Ca	109.3	617.7	21.1	97.8	62.1	11.7	317	100.0
Sc	0.7	6.0	0.0	0.3	0.9	1.6	32	10.1
Ti	10.9	55.0	0.0	8.8	8.6	1.7	306	96.5
V	0.5	2.9	0.0	0.3	0.5	1.1	55	17.4
Cr	0.8	52.4	0.0	0.6	3.0	0.9	113	35.6
Mn	1.8	7.4	0.0	1.5	1.4	0.7	252	79.5
Fe	141.1	878.5	4.9	114.3	113.6	14.7	317	100.0
Co	1.2	5.5	0.0	1.1	0.9	2.2	64	20.2
Ni	0.3	14.0	0.0	0.1	0.9	0.6	67	21.1
Cu	1.3	7.8	0.0	1.1	1.2	0.9	207	65.3
Zn	4.1	21.8	0.0	3.2	3.2	1.3	286	90.2
Ga	0.1	2.0	0.0	0.0	0.3	0.8	5	1.6
Ge	0.0	1.3	0.0	0.0	0.2	0.9	0	0.0
As	0.1	2.4	0.0	0.0	0.3	1.1	2	0.6
Se	0.1	2.8	0.0	0.0	0.4	1.4	0	0.0
Br	4.2	27.1	0.0	3.1	4.6	4.0	132	41.6
Rb	0.3	7.0	0.0	0.0	1.2	4.3	0	0.0
Sr	0.6	14.6	0.0	0.0	2.0	6.0	2	0.6
Mo	0.3	39.2	0.0	0.0	3.3	15.3	0	0.0
I	0.3	11.8	0.0	0.0	1.3	4.8	2	0.6
Ba	3.1	18.5	0.0	2.6	2.9	6.6	33	10.4
Hg	0.4	7.2	0.0	0.0	1.2	2.6	1	0.3
Pb	0.2	4.9	0.0	0.0	0.7	2.8	0	0.0

A6.3: Wellington central element concentrations in $PM_{2.5}$ particulate matter samples

Wellington central elemental concentrations PM2.5 filters (n = 292)

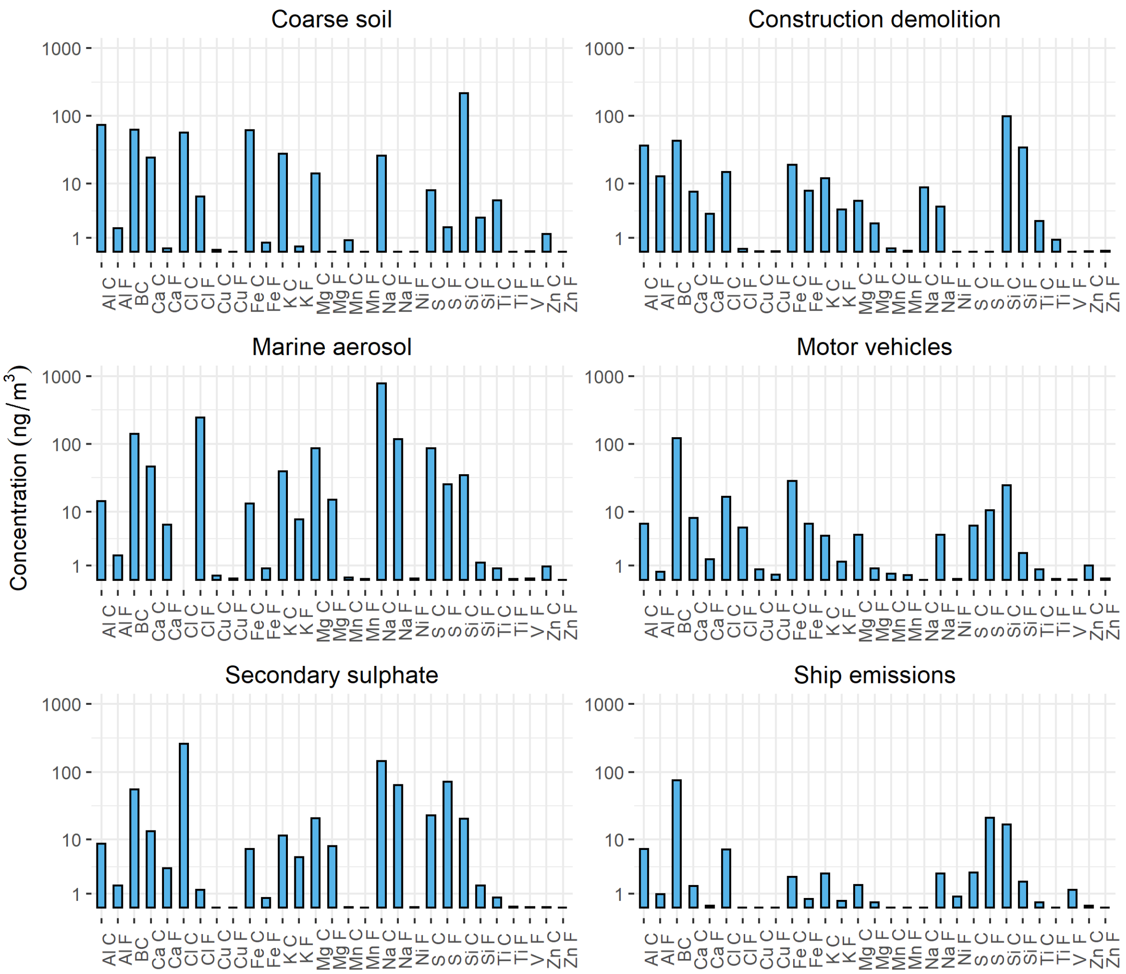
Species	Average	Max	Min	Median	SD	Ave LOD	n > LOD	% > LOD
PM2.5	5.2	22.2	0.0	4.9	2.8	0.6	283	96.9
BC	403.3	1,367.6	0.0	393.9	212.0	147.6	268	91.8
F Gam	8.5	160.6	0.0	0.0	22.0	158.4	0	0.0
Na Gam	145.8	683.4	0.0	125.1	137.5	227.8	74	25.3
Na	176.6	804.3	0.0	153.0	127.6	33.3	283	96.9
Mg	25.5	112.5	0.0	23.4	15.8	7.6	273	93.5
Al	10.8	71.0	0.0	9.2	8.7	4.2	265	90.8
Si	92.5	776.0	0.0	43.8	102.0	11.3	276	94.5
P	0.7	5.9	0.0	0.0	1.2	2.0	31	10.6
S	108.7	660.6	2.3	86.9	82.6	12.2	292	100.0
Cl	256.7	1,451.8	0.0	188.4	250.9	26.9	261	89.4
K	16.0	75.9	0.0	14.3	9.3	2.8	290	99.3
Ca	11.6	51.9	0.0	10.4	8.6	2.3	267	91.4
Sc	0.5	3.4	0.0	0.2	0.7	1.6	25	8.6
Ti	0.5	4.8	0.0	0.3	0.8	1.3	42	14.4
V	0.4	9.4	0.0	0.0	0.8	1.0	33	11.3
Cr	0.2	4.9	0.0	0.0	0.5	0.5	38	13.0
Mn	0.2	1.9	0.0	0.0	0.3	0.7	32	11.0
Fe	9.7	55.7	0.1	6.4	8.5	1.3	291	99.7
Co	0.3	1.7	0.0	0.2	0.4	0.8	41	14.0
Ni	0.3	3.6	0.0	0.0	0.5	0.6	40	13.7
Cu	0.4	3.9	0.0	0.2	0.6	0.8	67	22.9
Zn	0.7	11.9	0.0	0.5	1.1	1.0	93	31.8
Ga	0.1	1.6	0.0	0.0	0.3	1.1	5	1.7
Ge	0.1	1.9	0.0	0.0	0.4	1.5	5	1.7
As	0.3	4.0	0.0	0.0	0.7	2.1	9	3.1
Se	0.4	4.0	0.0	0.0	0.9	2.7	6	2.1
Br	0.8	9.6	0.0	0.0	1.4	4.0	10	3.4
Rb	0.7	10.9	0.0	0.0	1.9	6.3	5	1.7
Sr	1.0	14.3	0.0	0.0	2.5	8.9	4	1.4
Mo	4.5	70.1	0.0	0.0	12.1	34.1	7	2.4
I	1.0	9.9	0.0	0.0	1.8	5.0	10	3.4
Ba	0.6	4.7	0.0	0.0	1.1	4.1	0	0.0
Hg	0.8	8.7	0.0	0.0	1.6	4.3	5	1.7
Pb	0.5	7.9	0.0	0.0	1.2	5.3	0	0.0

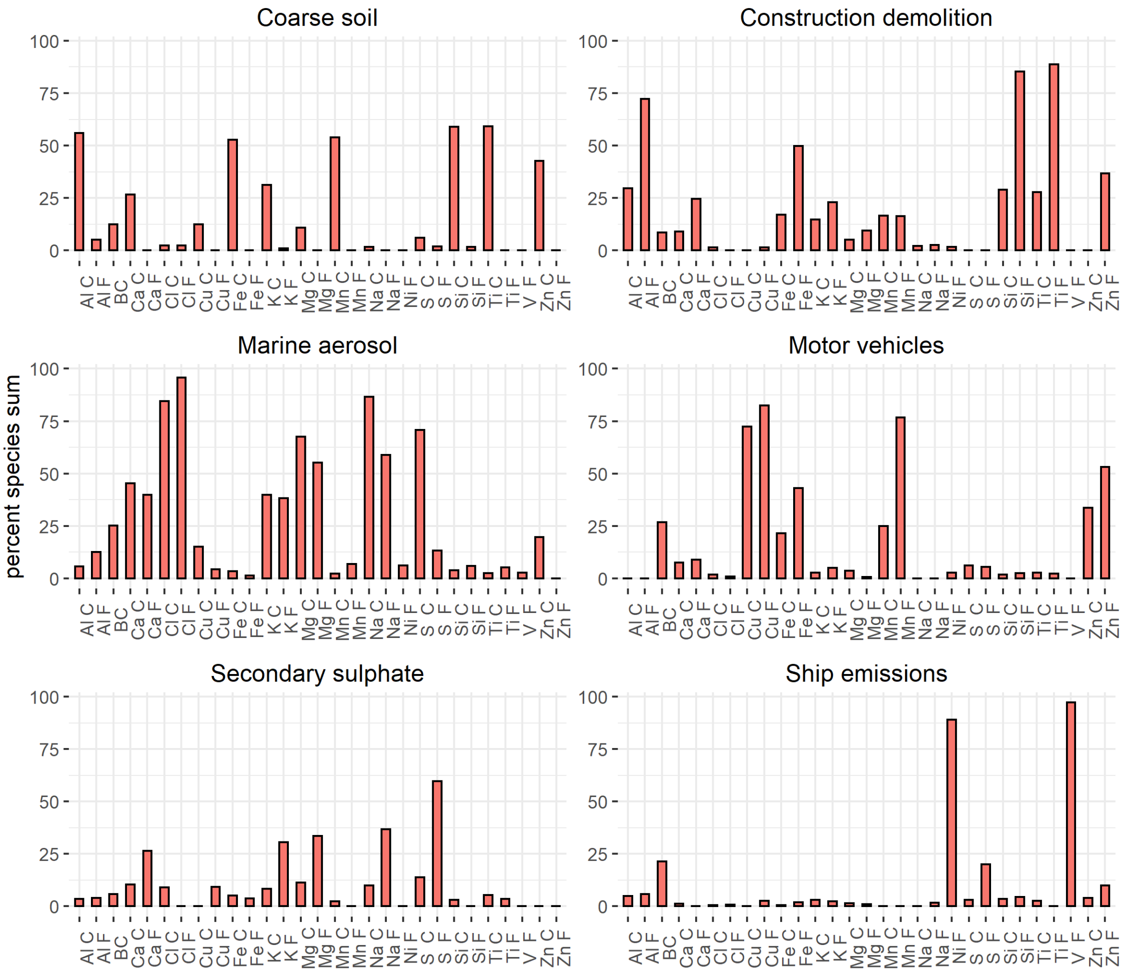
A6.4: Wellington central element concentrations in PM$_{10-2.5}$ particulate matter samples

Wellington central elemental concentrations PM10-2.5 filters (n = 292)

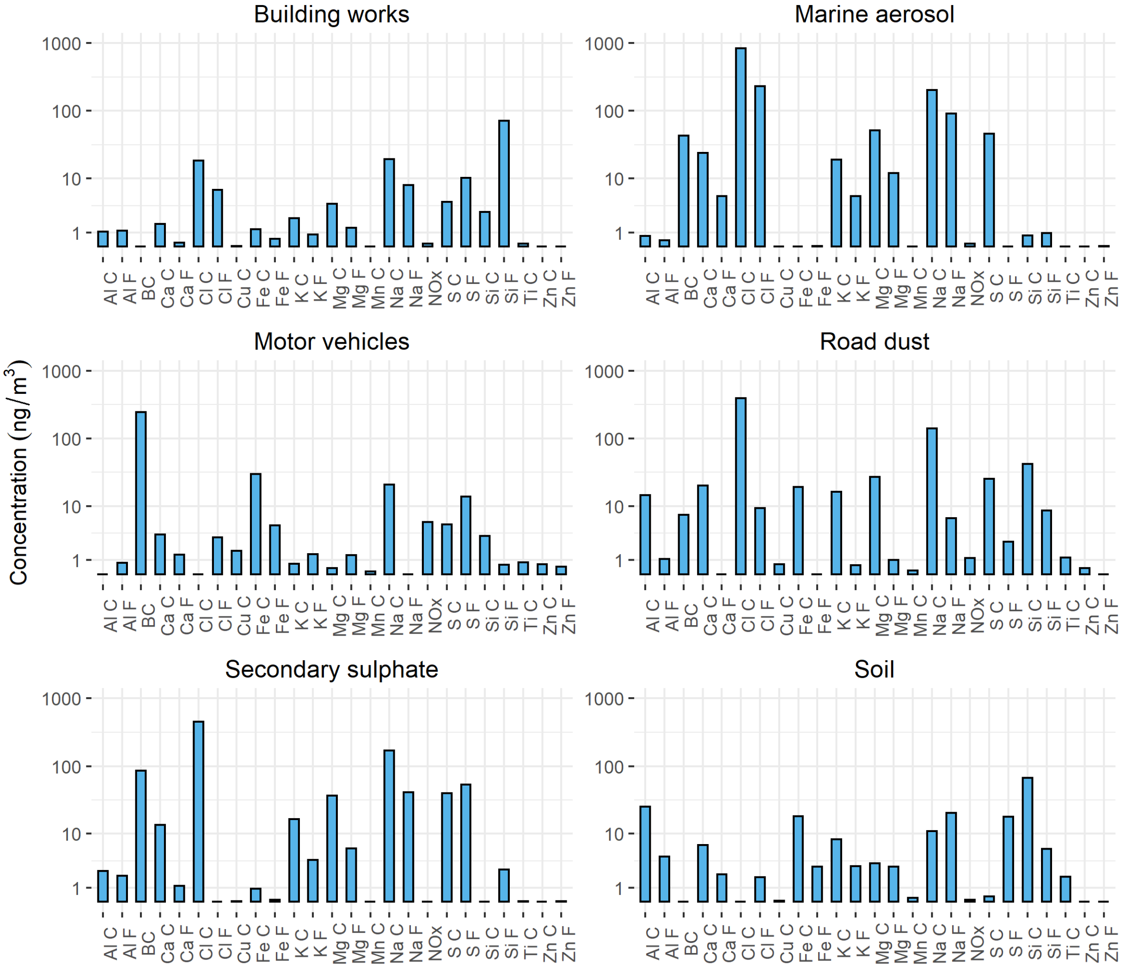
Species	Average	Max	Min	Median	SD	Ave LOD	n > LOD	% > LOD
PM10-2.5	7.4	30.2	0.0	7.3	4.3	0.9	283	96.9
F Gam	13.9	192.2	0.0	0.0	29.7	163.9	0	0.0
Na Gam	1,043.4	3,076.5	0.0	997.0	588.6	271.9	277	94.9
Na	576.8	2,173.4	105.5	542.6	271.3	87.2	292	100.0
Mg	123.6	293.5	17.8	120.6	55.3	17.3	292	100.0
Al	44.5	214.1	0.0	33.0	37.3	7.1	285	97.6
Si	117.6	549.7	2.2	83.1	101.8	13.6	292	100.0
P	2.0	18.0	0.0	0.3	3.0	2.2	96	32.9
S	121.8	282.9	20.1	116.6	51.9	14.3	292	100.0
Cl	1,722.2	5,918.5	158.4	1,620.4	912.4	172.7	292	100.0
K	63.6	189.9	9.6	59.4	26.7	7.1	292	100.0
Ca	75.5	224.5	6.0	69.1	38.8	8.3	292	100.0
Sc	1.1	3.6	0.0	1.0	0.8	1.6	87	29.8
Ti	4.3	19.3	0.0	3.4	3.4	1.1	262	89.7
V	0.1	1.4	0.0	0.0	0.3	0.8	11	3.8
Cr	0.6	12.5	0.0	0.4	0.9	0.8	99	33.9
Mn	0.7	3.6	0.0	0.6	0.6	0.6	161	55.1
Fe	71.3	349.5	4.2	60.1	46.7	7.7	292	100.0
Co	0.7	3.4	0.0	0.6	0.6	1.5	36	12.3
Ni	0.1	4.1	0.0	0.0	0.3	0.5	10	3.4
Cu	2.8	8.7	0.0	2.6	1.8	0.9	263	90.1
Zn	1.3	7.4	0.0	1.0	1.2	1.0	161	55.1
Ga	0.0	0.8	0.0	0.0	0.1	0.6	0	0.0
Ge	0.0	1.2	0.0	0.0	0.2	0.8	0	0.0
As	0.0	1.5	0.0	0.0	0.2	1.1	0	0.0
Se	0.0	1.9	0.0	0.0	0.3	1.2	0	0.0
Br	2.6	18.9	0.0	2.1	3.4	3.5	82	28.1
Rb	0.1	5.2	0.0	0.0	0.7	3.3	0	0.0
Sr	0.5	11.4	0.0	0.0	1.9	5.5	2	0.7
Mo	0.3	24.8	0.0	0.0	2.5	14.5	0	0.0
I	1.3	10.1	0.0	0.0	1.9	5.1	14	4.8
Ba	2.5	10.2	0.0	2.0	2.3	4.7	48	16.4
Hg	0.2	4.4	0.0	0.0	0.8	2.2	0	0.0
Pb	0.2	7.6	0.0	0.0	0.9	2.6	1	0.3

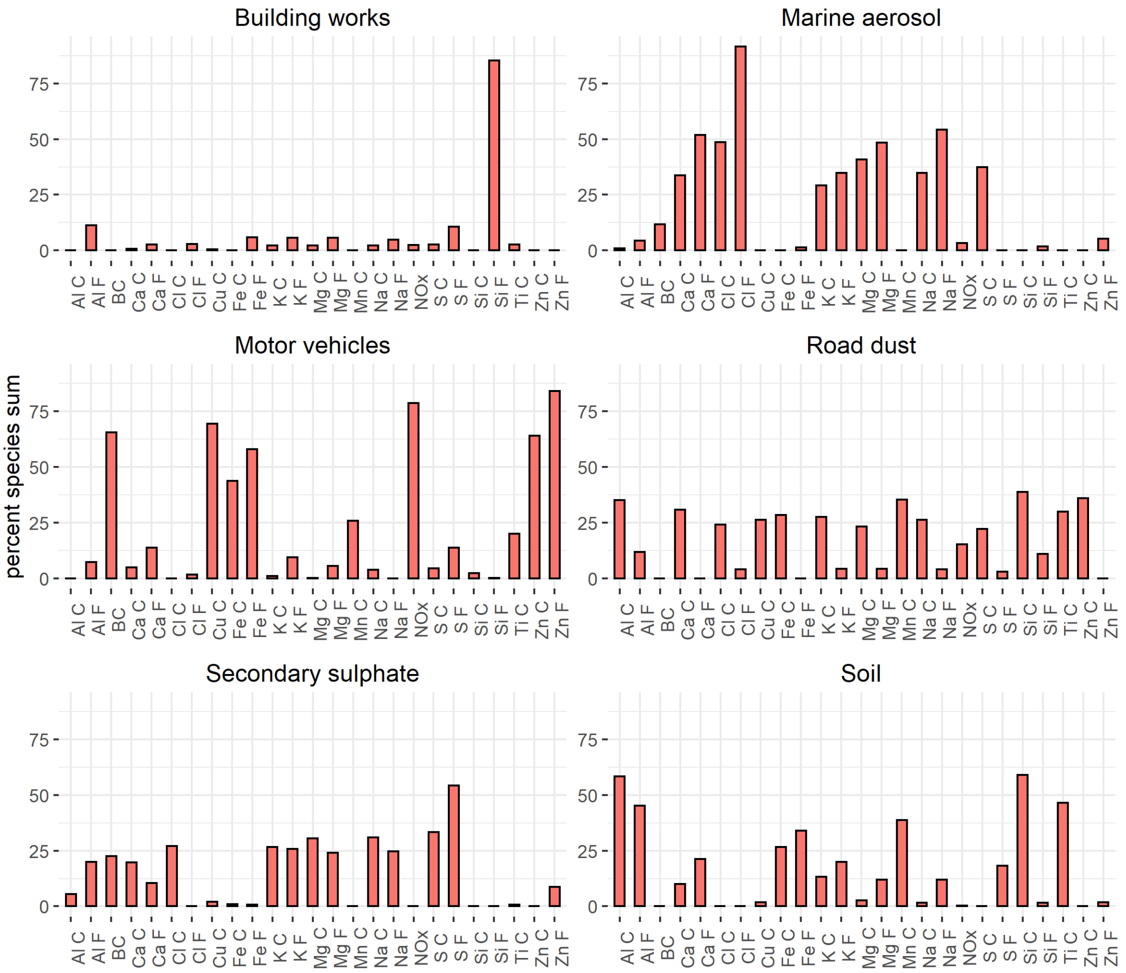
A6.5: Shed 39 elemental source profiles (top) and percentage contribution (bottom)



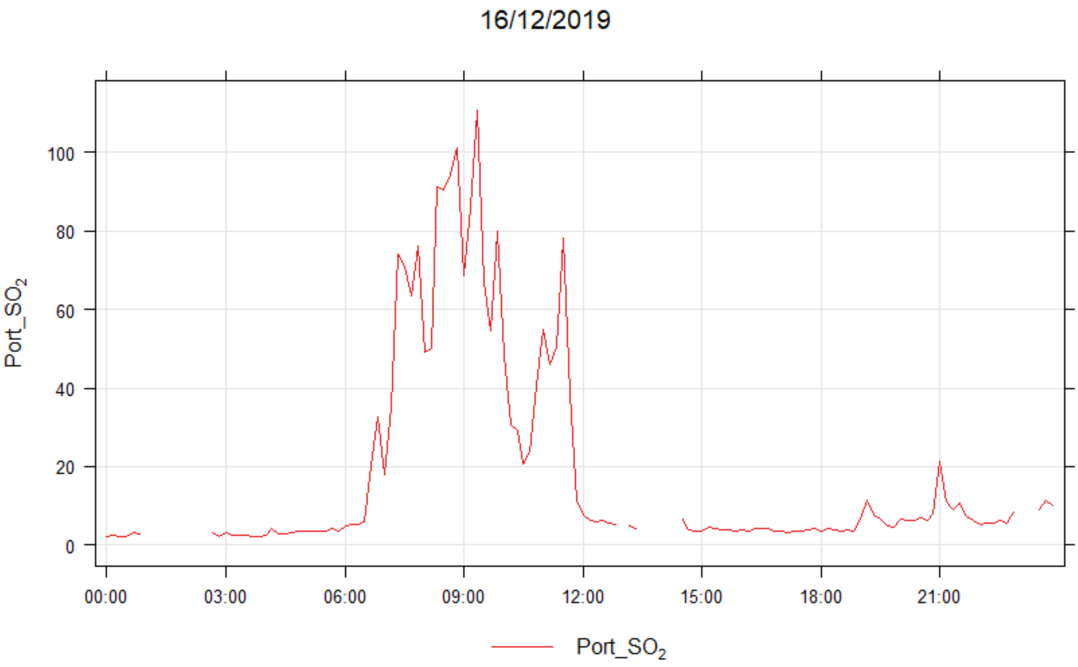

Coarse soil
Construction demolition
Marine aerosol
Motor vehicles
Secondary sulphate
Ship emissions
percent species sum
100
75
50
25
0
Al C
Al F
BC
Ca C
Ca F
Cl C
Cl F
Cu C
Cu F
Fe C
Fe F
K C
K F
Mg C
Mg F
Mn C
Mn F
Na C
Na F
Ni F
S C
S F
Si C
Si F
Ti C
Ti F
V F
Zn C
Zn F

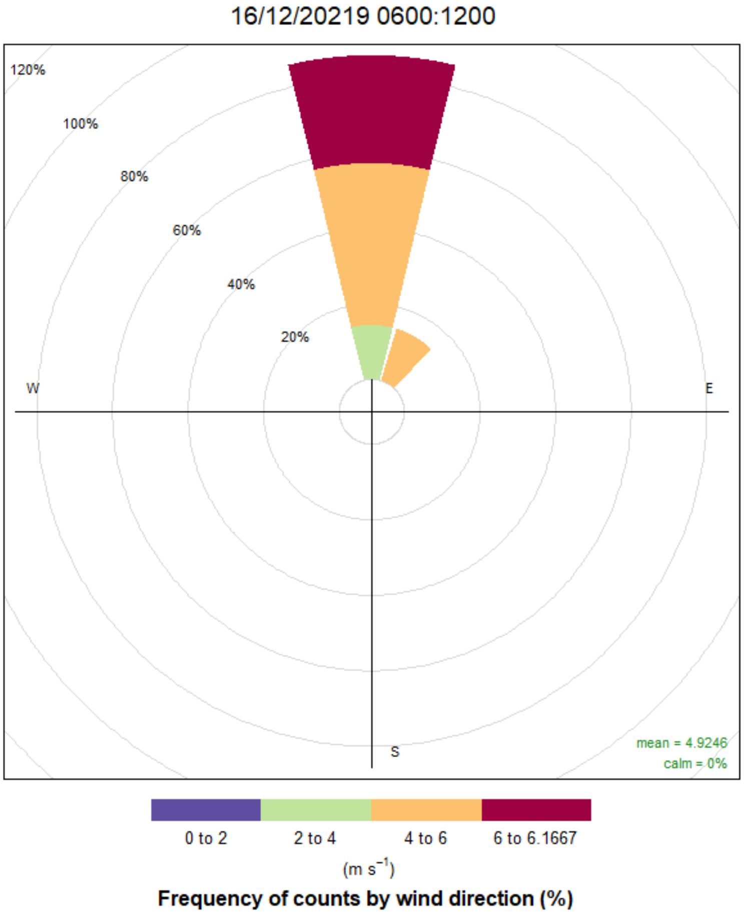
A6.6: Wellington central elemental source profiles (top) and percentage contribution (bottom)

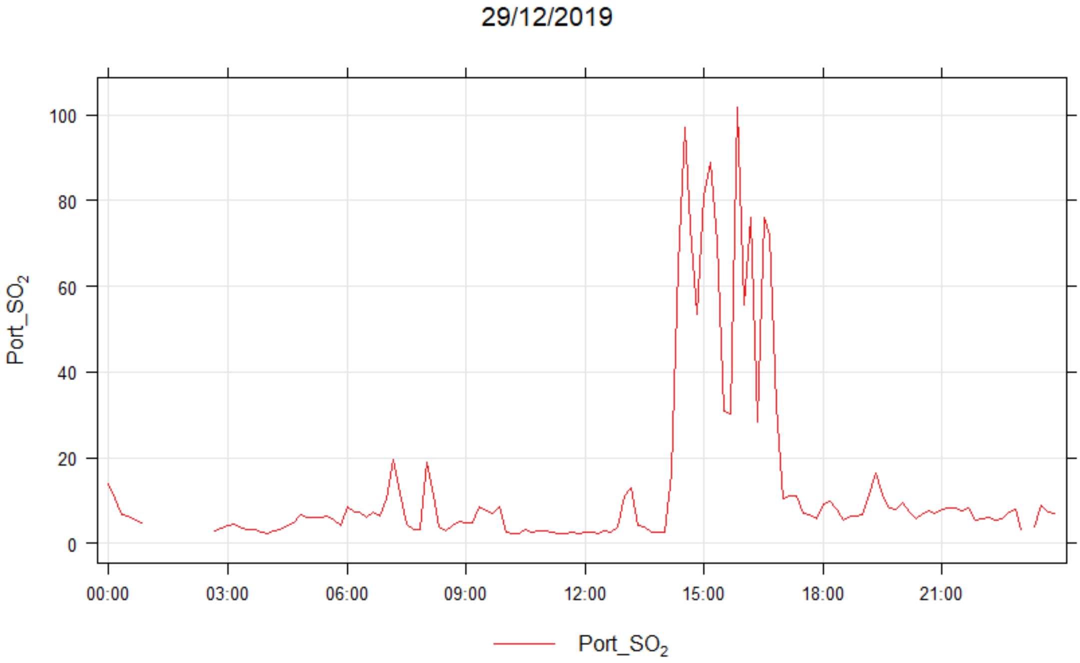


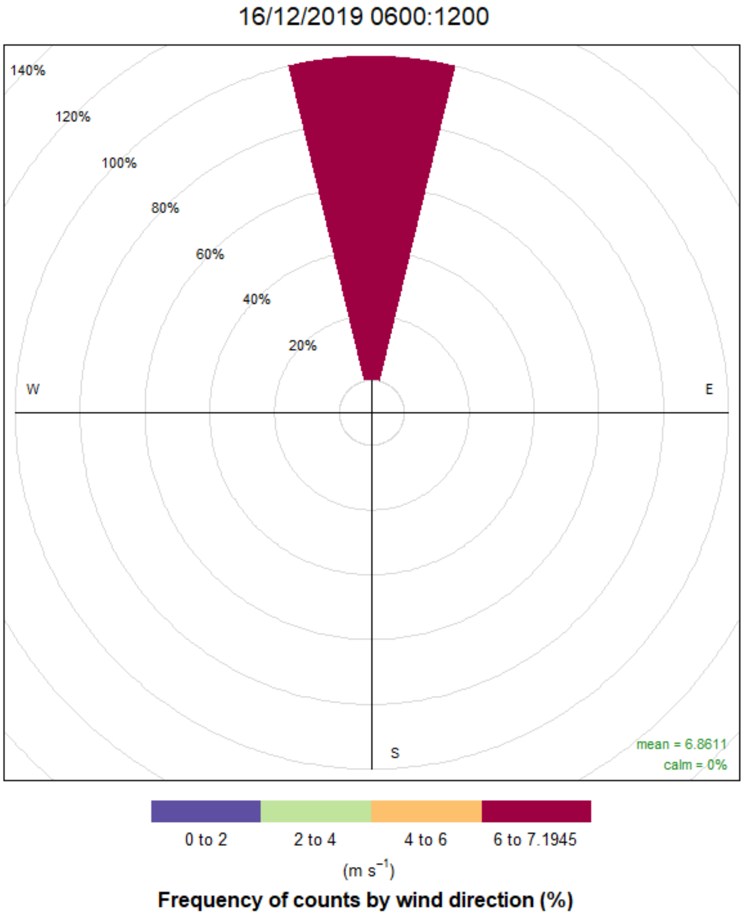

Building works
Marine aerosol
Motor vehicles
Road dust
Secondary sulphate
Soil
percent species sum
0
25
50
75
Al C
Al F
BC
Ca C
Ca F
Cl C
Cl F
Cu C
Fe C
Fe F
K C
K F
Mg C
Mg F
Mn C
Na C
Na F
NOx
S C
S F
Si C
Si F
Ti C
Zn C
Zn F

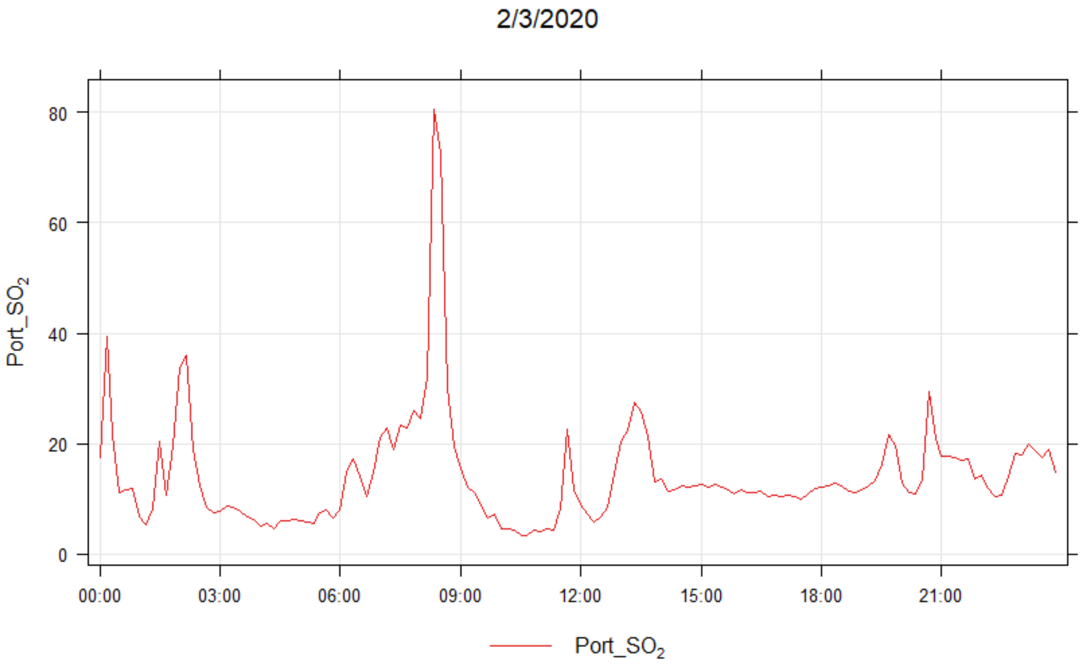
Appendix 7: Shed 39 SO_2 peak concentration days

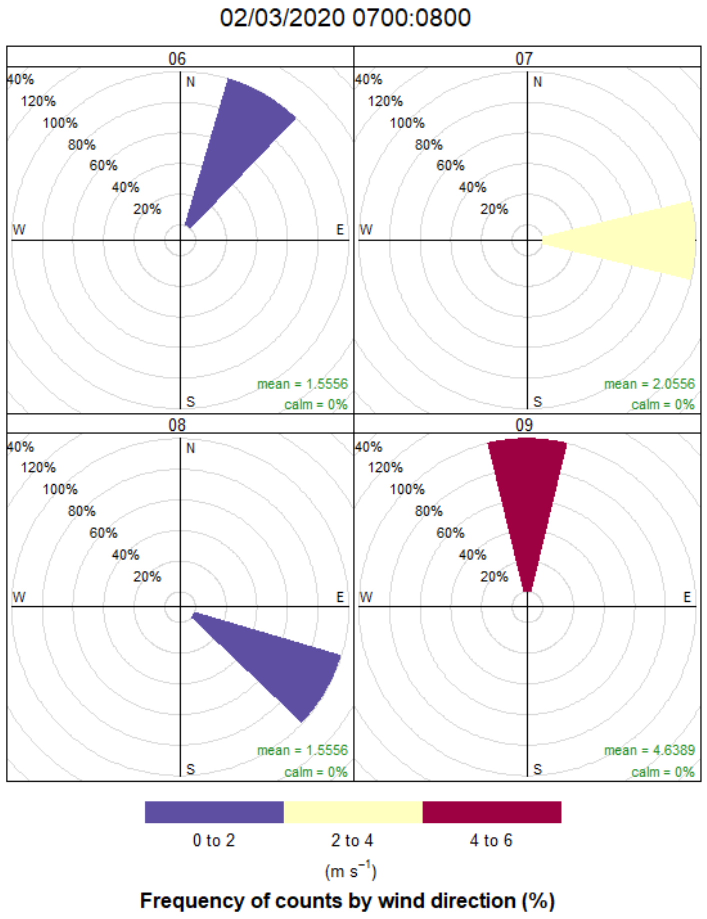


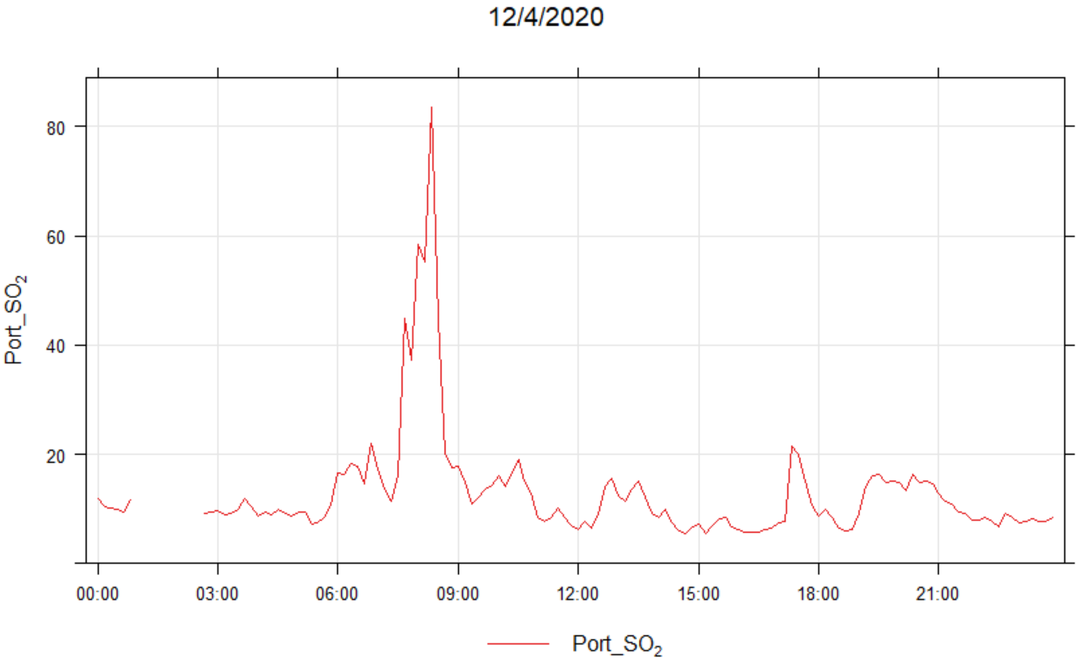


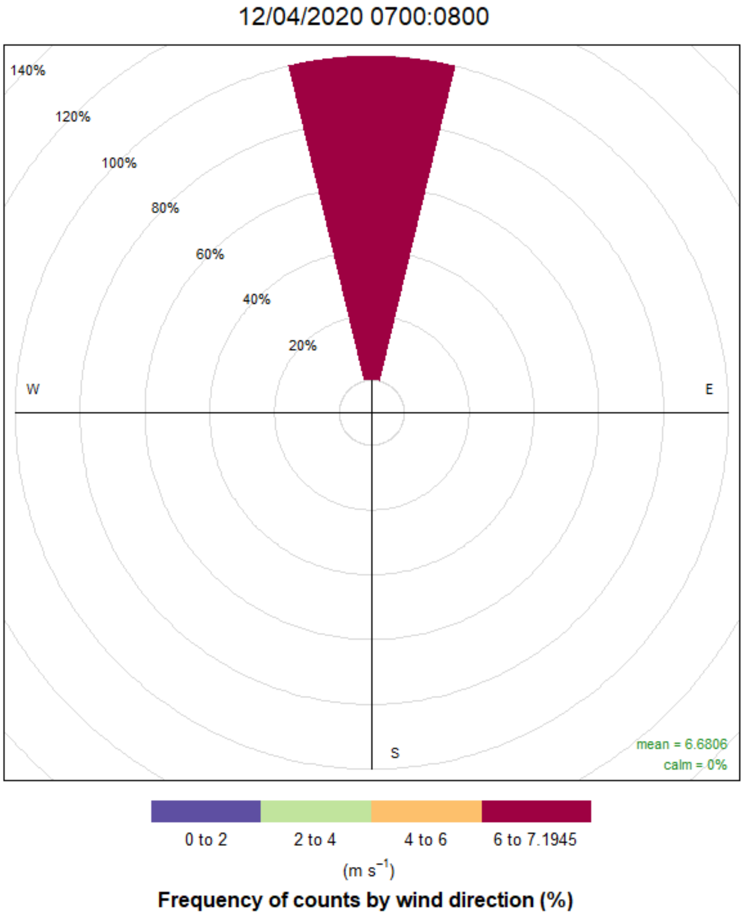

29/12/2019
Port_SO$_2$
0
20
40
60
80
100
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
Port_SO$_2$

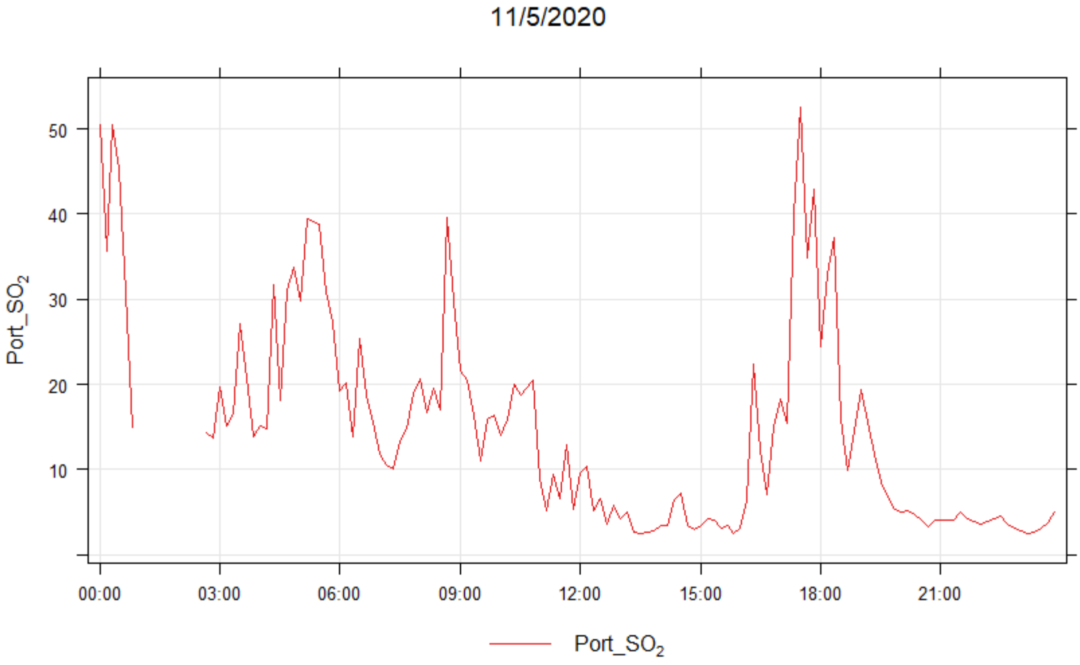

16/12/2019 0600:1200
140%
120%
100%
80%
60%
40%
20%
W
E
S
mean = 6.8611
calm = 0%
0 to 2
2 to 4
4 to 6
6 to 7.1945
(m s^{-1})
Frequency of counts by wind direction (%)

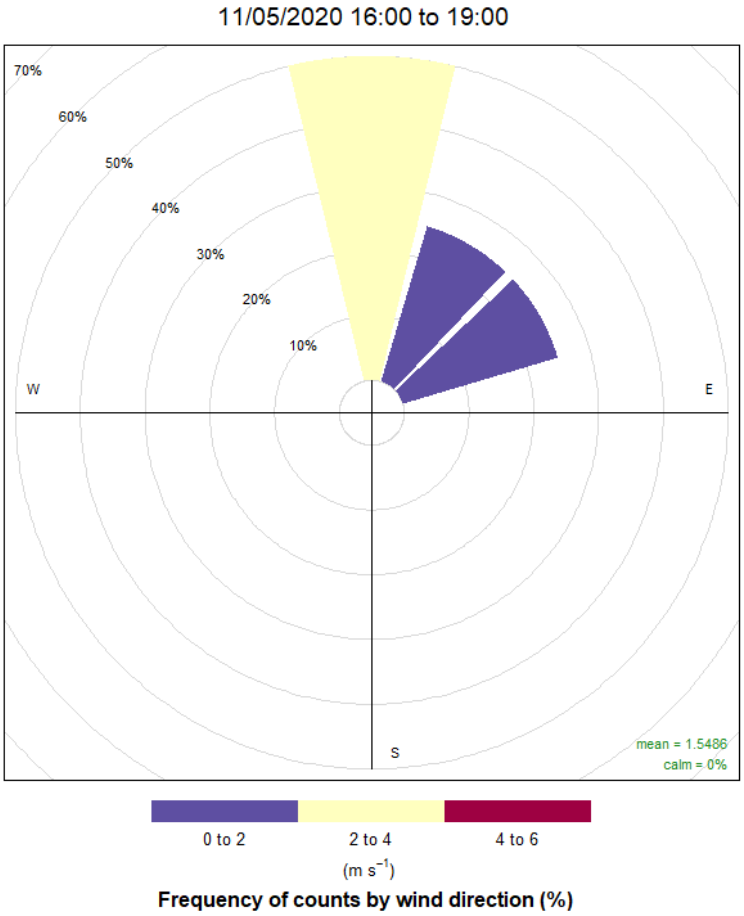

2/3/2020
Port_SO$_2$
0
20
40
60
80
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
Port_SO$_2$


02/03/2020 0700:0800
06
07
08
09
40%
120%
100%
80%
60%
40%
20%
N
E
S
W
mean = 1.5556
calm = 0%
mean = 2.0556
calm = 0%
mean = 1.5556
calm = 0%
mean = 4.6389
calm = 0%
0 to 2
2 to 4
4 to 6
(m s^{-1})
Frequency of counts by wind direction (%)


12/4/2020
Port_SO$_2$
80
60
40
20
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
Port_SO$_2$


12/04/2020 0700:0800
140%
120%
100%
80%
60%
40%
20%
W
E
S
mean = 6.6806
calm = 0%
0 to 2
2 to 4
4 to 6
6 to 7.1945
(m s^{-1})
Frequency of counts by wind direction (%)


11/5/2020
Port_SO$_2$
50
40
30
20
10
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
Port_SO$_2$


11/05/2020 16:00 to 19:00
70%
60%
50%
40%
30%
20%
10%
W
E
S
mean = 1.5486
calm = 0%
0 to 2
2 to 4
4 to 6
(m s^{-1})
Frequency of counts by wind direction (%)