Auckland Air Quality – 2022 Annual Data Report

Louis Boamponsem

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Technical Report 2023/8

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Executive summary

Air pollution is a significant environmental hazard globally, posing a severe risk to human health. According to recent estimates from the World Health Organization (WHO), air pollution is responsible for around seven million deaths annually. People with pre-existing respiratory and heart conditions, diabetes, the young, and elderly individuals are particularly susceptible to the adverse effects of air pollution. In Auckland alone, air pollution was responsible for 939 premature deaths in 2016, and the associated social cost of $PM_{2.5}$ and NO_2 air pollution was estimated at $4.45 billion. Air pollution has a detrimental impact on the atmosphere and climate, as some pollutants have warming and cooling properties, contributing to climate change.

Auckland is located on an isthmus between the Tasman Sea and the South Pacific Ocean, benefiting from a relatively clean and dependable airflow due to the absence of any nearby landmasses to the east or west of the city. However, despite these favourable conditions, certain human activities in Auckland still contribute to air pollution levels that exceed national and international standards, posing a threat to public health.

Transportation, residential heating, and industrial emissions are the primary sources of anthropogenic air pollutants in Auckland. The Auckland Council is responsible for managing air quality in the region, as mandated by the Resource Management Act 1991 and the National Environmental Standards for Air Quality (NESAQ). To achieve this, the council conducts continuous air quality monitoring, enabling it to assess compliance, develop policies, and evaluate their effectiveness. The council's data collection efforts help to quantify ambient air quality across the region, including spatial and temporal variations. The key air pollutants monitored in Auckland include particulate matter (PM_{10} and $PM_{2.5}$), black carbon, carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), sulphur dioxide (SO_2), and volatile organic compounds.

Data and information from the Auckland air quality monitoring network is reported in multiple ways. Monthly reports are regularly published on the Knowledge Auckland website, www.knowledgeauckland.org.nz. Data is available on the RIMU Environmental Data Portal, www.environmentauckland.org.nz and technical reports are produced in specific reporting years. This is the annual data report for 2022 data and its assessment against the NESAQ, Auckland Unitary Plan air quality target, and the 2021 WHO air quality guidelines.

Key findings:

- The annual average PM_{10} concentration of Auckland in 2022 increased by 2.5% compared to 2021. However, this increase did not exceed the 2021 WHO air quality guideline of 15 $\mu g/m^3$. The Queen Street site average exceeded the WHO guideline by 28.7%. On 18-19 August, the Queen Street site recorded two exceedances of NESAQ for PM_{10} (24-hour average). After further investigation, it was found that these exceedances were primarily due to a marine aerosol (sea salt) natural-source event.
- The overall annual average $PM_{2.5}$ concentration of Auckland in 2022 increased by 2.8% compared to 2021. This increase was above the 2021 WHO air quality guideline of 5 $\mu g/m^3$. Queen Street, Takapuna, Penrose and Patumahoe sites annual $PM_{2.5}$ averages exceeded the WHO guideline. The Auckland Unitary Plan air quality target (25 $\mu g/m^3$) for 24-hour average $PM_{2.5}$ was not exceeded.
- In general, Auckland's annual mean concentration of NO_2 marginally decreased by 0.2% compared to 2021. As expected, the highest NO_2 concentrations were measured at the city centre sites, although the concentrations were lower than the previous year. There were NO_2 breaches of both the national standard and WHO guideline at the Customs Street and Khyber Pass Road sites. These exceedances were not true representations of the wider emissions profile in the areas monitored by these sites. The Customs Street site NO_2 standard breaches were caused by exhaust fumes from a diesel power generator which was temporarily located near the monitoring station. Our investigation of the Khyber Pass Road site's NO_2 national standard exceedance suggests that emissions from a stationary vehicle and spray paint fumes from a tag graffiti artist were the likely causes.
- The average concentration of SO_2 in Auckland significantly increased by 40.8% in 2022 compared to 2021, which requires further investigation to identify the underlying cause of this rise.
- The average CO concentration at the Khyber Pass Road site decreased by 14.5% compared to 2021. This decrease can be attributed to the reduction in traffic in that area. There was no exceedance of NESAQ and the 2021 WHO air quality guideline for CO.
- The average O_3 concentration at Patumahoe in 2022 increased by 9.0% compared to 2021. Though there were occasional hourly spikes in O_3 mean concentrations, none were above the national standard and the 2021 WHO air quality guidelines for O_3.
- All key air pollutants were highest in winter, most likely due to domestic fires.

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Glossary of terms, acronyms, and abbreviations

Term	Meaning
Aerodynamic diameter	Used to describe the behaviour of a particle as it moves around in the air; it compares the behaviour with that of a spherical particle of unit density
Aerosol	A mixture of particles suspended in the atmosphere
Air pollutant/contaminant	Any substance in the air that could harm humans, animals, vegetation, or other parts of the environment when present in high enough concentrations
Air pollution	The presence of one or more air pollutants in high enough concentrations to cause harm
Air quality	Air quality is the degree to which air is suitable or clean enough for humans, animals, or plants to remain healthy
Airshed	A geographic area established to manage air pollution within the area as defined by the national environmental standard for air quality (NESAQ).
Ambient air	The external air environment (does not include the air environment inside buildings or structures)
Anthropogenic sources	Sources resulting from human activity (not natural sources) such as combustion of fuels
BAM	Beta attenuation monitor
Benzene	Benzene is an aromatic organic compound which is a minor constituent of petrol (about 2% by volume).
Black carbon	Is an air pollutant made up of tiny soot-like particles discharged into the atmosphere from combustion processes.
BTEX	Benzene, toluene, ethylbenzene and xylenes. A group of volatile organic compounds
CO	Carbon monoxide, a type of air pollutant
Exceedance	An exceedance defines a period of time during which the concentration of a pollutant is greater than the appropriate air quality criteria.
Ground-level ozone	At ground level, ozone is considered an air pollutant that can seriously affect the human respiratory system. It is a major component of photochemical smog.
HAPINZ	Health and Air Pollution in New Zealand. The HAPINZ 3.0 study investigated the impact of air pollution on New Zealanders' health.
MfE	Ministry for the Environment
MoH	Ministry of Health
Monitoring site	A facility for measuring the concentration of one or more pollutants in the ambient air; also referred to as 'monitoring station'.
NESAQ	National Environmental Standard for Air Quality
NO_2	Nitrogen dioxide, a type of air pollutant.

Term	Meaning
NOx	Oxides of nitrogen. NOx is principally formed by the oxidation of nitrogen contained in air at high combustion temperatures.
NZTA	New Zealand Transport Agency
Pb	Lead
PM	Particulate matter is made up of a mixture of various sizes of solid and liquid particles suspended in air; a type of air pollutant.
PM_{10}	Particulate matter with an aerodynamic diameter of 10 micrometres or less; a type of air pollutant
$PM_{2.5}$	Particulate matter with an aerodynamic diameter of 2.5 micrometres or less; a type of air pollutant.
Pollution rose	A graphic tool used to get a view of how wind direction and a pollutant are typically distributed at a particular site.
Relative humidity	Is a ratio, expressed in per cent, of the amount of atmospheric moisture present relative to the amount that would be present if the air were saturated.
SO_2	Sulphur dioxide, a type of air pollutant.
Stats NZ	Statistics New Zealand
TSP	Total suspended particulates; a type of air pollutant.
USEPA	United States Environmental Protection Agency
VOCs	Volatile organic compounds — chemical compounds that have high enough vapour pressure to exist at least partially as a gas at standard atmospheric temperature and pressure.
WHO	World Health Organization
Wind rose	A graphic tool used to get a view of how wind speed and direction are typically distributed at a particular site.
$\mu g/m^3$	Microgram of pollutant (1 millionth of a gram) per cubic metre of air, referenced to temperature of 0°C (273.15 K) and absolute pressure of 101.325 kilopascals (kPa).

1 Introduction

Air pollution is the leading environmental risk factor worldwide. World Health Organisation (WHO) estimates show that around seven million deaths are attributable to the joint effects of ambient and household air pollution (WHO, 2018, 2021). On average, a person inhales about 14,000 litres of air every day, and the presence of contaminants in this air can adversely affect people's health. People with pre-existing respiratory and heart conditions, diabetes, the young, and elderly people are particularly vulnerable to these effects (MfE and Stats NZ, 2014). Each year, air pollution causes premature deaths in Auckland and results in increased numbers of reduced activity days and hospital visits, and higher usage of medications. In 2016, air pollution caused 939 premature deaths in Auckland. The estimated associated social cost of $PM_{2.5}$ and NO_2 air pollution in Auckland was $4.45 billion (Kuschel et al., 2022). Auckland region factsheet from the HAPINZ 3.0 study is given by Appendix A.

Air pollution not only affects human health but also the environment, including the atmosphere and climate. It has both direct and indirect impacts on the atmosphere and climate. Directly, some air pollutants have warming or cooling properties that can alter the Earth's temperature. Additionally, air pollution can indirectly influence the atmosphere and climate by modifying the distribution and reflectivity of clouds and changing rainfall patterns. Particulate matter and ground-level ozone are two primary examples of air pollutants that affect our atmosphere and climate. Particulate matter can have direct cooling effects by reflecting solar radiation, while ground-level ozone has a warming effect on the atmosphere (MfE and Stats NZ, 2014).

Auckland is located on an isthmus between the Tasman Sea and the South Pacific Ocean, benefiting from a relatively clean and dependable airflow due to the absence of any nearby landmasses to the east or west of the city. However, despite these favourable conditions, certain human activities in Auckland still contribute to air pollution levels that exceed national and international standards, posing a threat to public health (Sridhar, 2013; Dirks et al., 2017; Talbot and Crimmins, 2020; Kuschel et al., 2022).

Transport emissions are the main anthropogenic source of air contaminants in Auckland. Domestic fires and industry also make important contributions to air pollutant levels (Xie et al., 2019; Davy et al., 2017; Talbot and Crimmins, 2020; MfE and Stats NZ, 2021). Key air contaminants monitored in Auckland are particulate matter (PM_{10} and $PM_{2.5}$), black carbon, carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), sulphur dioxide (SO_2), and volatile organic compounds (such as benzene). See Appendix B for a full list of Auckland specific air contaminate sources.

As the local governing body for the region, Auckland Council holds the responsibility for the management of air quality within the airsheds. Under the Resource Management Act 1991 and the National Environmental Standards for Air Quality (NESAQ), the council is mandated to monitor air quality continuously, collect data, and assess compliance. Public reporting is required for any breach of NESAQ, allowing for transparency in the management of air quality. The data collected by the council serves as a valuable resource for quantifying the ambient air quality in the region and identifying any spatial and temporal variations. This information is valuable for policy development, evaluation, and decision-making regarding air quality management in Auckland.

The Auckland air quality monitoring network provides data and information through various channels. Monthly reports are published on the Knowledge Auckland website, and the RIMU Environmental Data Portal and Land, Air, and Water Aotearoa (LAWA) website make data available for public access. Technical reports are also produced in specific reporting years. This annual data report presents the air quality data for 2022 and assesses it against the NESAQ, Auckland Unitary Plan air quality target, and the 2021 WHO air quality guidelines.

1.1 Why do we monitor air pollutants?

Auckland Council is committed to continuously collecting air quality data to monitor compliance with national standards, and to provide information that aids in policy development and evaluation. By collecting this data, the council is able to quantify ambient air quality in the region, and note spatial and temporal variations. This helps to support an understanding of whether national or regional air quality standards, targets, objectives, and environmental outcomes are being met. The data collected is used to inform decision-making processes, identify trends and patterns, and to develop strategies and interventions to improve air quality in the region.

The National Environmental Standards for Air Quality (NESAQ) establishes five ambient air quality standards for carbon monoxide (CO), particulate matter (PM_{10}), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), and ozone (O_3). In addition, the Auckland Unitary Plan sets further ambient air quality targets (Table 1). To minimise potential health risks, the objectives and policies of the Auckland Unitary Plan require Auckland Council to consider these targets. By monitoring air quality and assessing compliance with these standards and targets, the council is able to better understand potential health risks and develop policies to mitigate them (Talbot and Crimmins, 2020).

The ambient standards are the minimum requirements that outdoor air quality should meet in order to guarantee a set level of protection for human health and the environment. The table below provides details of the standards and guidelines.

Table 1. Comparison of 2021 WHO air quality guidelines to NESAQ and Auckland ambient air quality target.

Pollutant	Time period	NESAQ	Auckland target[a]	2021 WHO AQ guideline[c]	NESAQ number of exceedances allowed per year	Units
$PM_{2.5}$	Annual	NA	10	5	NA	µg/m³
	24 - hour	NA	25	15	NA	µg/m³
PM_{10}	Annual	NA	20	15	NA	µg/m³
	24 - hour	50	NA	45	1	µg/m³
O_3	8 - hour[b]	NA	100	100	NA	µg/m³
	1 - hour	150	NA	NA	0	µg/m³
NO_2	Annual	NA	40	10	NA	µg/m³
	24 - hour	NA	100	25	NA	µg/m³
	1 - hour	200	NA	200	9	µg/m³
SO_2	24 - hour	350	120	40	9	µg/m³
CO	1 - hour	NA	30	35	NA	mg/m³
	8 - hour	10	NA	10	1	mg/m³
	24 - hour	NA	NA	4	NA	mg/m³

[a] Auckland ambient air quality target

[b] 99th percentile (i.e. 3-4 exceedance days per year)

[C] 99th percentile (i.e. 3-4 exceedance days per year) for 24-hour guidelines

µg/m³ : micrograms per cubic metre

mg/m³ : milligrams per cubic metre

NA : Not available

1.2 Monitored air pollutants

a. Particulate matter ($PM_{2.5}$ and PM_{10})

Particulate matter refers to a mixture of solid particles and liquid droplets present in the air, which can have harmful effects on human health and the environment (US EPA, 2021; MfE & Stats NZ, 2021). The Auckland Council's air quality monitoring network measures two types of particulate matter (PM_{10} and $PM_{2.5}$). PM_{10} refers to larger particles with an aerodynamic diameter of 10 micrometres (µm) or less, which can still be inhaled and pose health risks. $PM_{2.5}$ refers to finer particles with an aerodynamic diameter of 2.5 micrometres or less, which can penetrate deeply into the lungs and cause more serious health problems.

Wood burning for home heating is a major contributor to particulate matter concentrations in Auckland, which are reflected in the winter peaks of PM_{10} and $PM_{2.5}$ concentrations and in bottom-up emission inventories (Metcalfe et al., 2018; Xie et al., 2019). In addition, secondary sulphates are a significant source of particulate matter. In Auckland, these are primarily generated from oceanic biogenic gas emissions such as dimethyl sulphate, which then condense as fine particulates in the atmosphere (Davy et al., 2017; Talbot and Crimmins, 2020).

In Auckland, combustion-related particulates account for 44% of total particulate concentrations, including $PM_{2.5}$ and PM_{10} (Davy et al., 2017; Talbot and Crimmins, 2020). Transport emissions are the main source of $PM_{2.5}$ in the region, particularly in urban areas and along major arterial routes (Talbot and Lehn, 2018). Non-exhaust transport sources of PM_{10}, such as brake and tire wear and unsealed road dust, are quickly deposited due to gravity but often become resuspended in the atmosphere through vehicle-induced turbulence near roads (Xie et al., 2016; Talbot and Crimmins, 2020; MfE and Stats NZ, 2021).

The PM_{10} size fraction is predominantly released from natural sources such as soil and rock abrasion released as dust (Carslaw et al., 2010). There is also a notable contribution across the Auckland region from sea salt, which can make up the majority of PM_{10} mass during summertime (Davy et al., 2017; Talbot and Crimmins, 2020; MfE & Stats NZ, 2021).

In New Zealand and around the world, the most significant human health impacts from poor air quality are associated with exposure to particulate matter (Health Effects Institute, 2018; MfE & Stats NZ, 2021). There is considerable evidence that inhaling PM is harmful to human health, particularly smaller particle sizes, such as $PM_{2.5}$ and finer. $PM_{2.5}$ can be particularly harmful because these particles can become trapped in the small airways deep in the lungs. When particles are very fine they can enter the bloodstream and penetrate organs in the body (EFCA, 2019; Talbot and Crimmins, 2020; MfE & Stats NZ, 2021).

Short- and long-term exposure to PM, even at low levels, can lead to a range of health impacts especially in vulnerable people (the young, the elderly, and people with existing respiratory conditions). At the less-severe end, it can cause temporary and reversible effects such as shortness of breath, coughing, or chest pain. There is strong evidence of more severe effects, such as illness and premature death from heart attacks, strokes, or emphysema (where the air sacs in the lungs are damaged) (MfE & Stats NZ, 2021).

Exposure to PM can also lead to lung cancer and exacerbate asthma. Research findings point to possible links with diabetes and atherosclerosis (the accumulation of fat, cholesterol, and other substances on artery walls, reducing blood flow) as a result of increased inflammation caused by PM (WHO, 2013; MfE & Stats NZ, 2021).

The WHO (2013) reported that $PM_{2.5}$ acts as a delivery mechanism into the bloodstream for hazardous semi-volatile pollutants and that there are no safe exposure thresholds below which health risks are not present (WHO, 2013; Talbot and Crimmins, 2020).

b. Nitrogen oxides (NOx)

Nitrogen oxides (NOx) are primarily produced when nitrogen in the air is oxidised at high combustion temperatures. The main source of anthropogenic NOx emissions is vehicle traffic, and nitrogen dioxide (NO_2) has been identified as a key indicator of motor vehicle pollution. Approximately 95% of NOx is emitted as nitric oxide (NO) at the point of discharge, which is generally considered harmless to human health. However, the remaining 5% of NOx is NO_2, which can negatively impact respiratory function in humans. The conversion of NO to NO_2 is facilitated by atmospheric oxidants, particularly ozone (O_3), which can increase the rate of conversion (Crimmins, 2018; Moore, 2019).

Nitrogen dioxide (NO_2) is a gas primarily generated by burning fossil fuels, mainly by motor vehicles (particularly diesel vehicles) but also from industrial emissions and home heating (MfE & Stats NZ, 2021). NO_2 is emitted almost entirely from anthropogenic activities (except for a small contribution from volcanic emissions) (Xie et al., 2014). Concentrations of NO_2 are highest along busy road corridors, especially routes that are used by buses and heavy goods vehicles (Longely et al., 2014; Talbot and Crimmins, 2020). Emissions of NO_2 have reduced due to improved engine technology and fuel quality, however, many improvements have been offset by higher traffic volumes, more distance travelled, and intensification along transport corridors. In addition, vehicles are getting heavier, with larger engines (MfE & Stats NZ, 2021).

There are health impacts from short-term and long-term exposure to NO_2. Short-term exposure to high concentrations of NO_2 causes inflammation of the airways and respiratory problems and can cause asthma attacks. Short-term exposure may also trigger heart attacks and increase the risk of premature death. Long-term exposure may cause asthma to develop and lead to decreased lung development in children. It may also increase the risk of certain forms of cancer and premature death. NO_2 also contributes to brown haze in Auckland, which is associated with an increase in hospital admissions (US EPA, 2016; MfE & Stats NZ, 2014, 2021).

Nitrogen dioxide also contributes to the formation of ground-level ozone and secondary particulate matter (when gases in the atmosphere react in the presence of sunlight), both of which can have adverse health impacts (MfE & Stats NZ, 2021).

NO_2 can have ecological impacts. It can cause injury to plant leaves and reduce growth in plants that are directly exposed to high levels (US EPA, 2008). In the atmosphere, NO_2 can combine with water to form nitrate, which has been shown to cause acidification and have adverse effects on freshwater ecosystems. It can also affect ecosystems by acting as a nutrient (Payne et al., 2017; MfE & Stats NZ, 2021).

c. Carbon monoxide (CO)

Carbon monoxide (CO) is a colourless, odourless gas formed by both natural processes (such as volcanic activity and wildfires) and anthropogenic activities (mostly from motor vehicles, home heating, and industry). CO is caused by the incomplete combustion of fuels, especially in petrol-fuelled motor vehicles (Sridhar, 2013; MfE & Stats NZ, 2014)

Exposure to CO has significantly reduced since the introduction of emission standards in the year 2000, which required catalytic converters (an exhaust emission control device that converts toxic gases and pollutants into less-toxic pollutants) to be installed in most vehicles (Bluett et al., 2016; MfE & Stats NZ, 2021)

Carbon monoxide (CO) can have a range of health effects even after short-term exposure to relatively low concentrations. When inhaled, CO enters the bloodstream and attaches to haemoglobin in red blood cells, which transport oxygen around the body. This reduces the amount of oxygen that body tissues receive and can have adverse effects on the brain, heart, and general health. Exposure to low levels can causes dizziness, nausea, weakness, confusion, and disorientation. Higher levels can cause collapse, loss of consciousness, coma, and death (US EPA, 2010; MfE & Stats NZ, 2021). A long-term guideline does not exist as most of the adverse health problems are associated with high short-term concentrations (MfE & Stats NZ, 2014).

d. Ground-level ozone (O_3)

Ozone (O_3) is a colourless gas found naturally in the outer atmosphere but is a pollutant when formed at ground level from reactions with other pollutants produced by motor vehicles, industrial activities, and domestic sources. Ozone helps screen out harmful ultraviolet radiation in the upper atmosphere. Ground-level ozone forms when nitrogen oxides and volatile organic compounds combine in the presence of sunlight (Sridhar, 2013; MfE & Stats NZ, 2021).

Exposure to high concentrations of ground-level ozone can cause respiratory health issues and is linked to cardiovascular health problems and increased mortality. People most at risk include children, older adults, people with asthma, and people who spend a lot of time outdoors. Exposure to ground-level ozone may also be associated with effects on the nervous and reproductive systems, and other developmental effects (WHO, 2013; MfE & Stats NZ, 2014, 2021).

Only a short-term guideline and standard exist as most of the adverse health problems are associated with high short-term concentrations. High concentrations occur away from where pollutants that form ozone are emitted. This is because it takes time for the chemical reactions to occur, by which stage the chemicals have dispersed away from their source. The increased duration and intensity of sunlight in summer make this primarily a summer issue (MfE & Stats NZ, 2014).

e. Sulphur dioxide (SO_2)

Sulphur dioxide is a colourless gas with a sharp, distinctive odour. It is produced from the combustion of fossil fuels that contain sulphur, such as coal and oil (used for home heating, industry, and shipping). Industrial sources include milk powder production, thermal electricity generation, petrol refining, smelting of mineral ores, production of fertilisers, and steel manufacturing. Natural sources include geothermal activity and volcanoes (Sridhar, 2013; Talbot et al., 2017; MfE & Stats NZ, 2014, 2021).

Levels of SO_2 have rapidly declined across the Auckland airshed since national regulations reduced the sulphur content of diesel and petrol (Talbot and Crimmins, 2020). At high levels, SO_2 can have human health and ecological impacts. When inhaled, SO_2 is associated with respiratory problems such as bronchitis. It can aggravate the symptoms of asthma and chronic lung disease and irritate the eyes (MfE & Stats NZ, 2014, 2021).

SO_2 can also interact with other compounds in the air to form sulphate particulate matter, a secondary pollutant. Sulphate PM is associated with significant health effects because of its small size and acidity. It is also a cause of haze, which impairs visibility (MfE & Stats NZ, 2021). In ecosystems, SO_2 can damage vegetation, acidify water and soil, and affect biodiversity (US EPA, 2017; MfE & Stats NZ, 2021).

f. Black carbon

Soot generated from combustion processes is a common type of $PM_{2.5}$ particle in urban areas. These ‘black carbon’ particles (BC) can be emitted from combustion sources (particularly diesel, coal and wood) and are known to be hazardous to human health (Janssen et al., 2011). As solar energy is absorbed by the dark particles, BC is also an atmospheric warming pollutant and has been identified as having the second greatest global warming impact (to carbon dioxide) over the industrial era (Bond et al., 2013).

The major contributors to black carbon in Auckland are diesel transport modes such as buses and trucks, and wood combustion for home heating (Crimmins et al., 2019, Talbot and Crimmins 2020). In Auckland, combustion sources are dominated by motor vehicle emissions and solid fuel fires for domestic heating (Davy et al., 2017).

g. Volatile organic compounds (VOCs)

Volatile organic compounds (VOCs) are organic compounds that are both naturally occurring and human-made (such as benzene and 1,3-butadiene). Benzene is a colourless, flammable gas produced by motor vehicles and domestic fires (Sridhar, 2013). Benzene and benzo(a)pyrene are pollutants that are associated with health problems ranging from respiratory irritation to cancer (MfE & Stats NZ, 2014). Benzo(a)pyrene (BaP) can irritate the eyes, nose, and throat, and is associated with lung cancer (MfE & Stats NZ, 2014). BaP in New Zealand is largely emitted from the combustion of fuels, such as wood and coal from home heating. Vehicle emissions and some industrial processes also emit BaP. Some industrial activities such as refineries, manufacturing and rubber producing emit benzene (MfE & Stats NZ, 2014).

h. Total suspended particulate (TSP) and associated lead (Pb) content

Lead (Pb) is a metal found naturally in the environment as well as in human-made products. Historically, the major source of lead emissions has been from fuels used by motor vehicles, specifically, leaded petrol (Sridhar, 2013). Pb can have adverse effects on the nervous system and can impair mental development in children and hearing (MfE & Stats NZ, 2014). Pb can be emitted from some industrial discharges, such as at metal smelters, houses, or other structures where lead-based paint is being or has been, removed without the proper safety precautions (MfE & Stats NZ, 2014).

2 Methods

2.1 Auckland air quality monitoring network

Continuous instrumental ambient air quality monitoring has been performed in the Auckland region for many decades and Auckland Council has data from 1964 to the present day. This dataset is the longest continuous air quality dataset in New Zealand. The current Auckland ambient air quality monitoring network comprises 10 fixed permanent sites.

The sites range in their scope of what they monitor and represent a variety of sources and exposures from suburban residential areas to peak traffic areas. Some sites are set up to monitor a single pollutant while others measure a suite of pollutants most on a continuous basis. Seven of the sites have co-located meteorological equipment and house the analysing equipment in air-conditioned sheds. In addition to the 10 permanent sites, are two mobile monitoring stations. These units are deployed on an ad-hoc basis across the region on an ‘as needs’ basis.

Continuous meteorological monitoring is undertaken at seven sites because information on local meteorology is essential for understanding pollutant sources, short-term events, chemical reactions, the trends in data, and why exceedances occur (Sridhar, 2013; Peterson and Giles 2014). Meteorological parameters measured include; ambient temperature (AT), wind speed (WS), wind direction (WD), and relative humidity (RH). The type of meteorological sensors and mast height for each site are provided in Table 2. The sites are owned by Auckland Council while data collection and equipment maintenance are contracted to the Air Quality Department of Watercare Services Limited. Source apportionment modelling that quantifies the contribution of sources to particulate matter is supported by GNS Science. Figure 1 presents a map of the current monitoring sites.

Over the years since the commencement of air monitoring, the nature of monitoring and overall objectives have evolved. This reflects international trends in monitoring, including increasing concern with smaller particles and hazardous air pollutants, improved instrumentation, and an improved understanding of air quality in Auckland. The main changes that have affected the monitoring network over the past 25 years include a shift to monitoring smaller particles, change in focus for gaseous pollutants, concern about photochemical smog, move to more frequent and continuous monitoring, changes in air quality guidelines and standards, and understanding sources of air pollution. Equipment and standard methods have changed and improved over the years, leading to the associated improvement in data quality and reliability (Peterson and Bronwen Harper 2006; Sridhar, 2013; Peterson and Giles, 2014) Table 2 provides characteristics of the current monitoring sites.

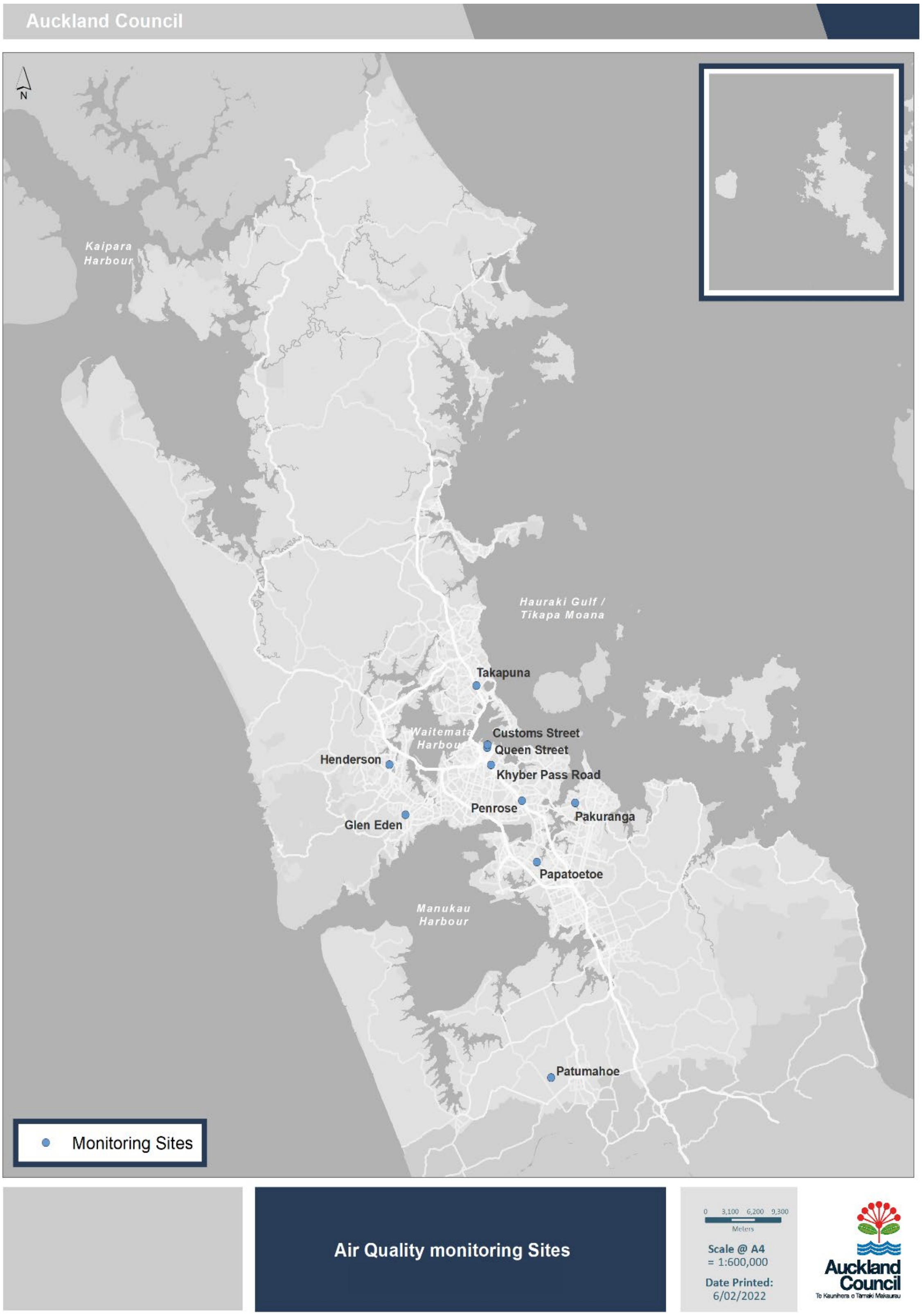

Figure 1. Auckland Council air quality monitoring sites.

Table 2. Monitoring sites pollutants, meteorological parameters measured.

Site	Established date	Pollutants monitored	Meteorological parameters measured on site[a]	Pollutant sensors used
Glen Eden[b]	2005	PM_{10}, $PM_{2.5}$ and NO_2,	WS, WD, AT, RH	NOx – API 200E Gas Analyser, PM_{10} – Thermo FH62C14 Beta Attenuation Monitor, $PM_{2.5}$ – MetOne ES642 Nephelometer (non-regulatory)
Pakuranga[b]	1998	PM_{10} and $PM_{2.5}$	WS, WD, AT, RH	PM_{10} – Thermo FH62C14 – Beta Attenuation Monitor $PM_{2.5}$ – MetOne ES642 Nephelometer (non-regulatory)
Patumahoe	1996	PM_{10}, $PM_{2.5}$, NO_2, and O_3	N/A	Ozone – Thermo 49i Gas Analyser NOx – API 200E Gas Analyser PM_{10} – Thermo FH62C14 Beta Attenuation Monitor $PM_{2.5}$ – Thermo 5014i Beta Attenuation Monitor
Khyber Pass Road	1995	PM_{10}, CO, NO_2, and VOCs	N/A	PM_{10} – Thermo FH62C14 Beta Attenuation Monitor CO – API 300E Gas Analyser NOx – API 200E Gas Analyser BTEX – Passive Samplers, Monthly sampling (Mountain Road West and Crowhurst St)
Papatoetoe[b]	2017	PM_{10}	WS, WD, AT, RH	PM_{10} – Thermo FH62C14 Beta Attenuation Monitor
Penrose[b]	2000	PM_{10}, $PM_{2.5}$, NO_2, SO_2, TSP/Lead, and VOCs	WS, WD, AT, RH	NOx – API 200E Gas Analyser, SO2 – API T100 Gas Analyser PM_{10} – Thermo FH62C14 Beta Attenuation Monitor $PM_{2.5}$ – Thermo 5014i Beta Attenuation Monitor TSP/Lead – Department of Health Medium Volume Sampler, VOC – Passive Sampler,
Takapuna[c]	1995	PM_{10}, $PM_{2.5}$, and NO_2	WS, WD, AT, RH	NOx – API T200 Gas Analyser PM_{10} – Thermo FH62C14 Beta Attenuation Monitor, $PM_{2.5}$ – Teledyne T640 PM Mass Monitor,
Queen Street[b]	1998	PM_{10}, $PM_{2.5}$, and NO_2	WS, WD, AT, RH	PM_{10} – T640 Teledyne PM Mass Monitor $PM_{2.5}$ – T640 Teledyne PM Mass Monitor NOx – API 200E Gas Analyser
Henderson[b]	1993	PM_{10}, black carbon, and NO_2	WS, WD, AT, RH	NOx – API 200E Gas Analyser, PM_{10} – Thermo FH62C14 Beta Attenuation Monitor, Black carbon – Magee AE33 Aethalometer
Customs Street	2020	$PM_{2.5}$, black carbon, NO_2, and SO_2	N/A	NOx – API T200 Gas Analyser SO_2 – API T100 Gas Analyser $PM_{2.5}$ – MetOne ES642 Nephelometer (non-regulatory) Black Carbon – MetOne 1060 Aethalometer
NB: N/A implies not applicable		WS : wind speed, WD : wind direction, AT : ambient temperature, RH : relative humidity		

[a] All meteorology parameters are measured in real time with Vaisala Weather Transmitter WXT520

[b] Meteorological mast height = 6m [c] Meteorological mast height = 10m

2.2 Data collection and analysis

Ten minutes average concentrations of air contaminants and meteorological variables are continuously measured by the sensors and instruments deployed at the 10 monitoring sites. Each instrument is connected to a data logger which transmits raw data to the council's Hydrotel cloud database system. The Air Quality Unit at Watercare Services Limited manages the network on behalf of the council and have in house quality control procedures for data collection and management in accordance with the Ministry for the Environment's *Good Practice Guide for Air Quality Monitoring and Data Management 2009* (Ministry for the Environment, 2009). Daily contaminants raw data are screened for exceedances of the national standards, invalid values (such as invalid concentrations logged due to instrument error), and then subsequently validated. Watercare Services Limited notifies the council when an exceedance of a standard occurs. Data stored in Hydrotel is treated as raw data until the data is validated and quality assured.

Data from the BTEX passive monitoring and TSP gravimetry and lead content analysis are received periodically on MS Excel spreadsheets from Watercare Services Ltd.

In this report, most graphs were plotted using MS Excel and the Openair R package (Carslaw & Ropkins 2012). Inferential statistical analysis was conducted using IBM SPSS version 20. Wind roses were generated using Kisters Aquisnet REP software. The parametric independent-samples t-test (or independent t-test) and general linear model (GLM) in SPSS were used to compare mean differences between sites and years (2021 and 2022). The seasons are defined as follows – Summer: December, January, and February, Autumn: March, April, and May, Winter: June, July, and August, Spring: September, October, and November. The data coverage for 2021 and 2022 is given by Appendix M.

The New Zealand Transport Agency (NZTA), in partnership with Auckland Council, implements a monitoring programme to track NO_2 concentrations in the Auckland region. This programme, which was established in 2007 as part of a national NO_2 monitoring initiative, involves the use of diffusion tube passive samplers at 35 monitoring sites. The programme's methodology and objectives are described in detail by the NZTA (2022) and Longley and Kachhara (2021). This report presents a summary of the NO_2 data collected by the monitoring network in 2022 and 2021. The data is crucial for evaluating the impact of transportation-related emissions on air quality in the Auckland region, and for informing policies and strategies aimed at reducing NO_2 concentrations.

3 Results

3.1 Weather conditions/meteorological differences

Auckland region experiences a subtropical climate. It has a mild climate with few extreme temperatures. Although this is partly due to the relatively low latitudes and elevations in the region, the extensive surrounding ocean also has a modifying effect on its temperatures. Auckland region experiences mean annual temperatures between 14 ^{O}C and 16 ^{O}C, with eastern areas generally warmer than western areas (Chappell, 2013; Boamponsem et al., 2017).

Weather conditions can influence temporal changes in air pollution levels. Air contaminants concentrations can vary over time according to emission source, meteorology, and human behaviour. Some contaminants (e.g., PM_{10} and $PM_{2.5}$) can rise above or near normal levels, possibly due to irregular wet and windy weather conditions which increase the contribution of non-traffic sources (e.g., dust or sea salt) (Xie, 2020). Particulate matter generated with different size ranges and chemical composition can in turn undergo atmospheric reactions and be affected by location specific meteorological factors including ambient temperature, relative humidity, and wind speed (Baldwin et al., 2015; Davy and Trompetter 2021).

Consequently, seasonal differences affect temporal variations of air contaminants in the Auckland region. Meteorology contributes significantly to increasing air pollution levels during winter. Cold winter nights under high atmospheric pressure can create temperature inversions close to the ground; these inversions greatly reduce the dispersal of pollutants (Ancelet et al., 2014; MfE, 2014; Talbot et al., 2017).

a. Ambient temperature

The overall average temperature of Auckland in 2022 significantly increased by 3.7% compared to 2021 (from 16.2 ± 4.2 ^{O}C to 16.8 ± 3.3 ^{O}C) ($p<0.05$). As shown by Figure 2, the pattern of temperature variations in 2022 was similar to the previous year. Except for Pakuranga, all the average annual ambient temperatures across the seven monitored sites significantly increased compared to 2021 ($p<0.05$). Appendix C presents the temperature descriptive statistics for each site.

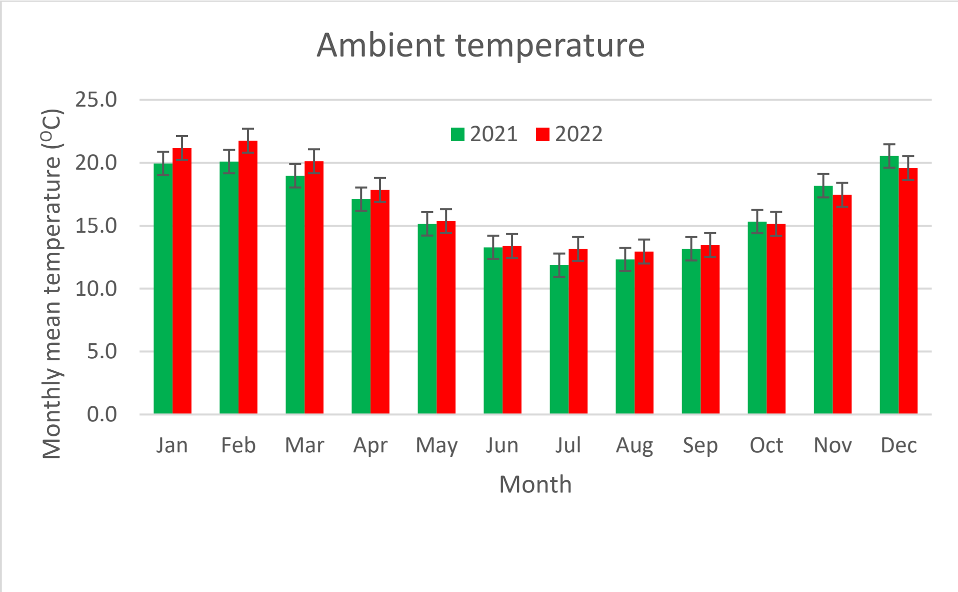

Figure 2. Monthly average ambient temperature measured at seven monitoring sites – 2022 compared to 2021. Error bars represent the standard errors of the mean.

b. Relative humidity

The overall average relative humidity of Auckland in 2022 increased by 2.3% compared to 2021 (from 69.4 ± 13.0% to 71.0 ± 5.0%) ($P>0.05$). The pattern of ambient relative humidity variations in 2022 was similar to the previous year (See Figure 3). All the monitoring sites but Papatoetoe recorded a marginal increase which was not statistically significant. Appendix C presents the relative humidity descriptive statistics for each site.

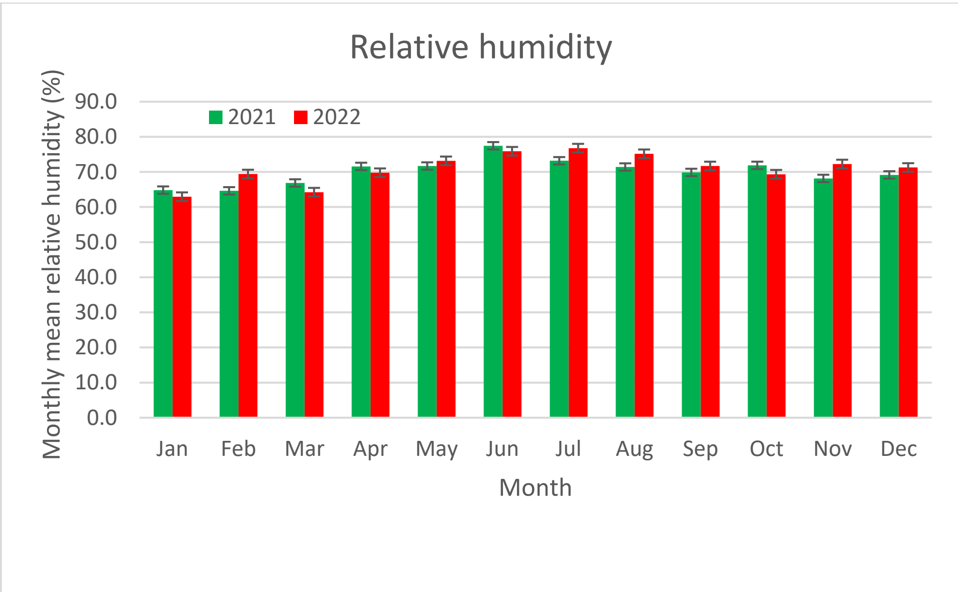

Figure 3. Monthly average relative humidity measured at six monitoring sites – 2022 compared to 2021. Error bars represent the standard errors of the mean.

3.1.1 Wind speed and direction

Wind roses are graphical charts used to represent the wind speed and direction at a monitoring site in a circular format. The length of each "spoke" around the circle indicates the amount of time that the wind blows from a specific direction, while the colours along the spokes show different categories of wind speed (see Figures 4 to 7). Wind roses provide a convenient way of summarizing meteorological data and are especially useful for identifying patterns of wind speed and direction over time (Carslaw and Ropkins, 2012). By examining a wind rose, we can determine the predominant wind direction and speed at a monitoring site for a specific period, which can provide valuable information for a range of applications.

The wind patterns at most monitoring sites in 2022 were similar to those of the previous year, with the exception of Queen Street and Papatoetoe. Wind rose diagrams showing the general frequency distribution of the wind speed and direction during 2022 and 2021 for seven sites are provided in figures 4 to 7.

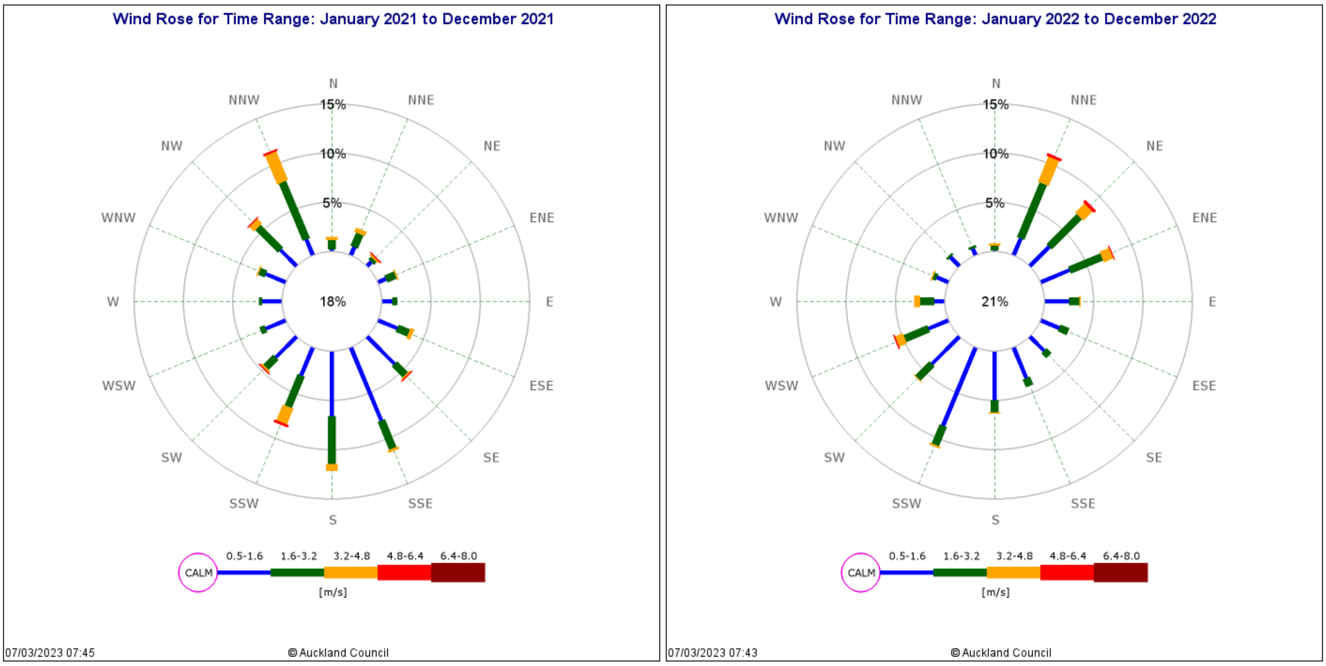

Figure 4. Wind roses for Papatoetoe.

Wind speeds are split into the intervals shown by the scale in each panel. The grey circles show the per cent frequencies. The plot on the left is for 2021 data while the right plot is for the 2022 data.

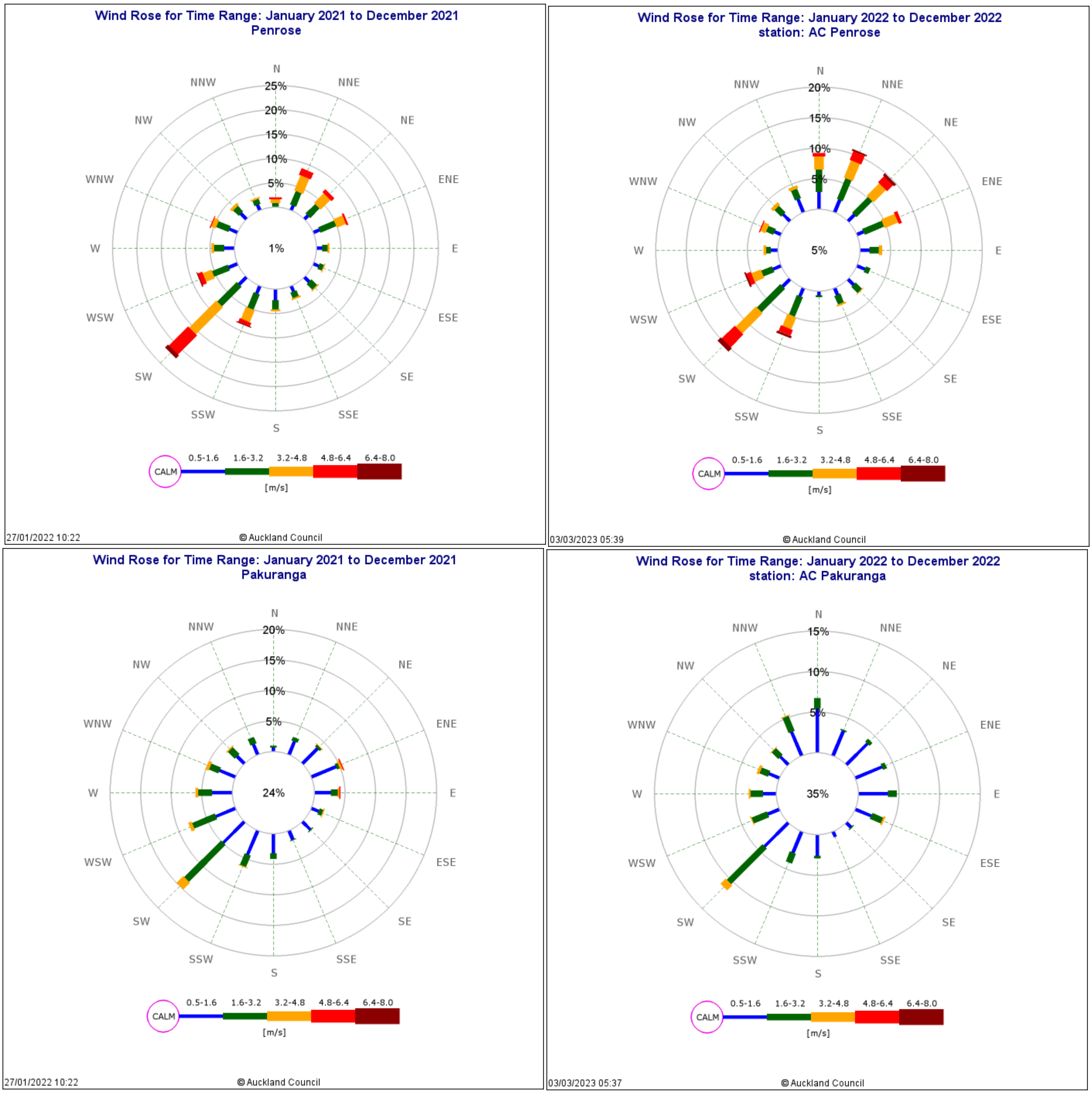

Figure 5. Wind roses for Penrose and Pakuranga.

Wind speeds are split into the intervals shown by the scale in each panel. The grey circles show the per cent frequencies. The plots on the left are for 2021 data while the right plots are for the 2022 data.

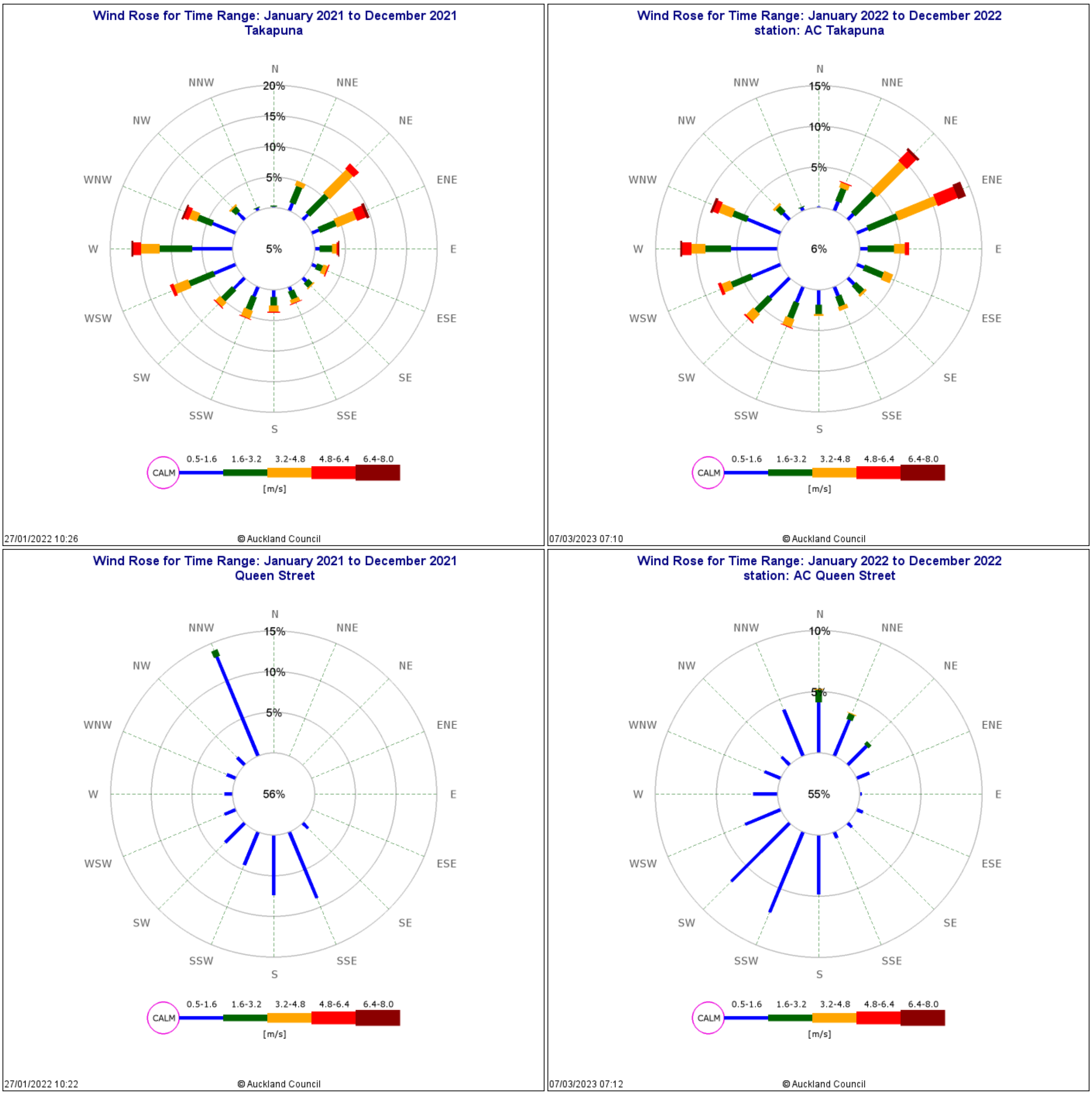

Figure 6. Wind roses for Takapuna and Queen Street.

Wind speeds are split into the intervals shown by the scale in each panel. The grey circles show the per cent frequencies. The plots on the left are for 2021 data while the right plots are for the 2022 data.

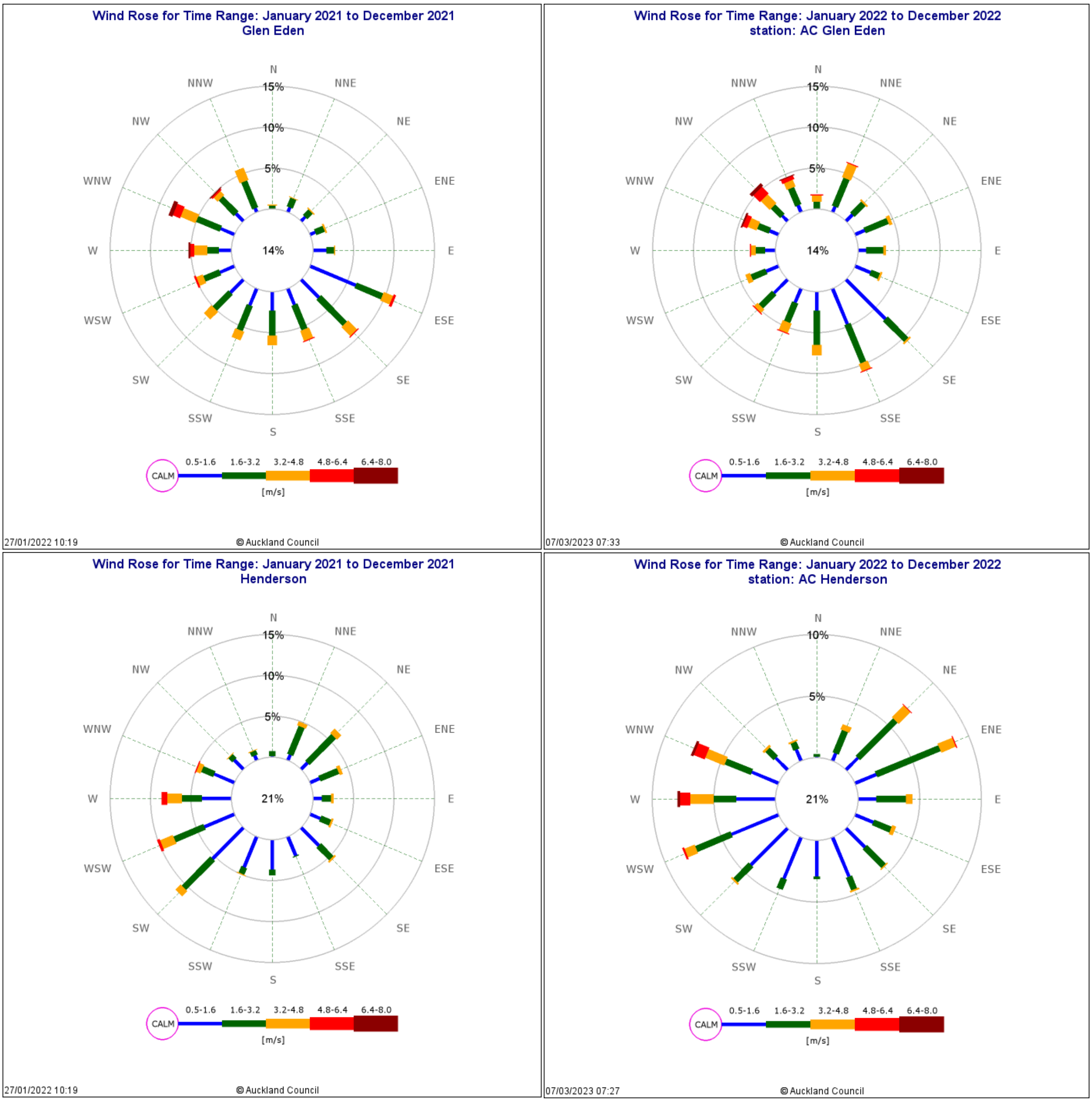

Figure 7. Wind roses for Glen Eden and Henderson.

Wind speeds are split into the intervals shown by the scale in each panel. The grey circles show the per cent frequencies. The plots on the left are for 2021 data while the right plots are for the 2022 data.

3.2 Auckland's air quality data – 2022

Auckland is not regarded as a polluted airshed under the National Environmental Standard for air quality (NESAQ). The region's geographic location provides a reliable airflow that aids to eliminate air pollutants. Despite this advantage, Auckland still experiences air pollution in particular locations and at certain times of the year. The recent state of Auckland's environment report indicated that overall air quality is good and improving (Auckland Council Research and Evaluation Unit, 2021).

Air pollutant concentrations in Auckland sometimes exceed the NESAQ or Auckland target limits due to exceptional events. For example, in October 2019, the smoke generated by the New Zealand International Convention Centre building site fire caused PM_{10} and $PM_{2.5}$ concentrations at the Queen Street monitoring site to surpass both the NESAQ and the Auckland targets. Additionally, in December 2019, the Australian dust storms and bushfires resulted in a PM_{10} exceedance detected at three locations (Papatoetoe, Penrose, and Patumahoe). For a list of air pollution sources specific to Auckland, please refer to Appendix B. Appendix N provides monthly averages for 2023 and the past two to five years of pollutant concentrations (when data is available).

3.2.1 Particulate matter (PM_{10})

The annual average PM_{10} concentration of Auckland in 2022 increased by 2.5% compared to 2021 (from 12.74 ± 8.6 µg/m^3 to 13.06 ± 8.8 µg/m^3) ($p<0.05$). However, this increase did not exceed the 2021 WHO air quality guideline of 15 µg/m^3. It is important to note that on the individual sites level, Queen Street exceeded the WHO guideline by 28.7%. The rural site, Patumahoe monitoring site recorded the lowest annual PM_{10} mean concentration of 11.0 µg/m^3, while Queen Street recorded the highest level of 19.3 µg/m^3. Figure 8 presents the variation of PM_{10} concentration across the nine monitoring sites.

Figure 8. PM_{10} annual mean concentrations at nine sites – arranged in increasing order from left to right.

Error bars represent the standard errors of the mean. Map b (right) shows sites and their 2022 annual mean PM_{10} concentration in brackets.

The annual PM_{10} concentration recorded at Papatoetoe site was statistically significantly ($p<0.05$) lower than the previous year (See Appendix D). Conversely, the annual PM_{10} concentrations measured at Queen Street, Pakuranga, Khyber Pass Road, and Takapuna sites were significantly higher than the previous year ($p<0.05$). The marginal decrease in the annual PM_{10} concentration at Patumahoe, Glen Eden and Henderson sites, were not statistically significant ($p>0.05$).

As indicated on Table 1, NESAQ requires an ambient air quality concentration limit of 50 μg/m³ (24-hour average) for PM_{10} to be met for all but one 24-hour period each year. In 2022, the Auckland Urban Airsheds breached this standard. The PM_{10} exceedance event occurred at the Queen Street air quality monitoring site where two exceedances of PM_{10} NESAQ were recorded on 18th and 19th August 2022. All other Auckland air quality monitoring sites where PM_{10} is monitored registered similar increases in PM_{10} concentrations but did not exceed the NESAQ. Further laboratory compositional analysis of particulate matter samples collected over the period by GNS Science, analyses of meteorological factors and air mass-transport mechanisms confirmed that the PM_{10} exceedances on 18 and 19 August 2022 at the Queen Street site were primarily the result of a marine aerosol (sea salt) natural-source event. The average source contributions estimated by receptor modelling indicate that marine aerosol (sea salt) normally contributes 41 % of total PM_{10} concentrations recorded at Queen Street site. The GNS Science report on the compositional analysis of filter-based samples of particulate matter collected at the Queen Street, Takapuna and Henderson sites immediately before, during and after the exceedance event indicated that the particulate matter was largely composed (> 66%) of sea salt. Consequently, Auckland Council has submitted an exemption application under National Environmental Standards for Air Quality – regulation 16A Exceptional Circumstances.

A box and whisker diagram depicting the hourly mean concentrations across the sites is given by Figure 9.

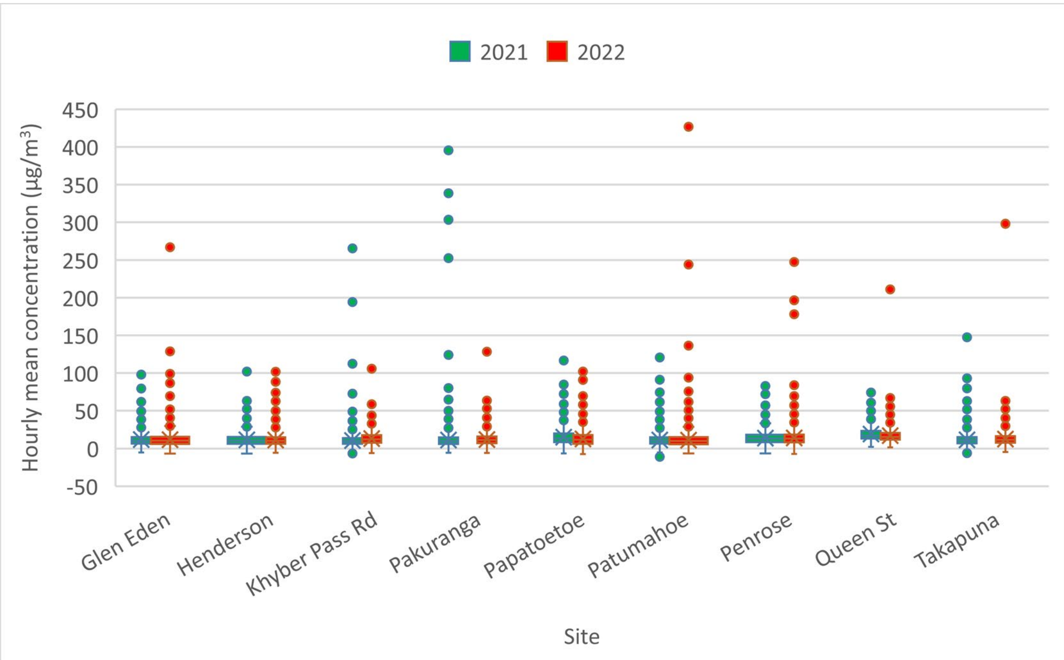

Figure 9. Boxplot of PM_{10} hourly mean concentration measured at nine sites.

Boxes represent 25th (bottom of the box) and 75th (top of box) percentile, central line through the box is the median, bars outside the box(whiskers) represent the 1.5× interquartile range, × markers are the means, and circles are outliers.

Similar to findings by Talbot et al. (2017) and previous report, daily PM_{10} emissions were higher in winter probably due to the use of solid fuels for home heating (See Figure 10). In summer, transport is the main anthropogenic source of daily PM_{10} emissions. Afternoon concentrations are generally lower than those of the evening due to increased mixing in the atmosphere (Figure 11). As the ground cools in the evening, so the atmosphere becomes more stable, and concentrations increase with less dispersion. Weekday concentrations are higher than weekends due to increased traffic (Talbot et al., 2017).

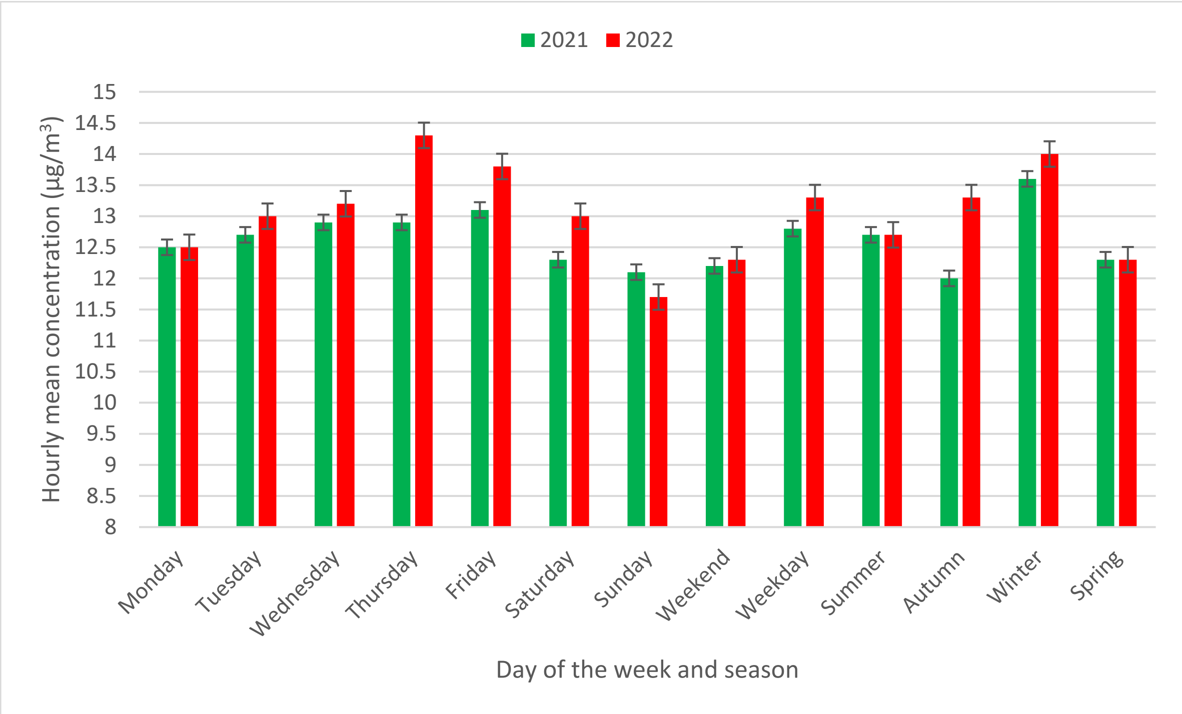

Figure 10. Temporal variations in Auckland PM_{10} annual mean concentrations. Error bars represent the standard errors of the mean.

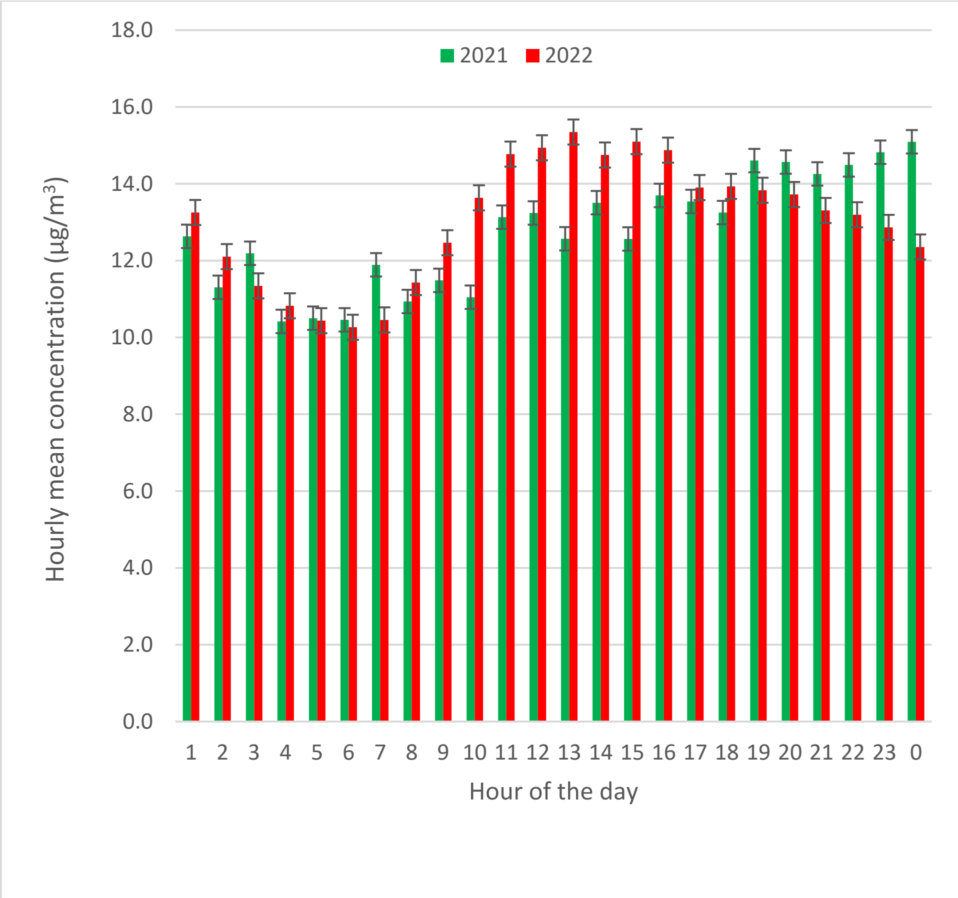

Figure 11. Time variations in Auckland PM_{10} hourly mean concentrations. Time variations in Auckland PM_{10} hourly mean concentrations. Error bars represent the standard errors of the mean.

As indicated in section 3.1, PM_{10} concentrations may vary from site to site depending on meteorological conditions and other factors. PM_{10} pollution rose charts are useful in showing which wind directions dominate the overall concentrations as well as providing information on the different concentration levels. Figures 12 and 13 indicate that different dominant wind speeds and directions occur at each monitoring site. For example, Figure 12 shows that in 2022, the highest PM_{10} concentrations arrive at the Penrose and Queen Street sites mostly from the south-west sector. It is important to note that apart from Queen Street and Papatoetoe sites, the patterns of PM_{10} pollution roses at all the sites in 2021 and 2022 were identical.

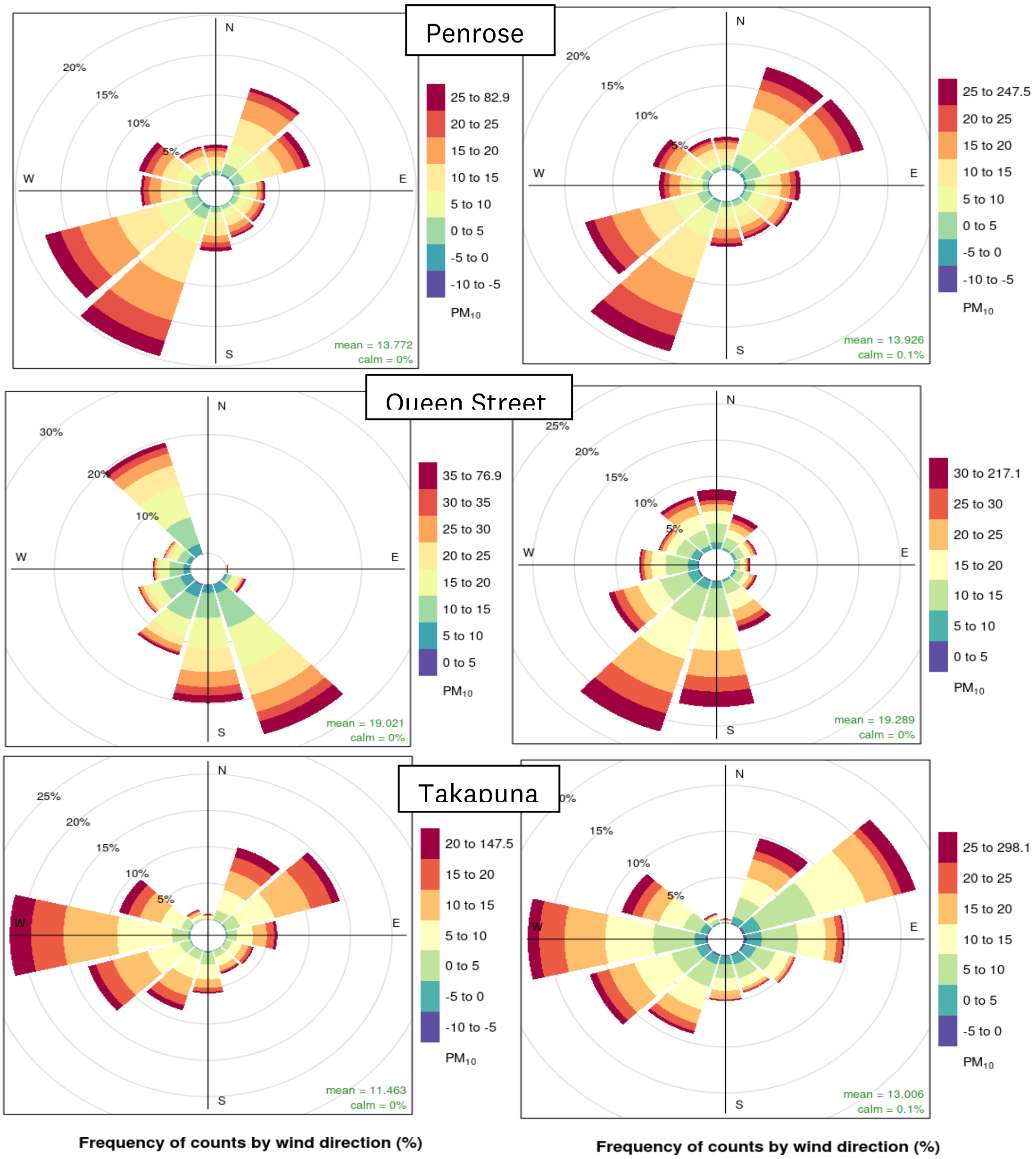

Figure 12. PM_{10} pollution roses for Penrose, Queen Street and Takapuna

Higher PM_{10} concentrations are associated with predominant prevailing wind direction as follows: Penrose: south-west, Queen Street: south-west (2022), and Takapuna: south-westerly. The plots on the left are for 2021 data while the right plots are for 2022 data.

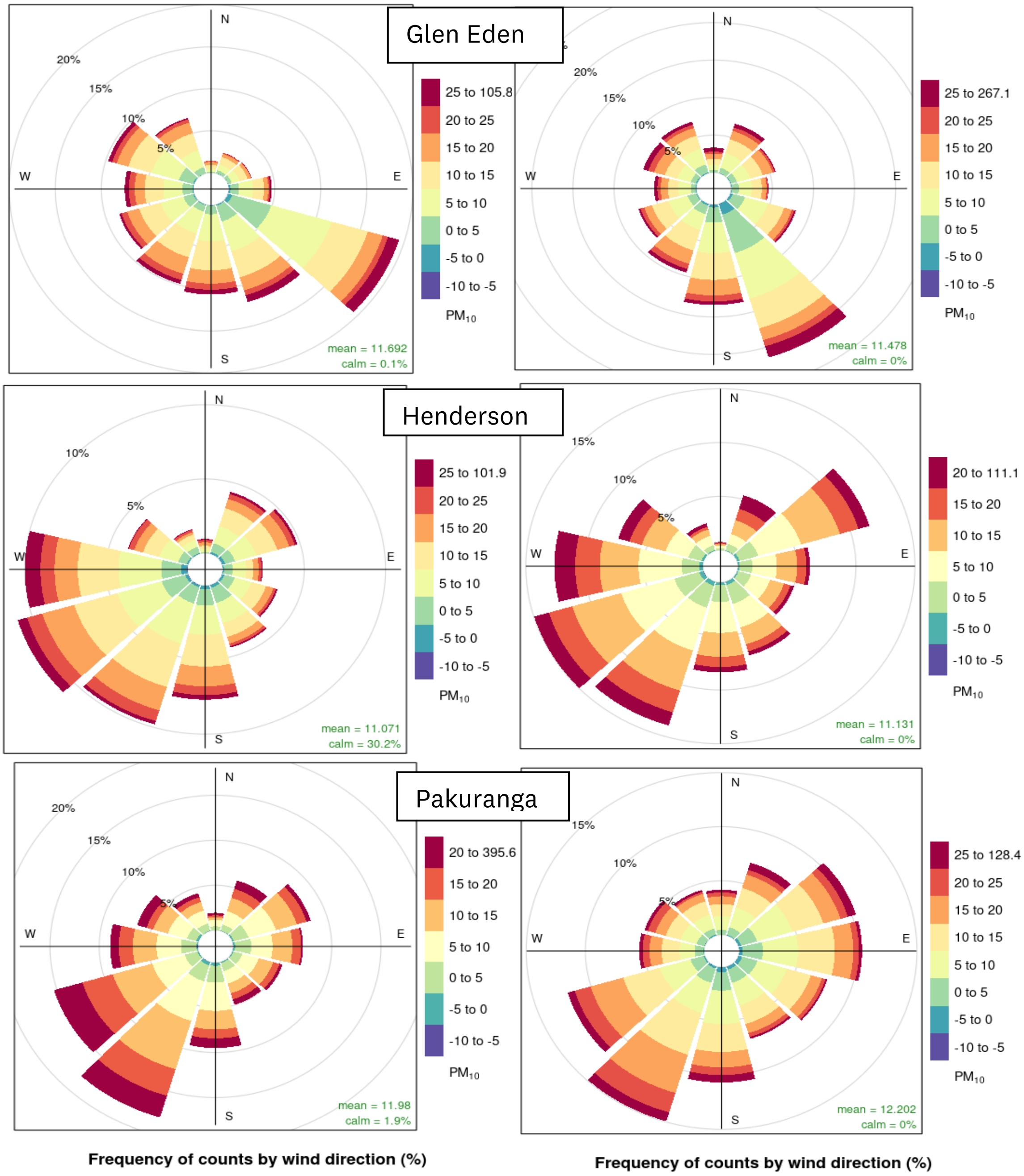

Figure 13. PM_{10} pollution roses for Glen Eden, Henderson, and Pakuranga sites.

Higher PM_{10} concentrations are associated with predominant prevailing wind direction as follows: Glen Eden: south-east, Henderson: south-west, and Pakuranga: south-west. The plots on the left are for 2021 data while the right plots are for 2022 data.

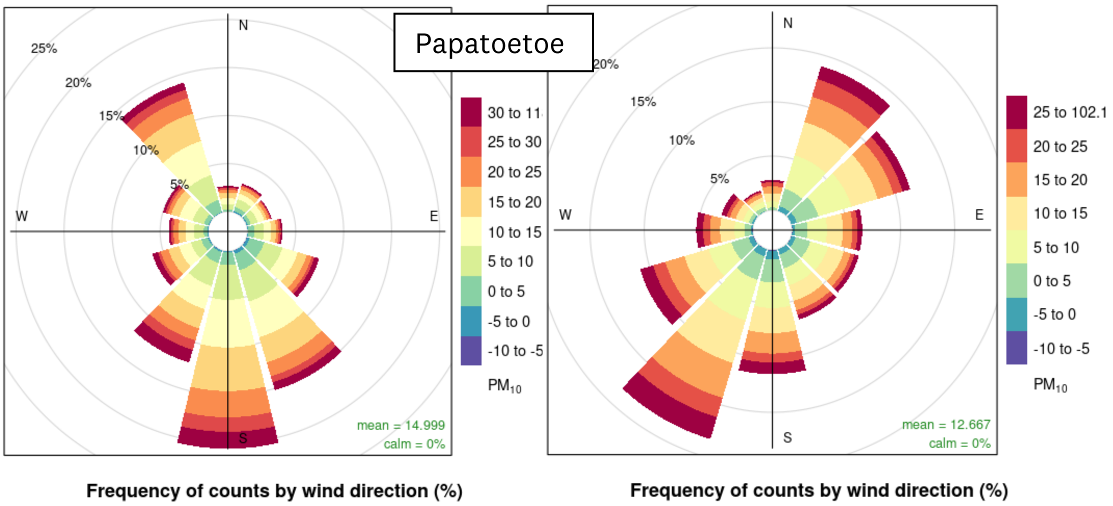

Figure 14. PM_{10} pollution roses for Papatoetoe site.

Higher PM_{10} concentrations are associated with predominant prevailing wind direction as follows: Papatoetoe: south and south-west for 2021 and 2022 respectively. The plot on the left is for 2021 data while the right plot is for 2022 data.

Source apportionment studies have found that the key contributing influences on PM_{10} concentrations in Auckland are (in decreasing degrees of importance): marine aerosol, motor vehicle exhaust emissions, residential wood burning, and crustal matter. Emissions from transport and home heating are the main anthropogenic sources of PM_{10} in Auckland (Davy et al., 2017).

Auckland regional emissions of PM_{10} from wood burning were estimated at approximately 12 tonnes per winter day or approximately 1200 tonnes per year in 2016 (Metcalfe et al., 2018). It was estimated that on-road motor vehicles contribute 647 tonnes/year of PM_{10}. Total regional emissions of PM_{10} from the transport sector in 2016 were estimated as 1991 tonnes/year (51% unsealed road dust, 32% motor vehicles, 9% offroad vehicles) (Sridhar and Metcalfe, 2019). Emissions from motor vehicles represent 32% of total regional PM_{10} emissions from transport in the Auckland region. Within the Auckland urban airshed, emissions from motor vehicles account for 71% of total PM_{10} anthropogenic emissions. (Sridhar and Metcalfe, 2019; Xie et al., 2019).

Crustal matter is a minor contributor to PM_{10} concentration at all sites and is largely dependent on the nature of local dust-generating activities (Davy et al., 2017). At some sites, there is a minor contribution to PM_{10} concentrations from local industrial activities (e.g., Penrose). Industrial point sources within Auckland's urban area are estimated to have discharged 47.6 tonnes of PM_{10} in 2016 (Crimmins, 2018). Emissions from ships are impacting the PM_{10} levels measured at Auckland city centre sites (Davy et al., 2017).

In Auckland, natural sources (e.g., sea spray) significantly contribute to PM_{10} concentration (approximately 50%). This natural background concentration is challenging to manage (Davy, 2021; Talbot and Crimmins, 2020).

3.2.2 Particulate matter ($PM_{2.5}$)

The average $PM_{2.5}$ concentration of Auckland in 2022 increased by 2.8% compared to 2021 (from 6.04 ± 5.11 μg/m^3 to 6.21 ± 4.54 μg/m^3) ($p<0.05$). This increase was over the 2021 WHO air quality guideline of 5 μg/m^3. Penrose monitoring site had the lowest annual $PM_{2.5}$ mean concentration of 5.0 μg/m^3, while Queen Street recorded the highest mean of 8.1 μg/m^3. Patumahoe and Queen Street monitoring sites registered annual mean concentrations higher than the previous year. Penrose and Takapuna monitoring sites recorded annual mean concentrations lower than the previous year. All the differences in annual mean concentrations were statistically significant ($p<0.05$) (See Appendix D). Figure 15 presents the variation of $PM_{2.5}$ annual concentration for four monitoring sites.

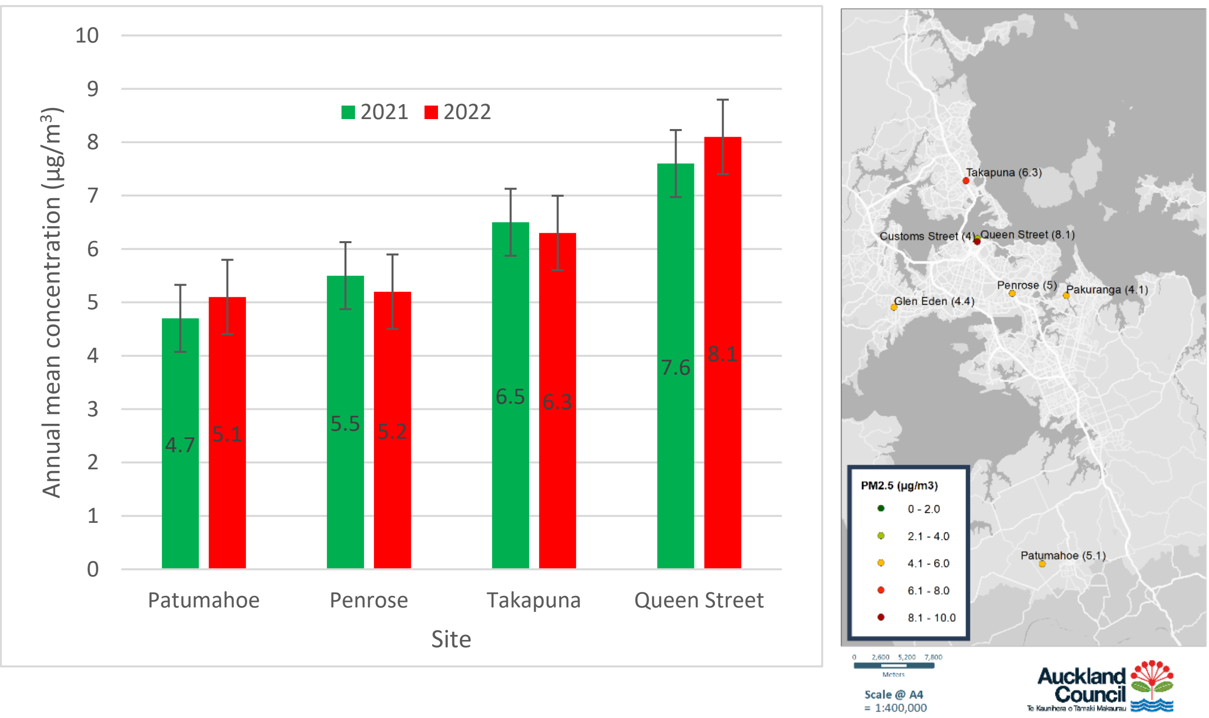

Figure 15. $PM_{2.5}$ annual mean concentrations at four sites – arranged in increasing order from left to right.

Error bars represent the standard errors of the mean. Map b (right) shows sites and their annual mean $PM_{2.5}$ concentration in brackets. Please note that further data analysis was not performed on Glen Eden, Pakuranga, and Customs Street due to less than 75% data coverage in 2021 or 2022 ($PM_{2.5}$ instrument failure occurred between August 2021 and March 2022)

As with PM_{10}, there were occasional hourly spikes in $PM_{2.5}$ mean concentrations in all the sites (See Appendix E). On 18th and 19th August 2022, a 24-hour $PM_{2.5}$ mean concentrations of 23.3 and 22.3 µg/m³ were recorded at Queen Street. This did not exceed the Auckland Unitary Plan target of 25 µg/m³. This spike is due to marine aerosol as revealed by the further laboratory analysis by GNS Science. The annual $PM_{2.5}$ average concentrations for Queen Street, Takapuna, and Patumahoe sites were higher than the more stringent WHO air quality guideline of 5 µg/m³. A box and whisker diagram showing the distribution of hourly mean concentrations across the sites is presented in Figure 14.

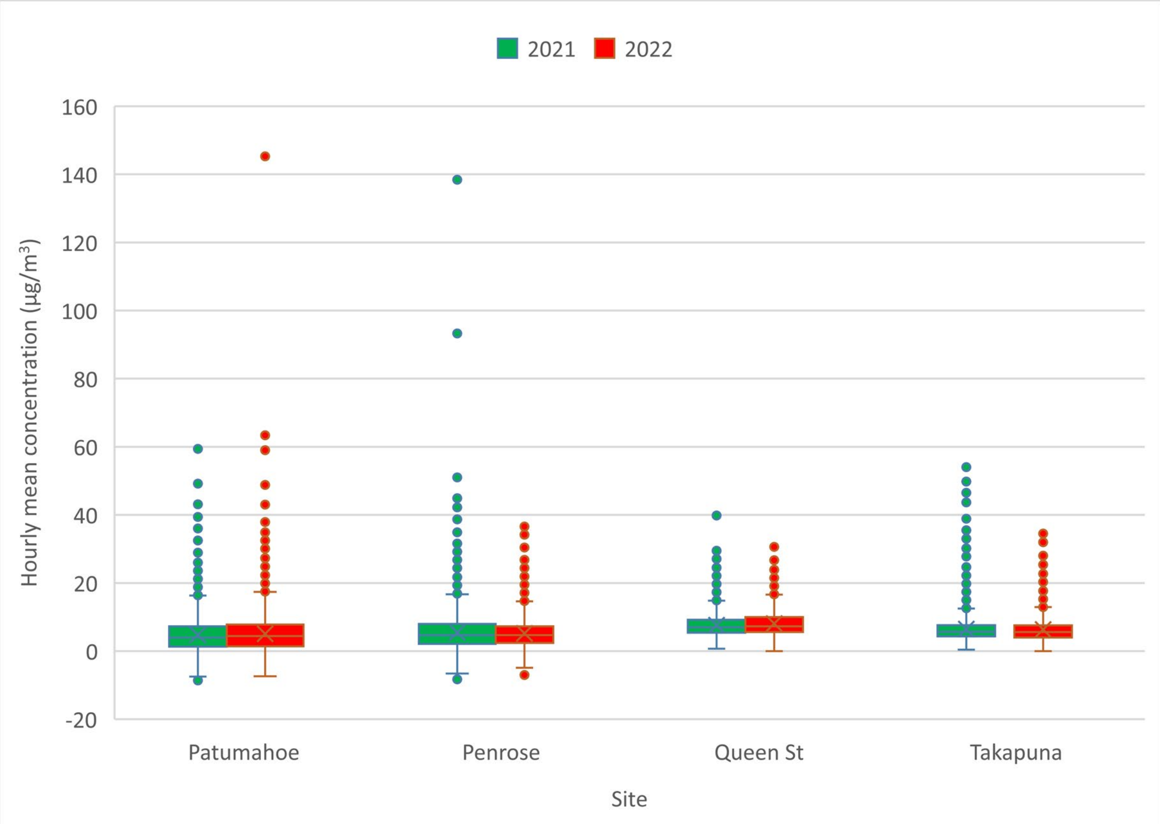

Figure 16. Boxplot of $PM_{2.5}$ hourly mean concentration measured at four sites.

Boxes represent 25th (bottom of the box) and 75th (top of box) percentile, central line through the box is the median, bars outside the box (whiskers) represent the 1.5× interquartile range, × markers are the means, and circles are outliers.

In the same manner as PM_{10}, $PM_{2.5}$ concentrations were higher in winter most likely due to domestic fires. Overall, concentrations peak in the afternoon and night hours (See Figure 18). Overall, between the hours 12 noon and 6 pm, lower average $PM_{2.5}$ values were recorded in 2022 than in 2021. This is most likely due to decreased traffic volumes in 2022 compared to 2021. Concentrations of $PM_{2.5}$ tend to increase later in the week with the highest concentrations typically occurring on Wednesday to Friday (Figure 17). Weekday concentrations are slightly higher than weekends most probably due to increased human activities.

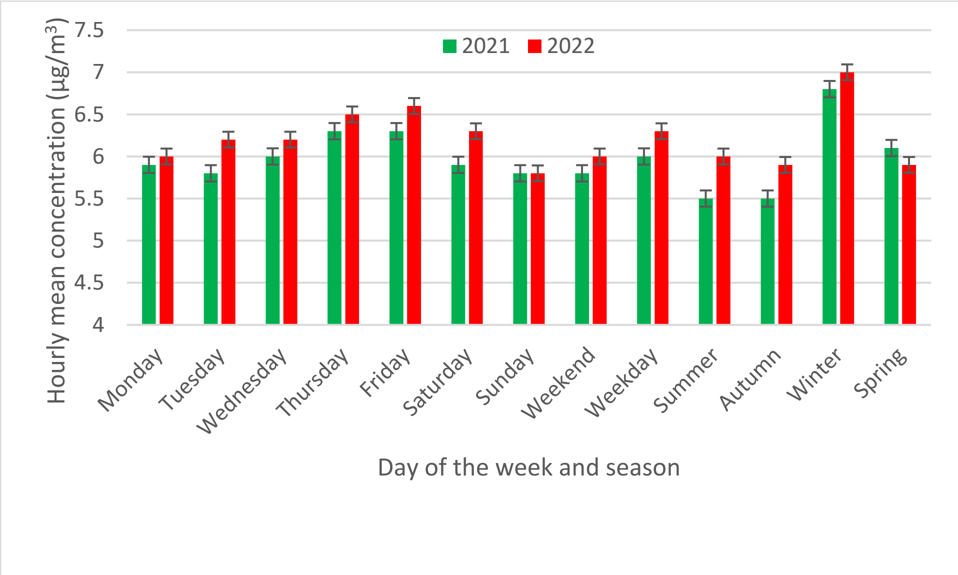

Figure 17. Temporal variations in Auckland $PM_{2.5}$ annual mean concentrations. Error bars represent the standard errors of the mean.

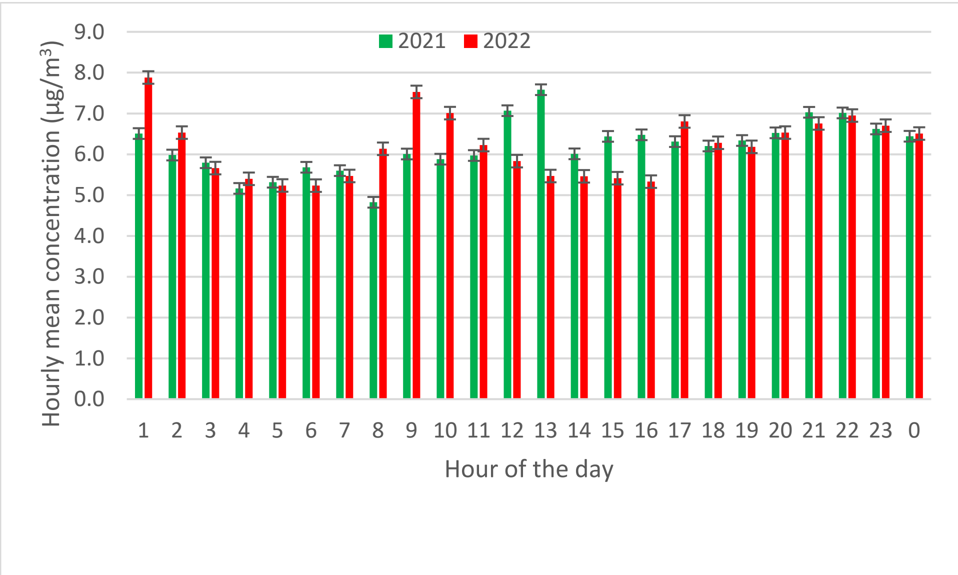

Figure 18. Time variations in Auckland $PM_{2.5}$ hourly mean concentrations. Error bars represent the standard errors of the mean.

Unlike PM_{10}, anthropogenic emissions dominate $PM_{2.5}$ concentrations (approximately 70%) (Davy, 2021). Research by Davy and Trompetter (2021) shows that tailpipe particulate matter emissions from fuel combustion are primarily less than 2.5 µm, with most in the ultra-fine size range (<0.1 µm). They also found that the contribution of diesel-fuelled vehicles to $PM_{2.5}$ at the Takapuna site was 90% of the total (diesel + petrol) motor vehicle burden (Davy and Trompetter, 2021). Whereas emissions of some pollutants have been reduced due to improved engine technology and fuel quality, many improvements have been offset by higher traffic volumes, more distance travelled, and intensification along transport corridors. In addition, vehicles are getting heavier, with larger engines (MfE and Stats NZ, 2021).

Similar to PM_{10}, source attribution studies have identified five common source contributors to $PM_{2.5}$ in Auckland. These are biomass burning, motor vehicles, secondary sulphate, marine aerosol (sea spray), and crustal matter. Biomass burning and motor vehicle emissions are the main anthropogenic sources of $PM_{2.5}$ across all sites in Auckland (Davy et al., 2017; Talbot et al., 2017). About 45% of $PM_{2.5}$ comes from wood burning used for home heating (Xie et al., 2019). For sites near harbours such as Queen Street and Takapuna, marine aerosol is a significant contributor to $PM_{2.5}$ (Davy et al., 2017; Talbot and Crimmins, 2020).

Auckland's regional emissions of $PM_{2.5}$ are estimated at approximately 12 tonnes per winter day or approximately 1220 tonnes per year (Metcalfe et al., 2018). Overall, it was estimated that 275 tonnes of $PM_{2.5}$ were emitted from stacks and other industrial point sources in 2016 (Crimmins, 2018).

$PM_{2.5}$ pollution rose plots show that the predominant wind direction where the $PM_{2.5}$ contaminants are originating from are similar to the previous year, except for Queen Street. Figure 19 shows the $PM_{2.5}$ pollution roses for Queen Street, Penrose and Takapuna where wind speed and direction are monitored.

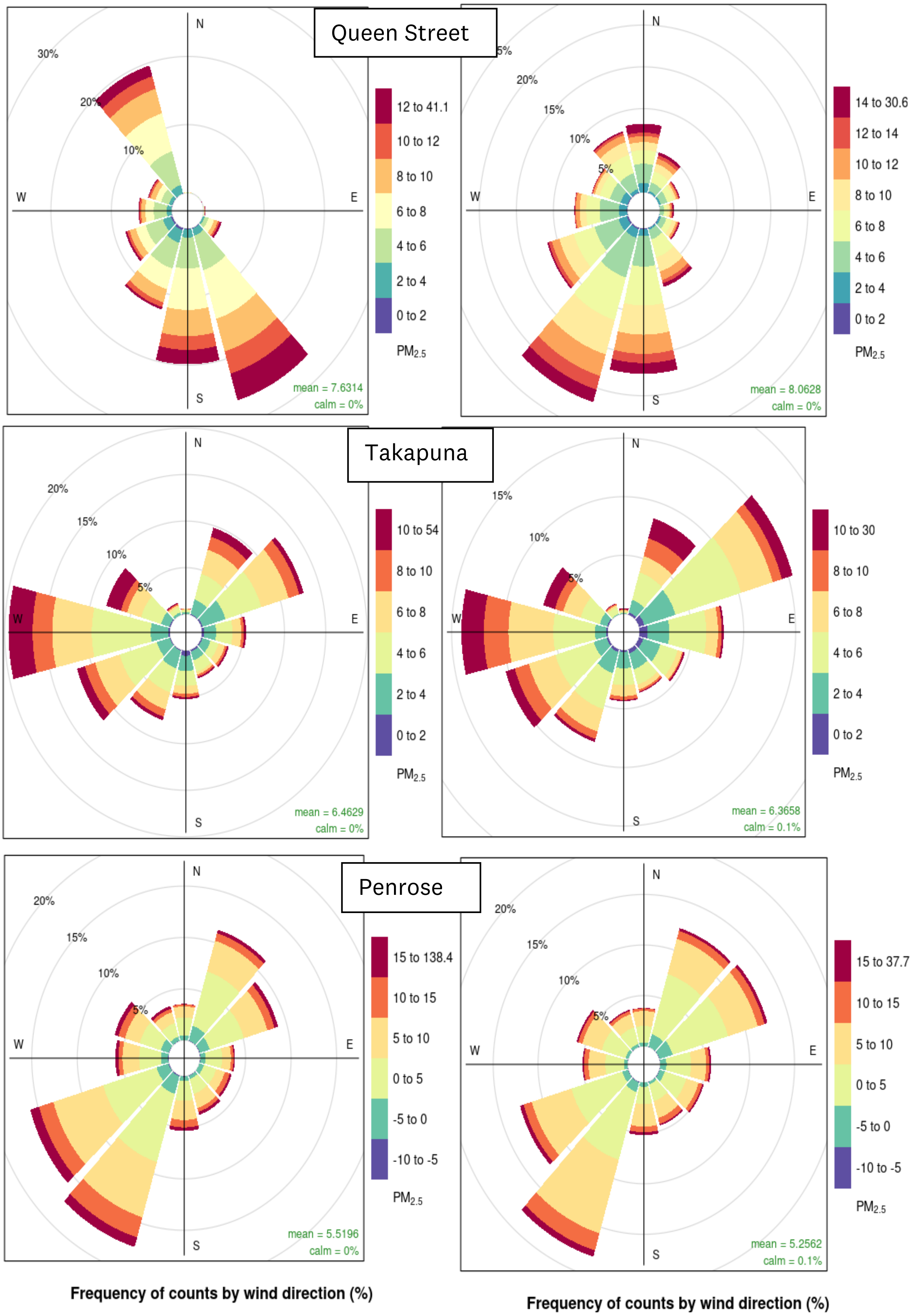

Figure 19. $PM_{2.5}$ pollution roses for Queen Street, Takapuna, and Penrose sites.

Higher $PM_{2.5}$ concentrations are associated with predominant prevailing wind direction as follows: Queen Street: south-west (2022), Takapuna: west and north-east, and Penrose: south-west. The plots on the left are for 2021 data while the right plots are for the 2022 data.

3.2.3 Nitrogen dioxide (NO_2)

The mean annual NO_2 concentration for 2022 marginally decreased by 0.2% (from 15.47 ± 17.5 µg/m^3 to 15.44 ± 17.6 µg/m^3) compared to 2021 ($p>0.05$). However, Auckland's overall annual average NO_2 concentration exceeded the 2021 WHO air quality guideline of 10 µg/m^3. As in the previous year, the Patumahoe monitoring site recorded the lowest annual NO_2 mean concentration of 4.6 µg/m^3, while Customs Street registered the highest of 30.0 µg/m^3. Figure 20 presents the variation of NO_2 concentration across the monitoring sites.

The annual NO_2 mean concentrations recorded at Queen Street, Customs Street, and Khyber Pass Road sites were statistically significantly ($p<0.05$) lower than the previous year (See Appendix D). The increase in the annual NO_2 mean concentration at Patumahoe, Penrose, Henderson, Glen Eden, and Takapuna were statistically significant ($p<0.05$). As expected, the highest NO_2 concentrations were measured at the city centre sites, although the concentrations were lower than the previous year. Auckland transport traffic volume data, collected between 15-21 August 2022, shows that 24-hour traffic volume at the city centre monitored intersections are between 70 % to 80 % relative to normal (pre-covid levels).

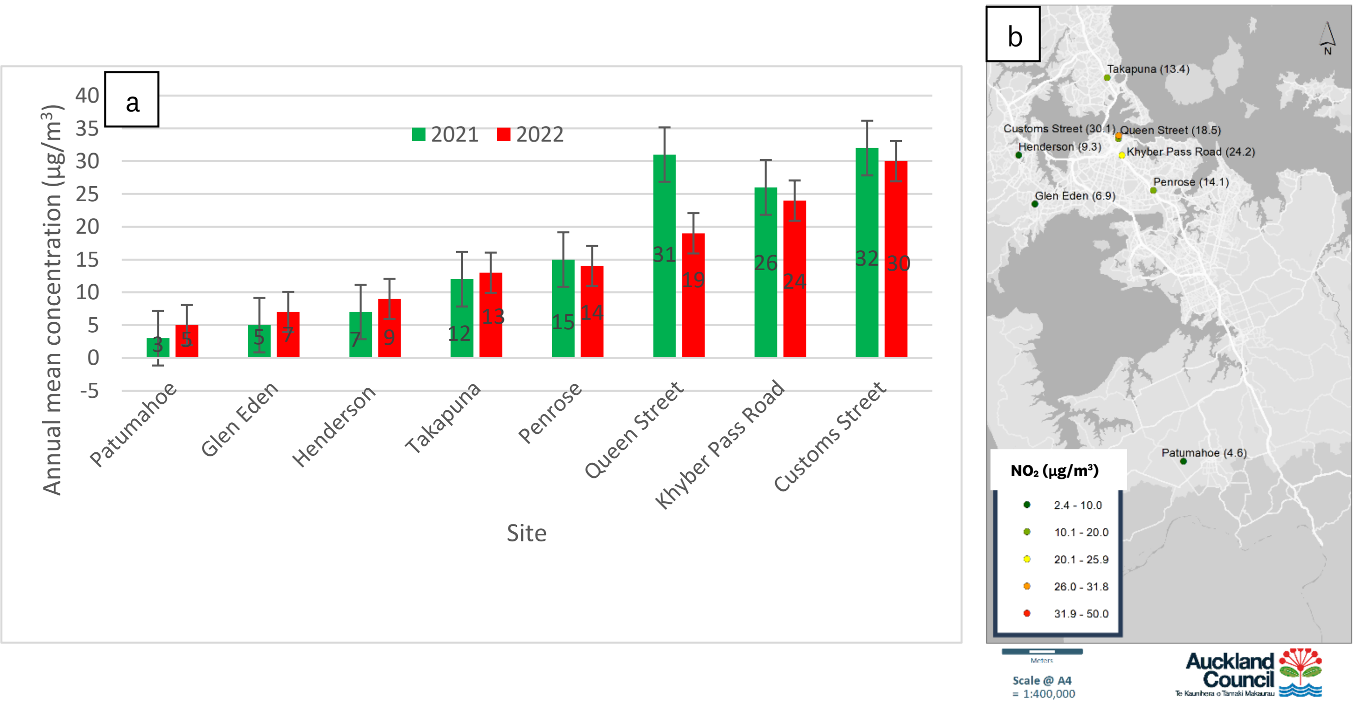

Figure 20. NO_2 annual mean concentrations at eight sites – arranged in increasing order from left to right.

Error bars represent the standard errors of the mean. Map b (right) shows sites and their annual mean NO_2 concentration in brackets.

A box and whisker diagram showing the distribution of the hourly mean concentrations across the sites is given by Figure 21.

The National Environmental Standard for Air Quality (NESAQ) requires an ambient air quality concentration limit of 200 µg/m³ (one hour average) NO_2 to be met for all but nine hours each year. In 2022, the Auckland Urban Airsheds breached this standard at two monitoring stations. The first exceedance event occurred at the Customs Street air quality monitoring station where 94 exceedances of the NESAQ for NO_2 were recorded between 9th and 17th June 2022.

This breach is the result of the exhaust emissions from a mobile power generator that was running intermittently approximately 50 metres to the north of the monitoring site. Vector Limited operated this generator while replacing and upgrading an existing high voltage network switch in the area. The emissions from the diesel generator represent a strong localised impact on the Customs Street monitoring site and are not representative of the wider emissions profile in the area generally monitored by this site. The upgrade works carried out by Vector Ltd was unforeseen and critical to ensure power supply to the upgrade operation.

The second NO_2 exceedance event occurred at the Khyber Pass Road air quality monitoring site on 24th August 2022, where one exceedance of the NESAQ NO_2 was recorded. The unusual nature of this exceedance led to an investigation which revealed that it was most likely caused by the activity of a tag graffiti artist who intruded the station. The exceedance was the result of emissions from a temporary stationary running vehicle and spray paint fumes. The emissions from the graffiti artist's vehicle and spray paint fumes represent a strong localised impact on the Khyber Pass Road monitoring site and are not representative of the wider emissions profile in the area generally monitored by this site.

When the Customs Street and Khyber Pass Road sites' data are excluded from the overall NO_2 data, Auckland on twelve occasions exceeded the 2021 WHO air quality 24-hour guideline for NO_2 (See Appendix G). Figure 22 presents the annotated calendar plot of the daily NO_2 mean concentrations indicating the days where the measured values reached or exceeded the WHO guideline of 25 µg/m^3. In more than half of the days in 2022, the three Auckland city centre sites recorded 24-hour average NO_2 concentrations more than the 2021 WHO guideline (See Appendix G; Figures G4, G5, and G6).

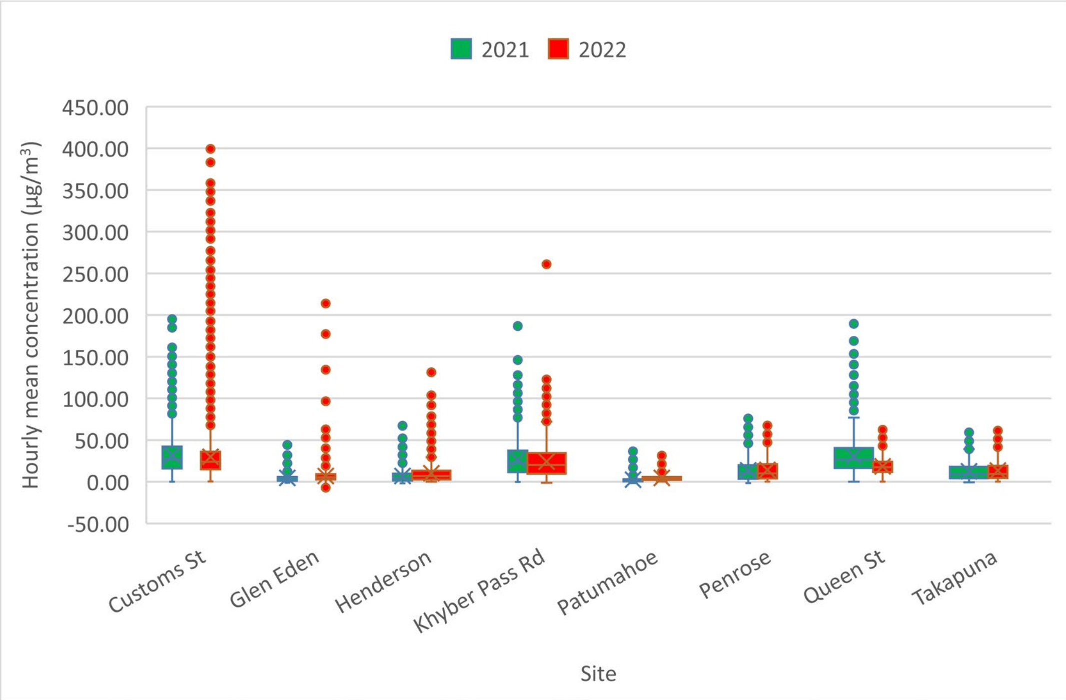

Figure 21. Boxplot of NO_2 hourly mean concentration measured at eight sites.

Boxes represent 25th (bottom of the box) and 75th (top of box) percentile, central line through the box is the median, bars outside the box(whiskers) represent the 1.5× interquartile range, × markers are the means, and circles are outliers.

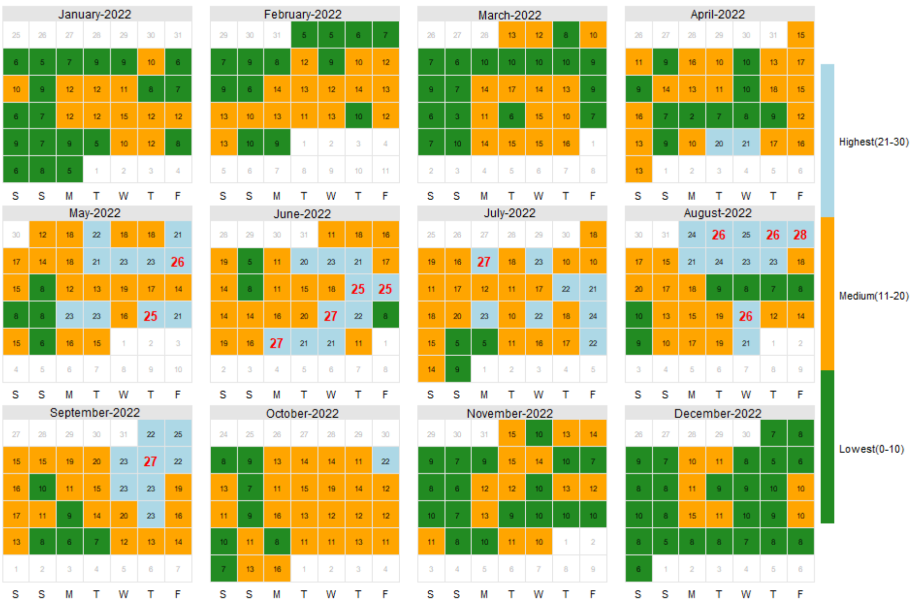

Figure 22. Calendar plot for NO_2 overall Auckland concentrations in 2022 with annotations highlighting those days where the concentration of NO_2 were equal or greater than the 2021 WHO guideline of 25 µg/m³. The numbers show the NO_2 24-hour mean concentration in µg/m³.

The highest NO_2 concentrations were recorded in winter (Figure 23). Reduced pollution dispersion during the cold winter months is known to increase overall concentrations along with increased emissions from colder engines (Talbot and Crimmins, 2020). Concentrations of NO_2 tend to increase from mid-week with the highest concentrations typically seen on Wednesday to Friday. In the same manner as the findings reported by Talbot and Crimmins (2020), the overall, concentrations peak in the morning and evening likely due to 'rush hour' traffic peak, evident in Figure 24 with the increase between 7am and 9am, and 5pm and 9pm. Weekday concentrations are slightly higher than weekends most likely due to increased traffic volume.

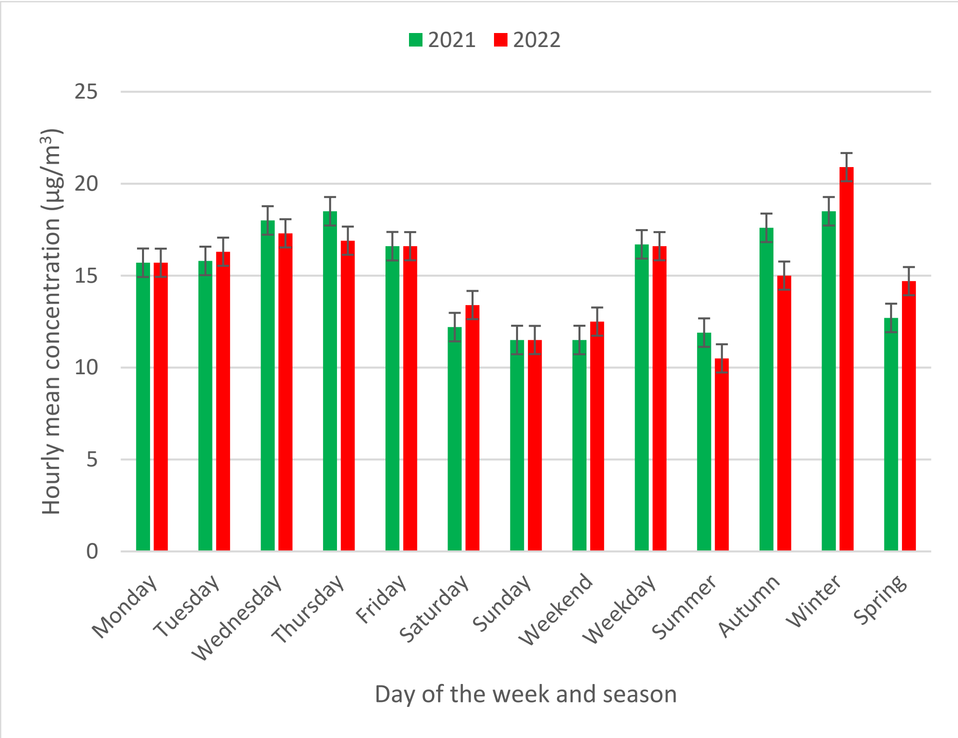

Figure 23. Temporal variations in Auckland NO_2 annual mean concentrations. Error bars represent the standard errors of the mean.

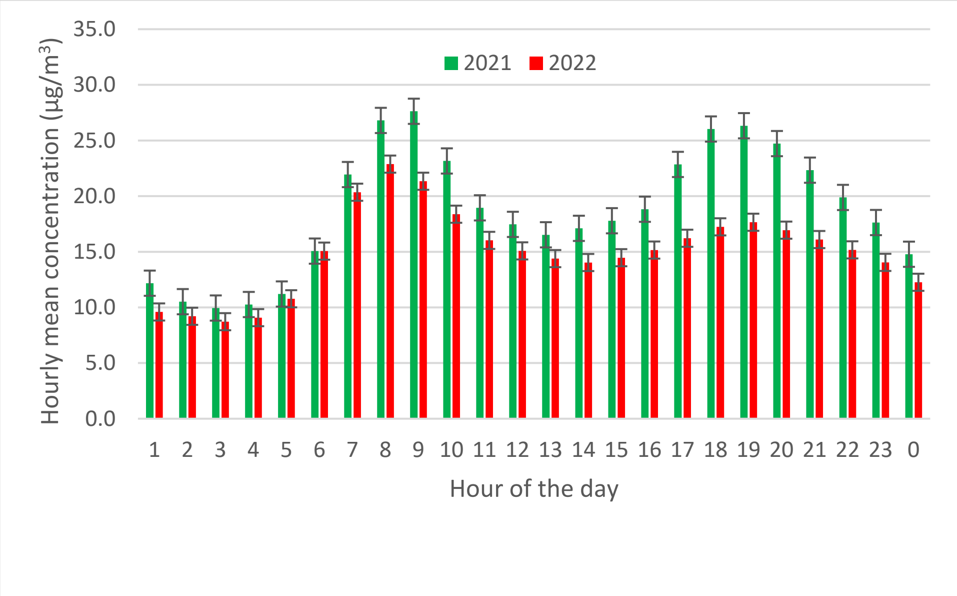

Figure 24. Time variations in Auckland NO_2 hourly mean concentrations. Error bars represent the standard errors of the mean.

The NZTA Air Quality Monitoring Network, which uses passive diffusion tubes, recorded a 0.2% decrease in annual NO_2 concentration for 2022 compared to 2021, from 19.3 ± 6.4 µg/m3 to 18.4 ± 6.1 µg/m^3. However, this difference was not statistically significant ($p>0.05$) and is consistent with the overall annual average from the regular Auckland Council air quality monitoring network. Figure 25 and Appendix H provide further data from this network.

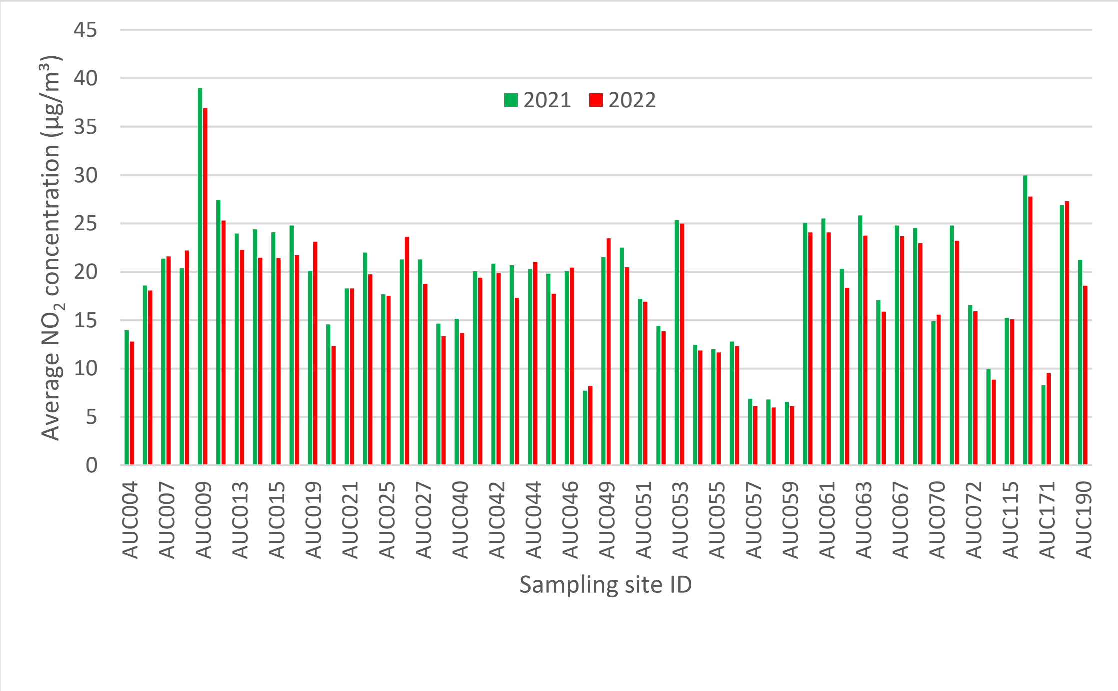

Figure 25. Annual NO_2 average levels at NZTA Air Quality Monitoring Sites across Auckland. See Appendix H for description of each site.

The combustion of any fuel generates a range of nitrogen oxides (NOx), as nitrogen in the air is oxidised in the combustion process. For industrial combustion processes, the majority of NOx is emitted as nitrogen oxide (NO), which is generally considered not to be harmful to human health or the environment at typical ambient concentrations. However, over time in the presence of sunlight, atmospheric ozone and/or organic compounds, NO is oxidised to the hazardous air pollutant NO_2 (Crimmins, 2018).

In 2016 estimate 15,473 tonnes per year of NOx were emitted from transport (67% motor vehicles, 17% aircraft, 15% off-road vehicles). It was estimated that on-road motor vehicles contribute 10,251 t/yr of NOx (Sridhar and Metcalfe, 2019). In 2016, it was estimated that 2606 tonnes of NOx were emitted from stacks and other industrial point sources. Within the Auckland urban boundary, industry is estimated to have emitted 775 tonnes of NOx in 2016.

In 2016, an estimate of 20,520 t/yr of NOx were emitted into Auckland air (85.6% transport, 1.3% domestic, 13.1% industry) with 58.4 per cent from the urban area. Within the Auckland Urban Airshed, emissions from motor vehicles account for 71 per cent of total NOx emissions (Sridhar and Metcalfe, 2019; Xie et al., 2019).

As indicated in section 3.1, NO_2 concentrations may vary from site to site depending on meteorological conditions and other factors. NO_2 pollution rose charts are useful in showing which wind directions dominate the overall concentrations as well as providing information on the different concentration levels. Figures 26 and 27 indicate that different dominant wind speeds and directions occur at the monitoring sites. For instance, Figures 26 and 27 show that the highest NO_2 concentrations arrived at the Penrose and Henderson sites mostly from the south-west sector. In the same manner as the other contaminants, patterns of NO_2 pollution roses at all the sites in 2021 and 2022 were mostly similar, except for Queen Street.

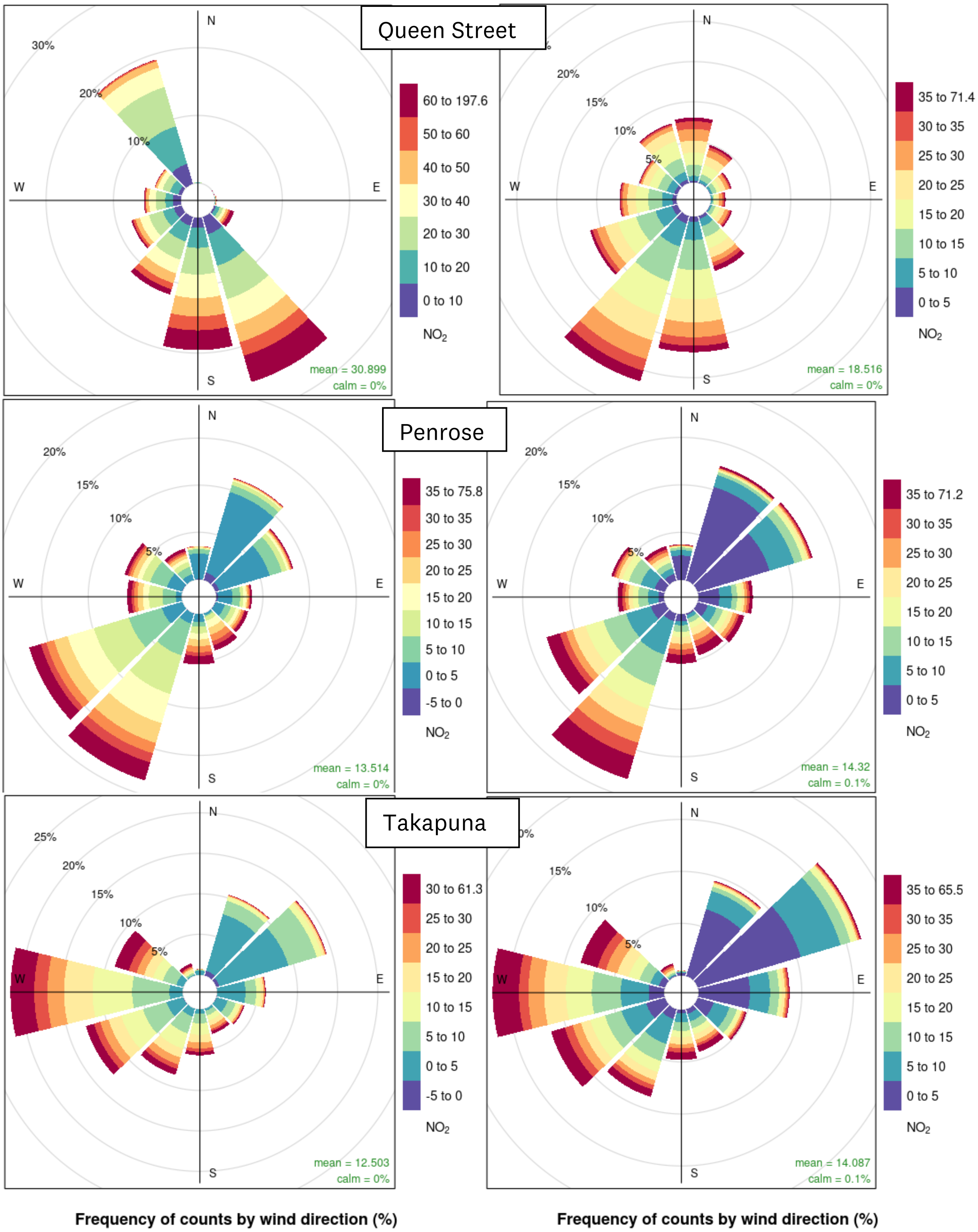

Figure 26. NO_2 pollution roses for Queen Street, Penrose, and Takapuna sites.

Higher NO_2 concentrations are associated with predominant prevailing wind direction as follows: Queen Street: south-west, Penrose and Takapuna: sout-hwest. The plots on the left are for 2021 data while the right plots are for 2022 data.

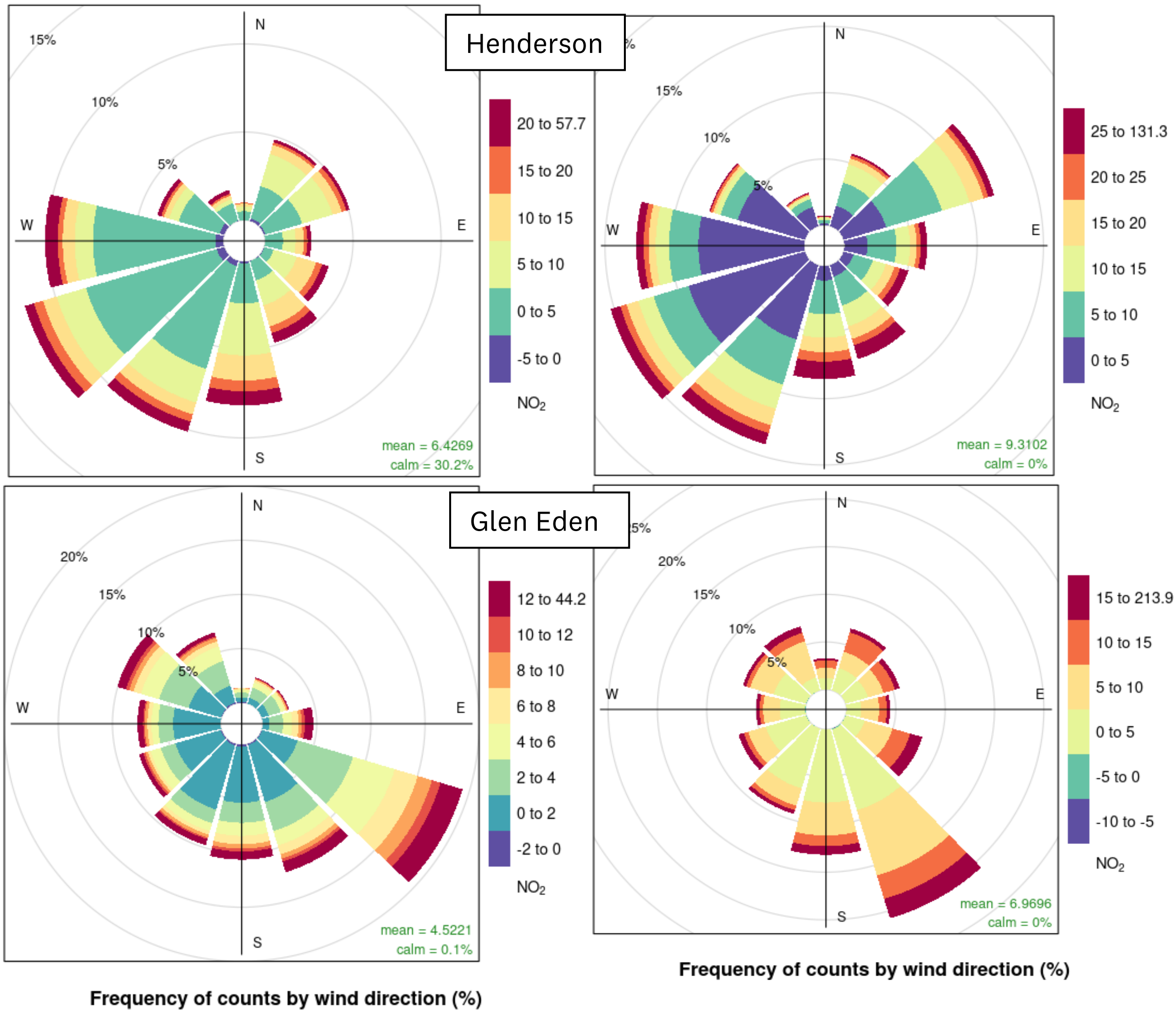

Figure 27. NO_2 pollution roses for Henderson and Glen Eden sites.

Higher NO_2 concentrations are associated with predominant prevailing wind direction as follows: Henderson: south-west, and Glen Eden: south-east. The plots on the left are for 2021 data while the right plots are for 2022 data.

3.2.4 Sulphur dioxide (SO_2)

The average SO_2 concentration of Auckland in 2022 significantly increased by 40.8% compared to 2021 (from 1.52 ± 1.99 µg/m^3 to 2.14 ± 3.57 µg/m^3) ($p<0.05$). The reason for this increase is not clear. Further investigation is needed. As found in 2021, the annual SO_2 mean concentration at Customs Street was higher than at the Penrose site. The increase in the 2022 SO_2 annual mean concentrations at both sites were significantly higher than the previous year ($p<0.05$) (see Appendix D). Figure 28 presents the variation of SO_2 annual concentrations for the two sites.

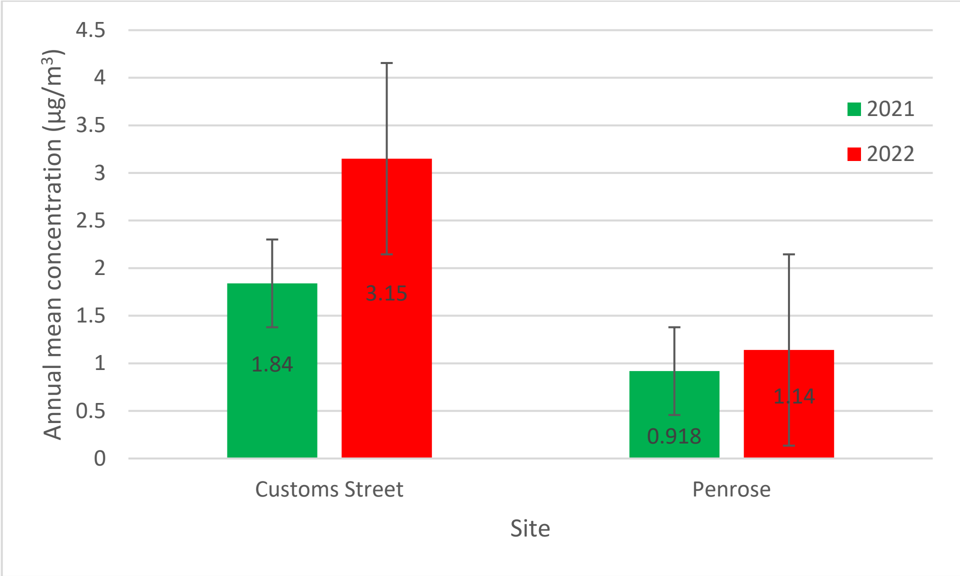

Figure 28. SO_2 annual mean concentrations at Customs Street and Penrose sites. Error bars represent the standard errors of the mean.

As with air particulates and NO_2, there were occasional hourly spikes in SO_2 mean concentrations at both sites. However, none of the sites exceeded the national standard and WHO guidelines (See Appendix I). A box and whisker diagram showing the distribution of hourly mean concentrations across the sites is presented in Figure 29.

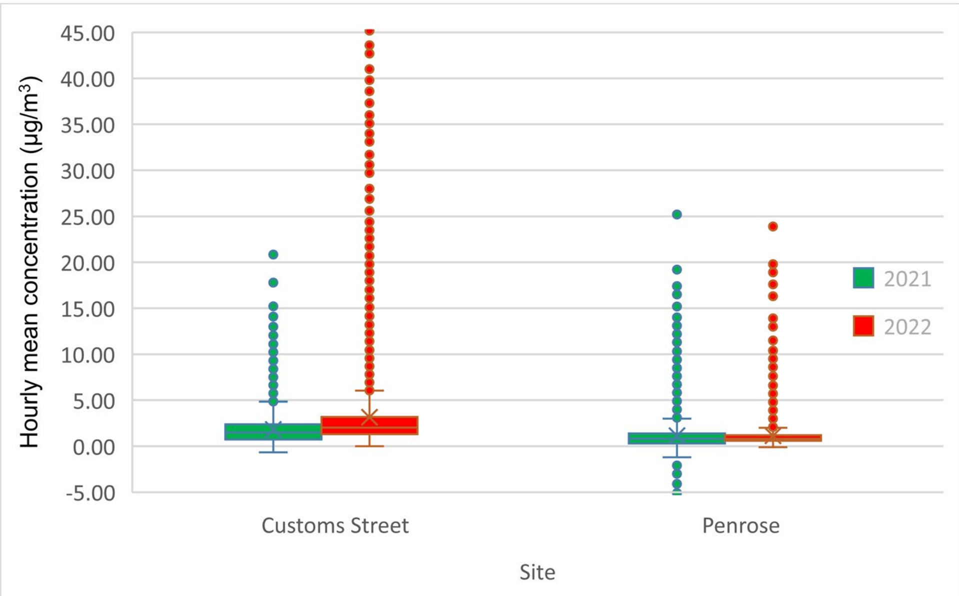

Figure 29. Boxplot of SO_2 hourly mean concentration measured at Customs Street and Penrose.

Boxes represent 25th (bottom of the box) and 75th (top of box) percentile, central line through the box is the median, bars outside the box (whiskers) represent the 1.5× interquartile range, × markers are the means, and circles are outliers.

In general, SO_2 concentrations peak in the morning and late afternoon probably due to traffic (Figure 30) with the increase between 7am and 9am, and 4pm and 6pm. This was probably due to traffic patterns. Weekday SO_2 concentrations are higher than weekends due to the timing of peak traffic hours. The highest SO_2 concentrations were recorded in winter and spring. Concentrations of SO_2 tend to increase later in the week with the highest concentrations mostly seen on Wednesday to Friday (See Figure 31). Higher traffic volume is the likely contributing factor.

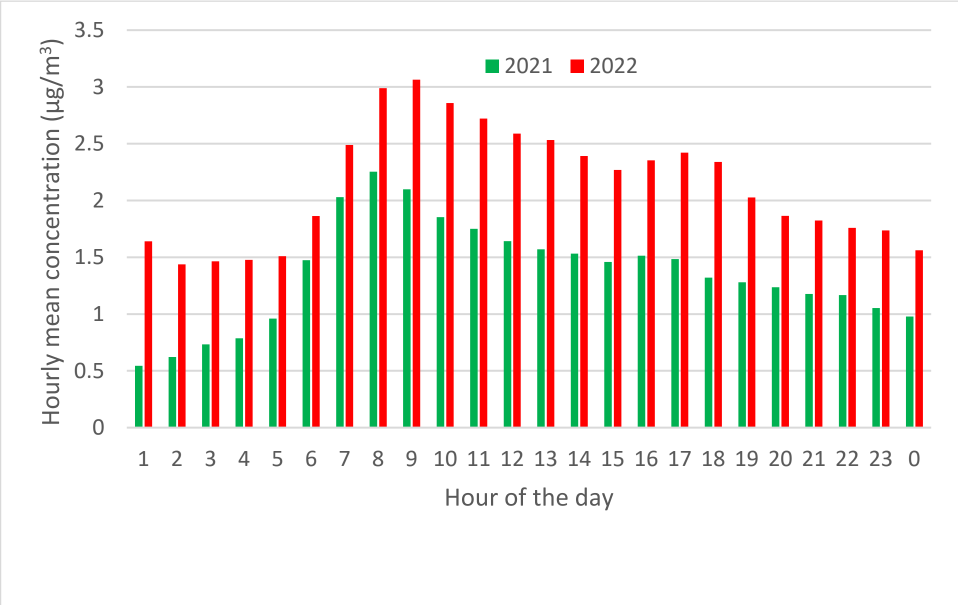

Figure 30. Time variations in SO_2 hourly mean concentrations. Error bars represent the standard errors of the mean.

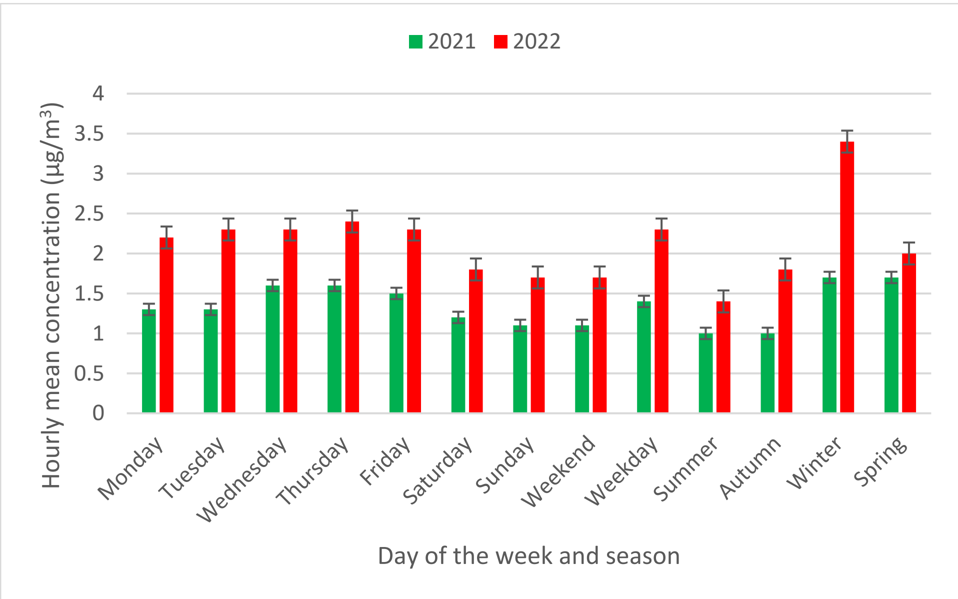

Figure 31. Temporal variations in Auckland SO_2 annual mean concentrations. Error bars represent the standard errors of the mean.

In the same manner as particulates and NO_2, SO_2 concentrations may vary from site to site depending on meteorological conditions and other factors. SO_2 pollution rose charts are important in showing which wind directions dominate the overall concentrations as well as providing information on the different concentration levels. Figure 32 shows that the highest SO_2 concentrations were at the Penrose site mostly from the south-west sector. It is important to note that the pattern of SO_2 pollution roses at the Penrose site in 2021 and 2022 was similar.

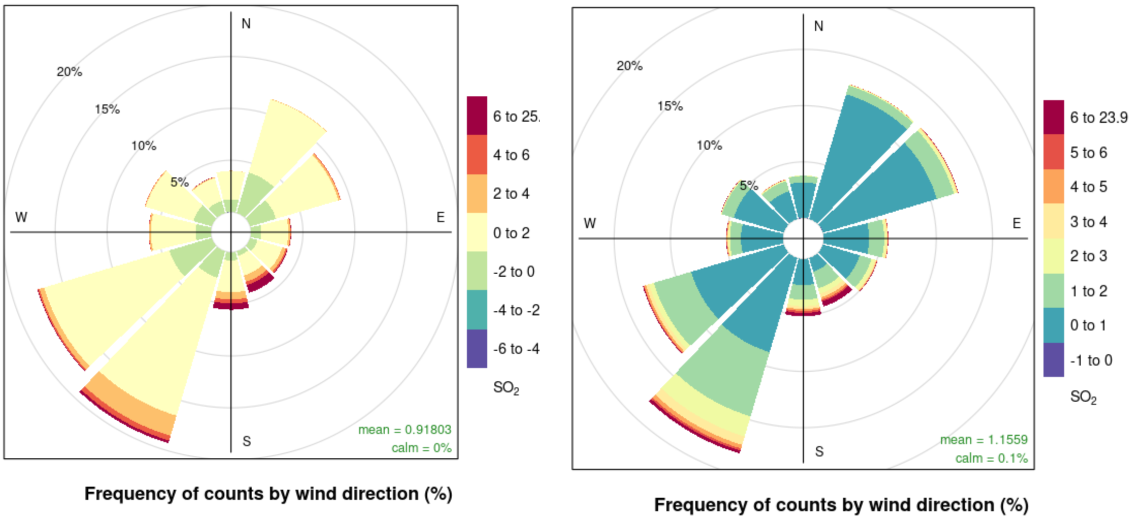

Figure 32. SO_2 pollution roses for Penrose site.

Higher SO_2 concentrations are associated with the southwest predominant prevailing wind direction. The plot on the left is for 2021 data while the right plot is for 2022 data.

Emission inventory estimates have shown that in 2016 about 2657 tonnes of SO_2 are emitted into Auckland's air (59.2% transport, 1.5% domestic, 39.3% industry) with 29.6% from the urban area (Xie et al., 2019). The 2016 estimate indicated that the transport sector emitted 196 tonnes of SO_2 per year into Auckland's air (62% aircraft, 37% motor vehicles) (Sridhar and Metcalfe, 2019). The combined total of all other industrial point sources of SO_2 discharges is estimated to be 11.1 tonnes/year, predominantly from starch manufacturing, asphalt production, and the combustion of biogas that occurs at landfills and the region's two major wastewater treatment plants (Crimmins, 2018).

3.2.5 Carbon monoxide (CO)

The average CO concentration at Khyber Pass Road site in 2022 significantly decreased by 14.5% compared to 2021 (from 0.22 ± 0.19 mg/m^3 to 0.19 ± 0.17 mg/m^3) ($p<0.05$). Interestingly even though there were occasional hourly and 8-hour running means spikes in CO concentrations, there was no exceedance of national standard and 2021 WHO air quality guideline (See Appendix J). Figure 33 compares the annual CO concentration for 2022 and

2021. A box and whisker diagram showing the hourly mean concentrations is presented in Figure 34.

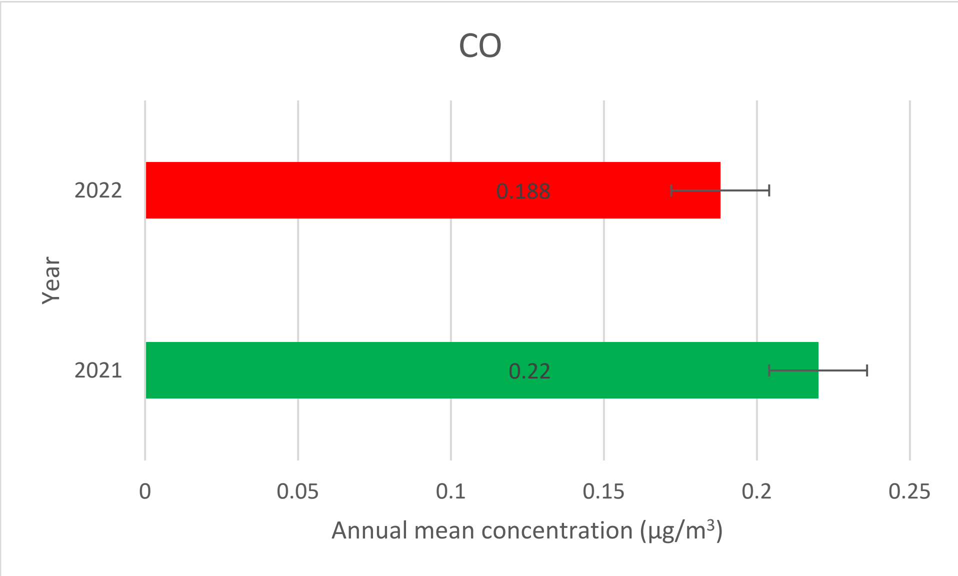

Figure 33. CO annual mean concentration. Error bars represent the standard errors of the mean.

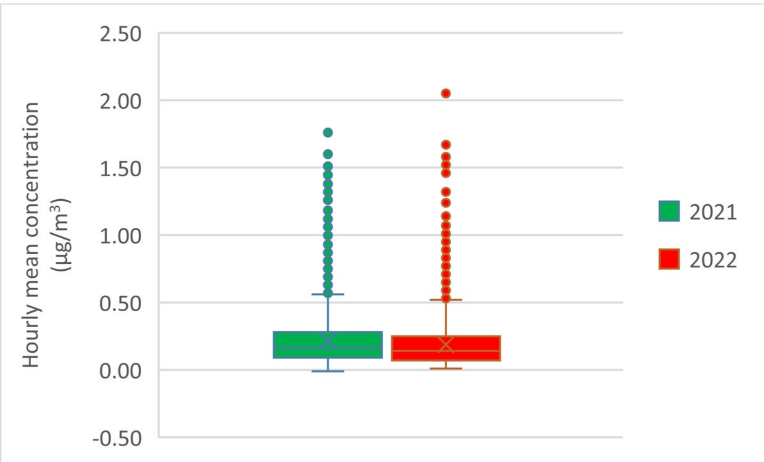

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Figure 34. Boxplot of CO hourly mean concentration.

Boxes represent 25th (bottom of the box) and 75th (top of box) percentile, central line through the box is the median, bars outside the box (whiskers) represent the 1.5× interquartile range, × markers are the means, and circles are outliers.

The highest CO concentrations were measured in winter (See Figure 35). In general, CO concentrations were highest in the morning and late afternoon likely due to peak traffic, as presented in Figure 36 with the increase between 7am and 9am, and 5pm and 9pm.Traffic volume data from Auckland Transport's 7-day survey at the Khyber Pass Road is presented in Appendix O. CO concentrations are significantly higher on weekdays than on weekends. Higher traffic volume is the likely contributing factor.

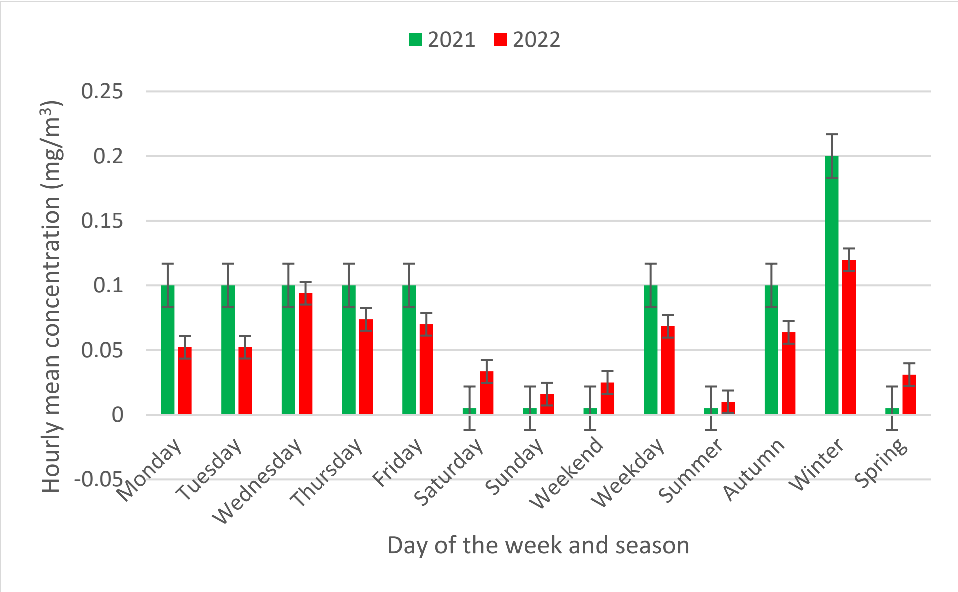

Figure 35. Temporal variations in CO annual mean concentrations. Error bars represent the standard errors of the mean.

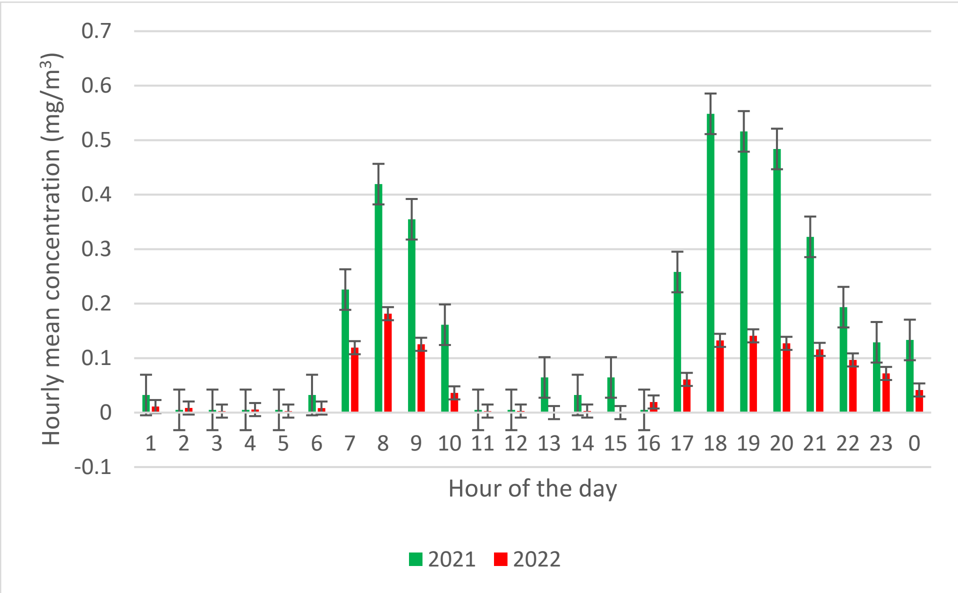

Figure 36. Time variations in CO hourly mean concentrations. Error bars represent the standard errors of the mean.

The 2016 emission inventory data indicates that 65,757 tonnes/year of CO was emitted into Auckland's air (66.8% transport, 28.1% domestic, 5.2% industry) with 65.6% from the urban area (Xie et al., 2019). The 2016 estimate showed that the transport sector emitted 45,185 tonnes of CO per year into Auckland's air (91% motor vehicles, 4% lawnmowers, 3% aircraft) (Metcalfe et al., 2018). In winter, domestic sources overtake transport as the dominant source of CO. This is because transport and industrial activities are constant throughout the year, however domestic home heating occurs mainly over the winter season only (Xie et al., 2019).

3.2.6 Ground level ozone (O_3)

The average O_3 concentration at Patumahoe in 2022 increased by 9.0% compared to 2021 (from 36.8 ± 13.8 µg/m^3 to 40.1 ± 15.1 µg/m^3) ($p<0.05$). Figure 37 compares the annual ozone concentrations for 2022 with 2021. As shown by Figure 35 (and Appendix K), there were occasional hourly mean spikes in O_3 concentrations, however, they did not cause any exceedance of national standard and 2021 WHO air quality guidelines. A box and whisker diagram showing the hourly mean concentrations is given in Figure 38.

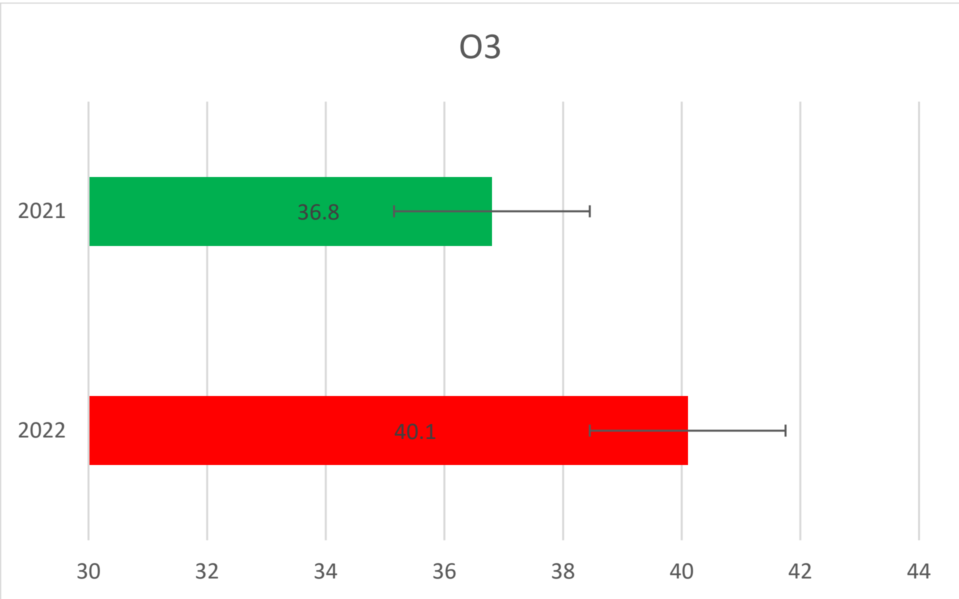

Figure 37. Ozone annual mean concentrations. Error bars represent the standard errors of the mean.

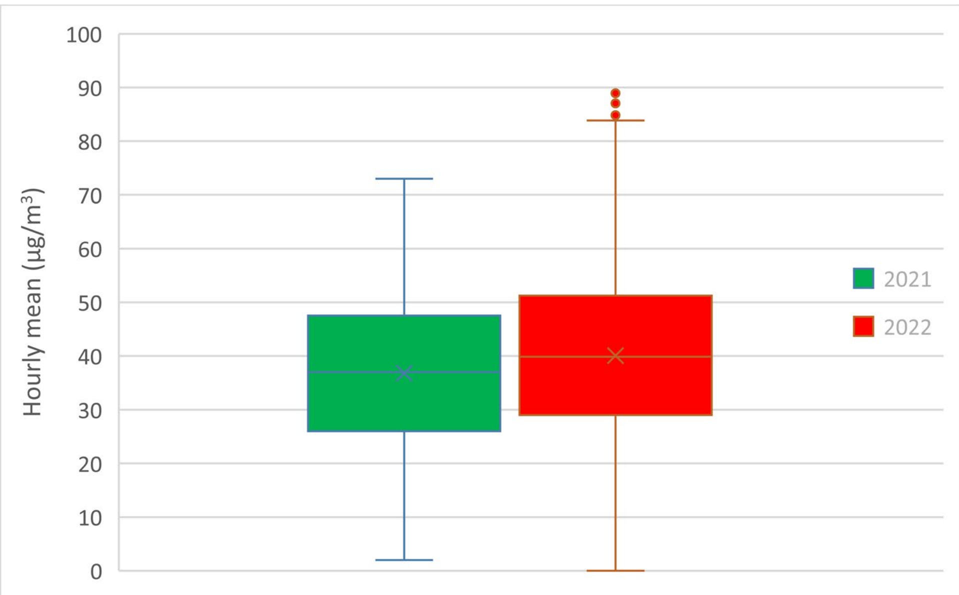

Figure 38. Boxplot of ozone hourly mean concentration.

Boxes represent 25th (bottom of the box) and 75th (top of box) percentile, central line through the box is the median, bars outside the box (whiskers) represent the 1.5× interquartile range, × markers are the means, and circles are outliers.

The highest O_3 concentrations were measured in spring and winter (Figure 39). In general, O_3 concentrations were highest in the afternoon as shown in Figure 40, with an increase between 1pm and 4pm. Concentrations of O_3 were found to be uniform on weekdays. Unlike most air contaminants examined in this report, the average O_3 concentrations on weekends and weekdays were similar. It is important to note that O_3 concentrations increase with decreasing NO_2, a predictable inverse relationship given the relationship between NO_2 and O_3 in the presence of sunlight (Xie et al., 2014; Talbot and Crimmins, 2020).

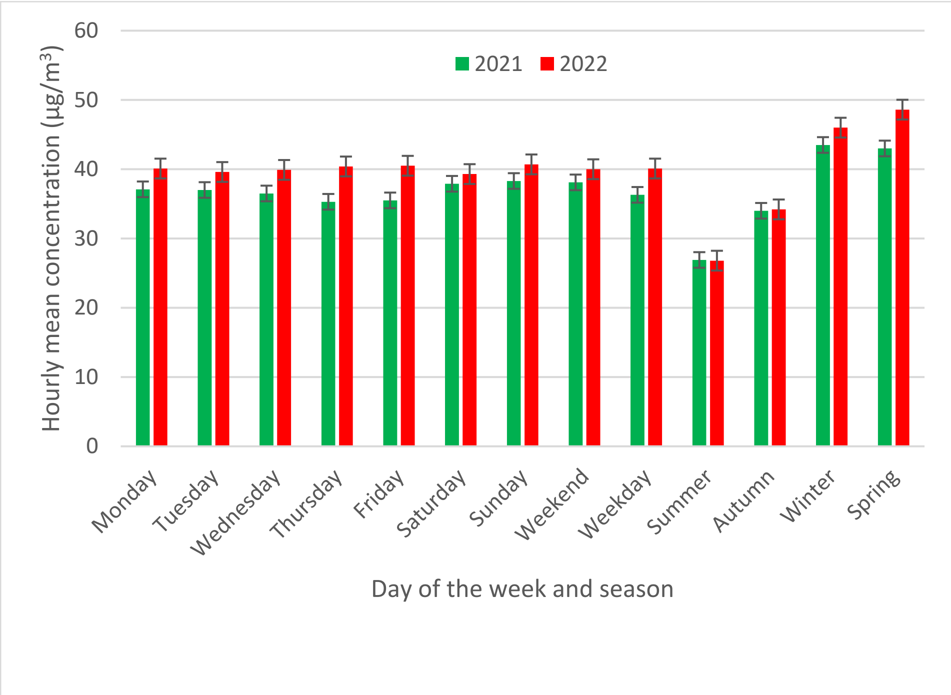

Figure 39. Temporal variations in ozone annual mean concentrations. Error bars represent the standard errors of the mean.

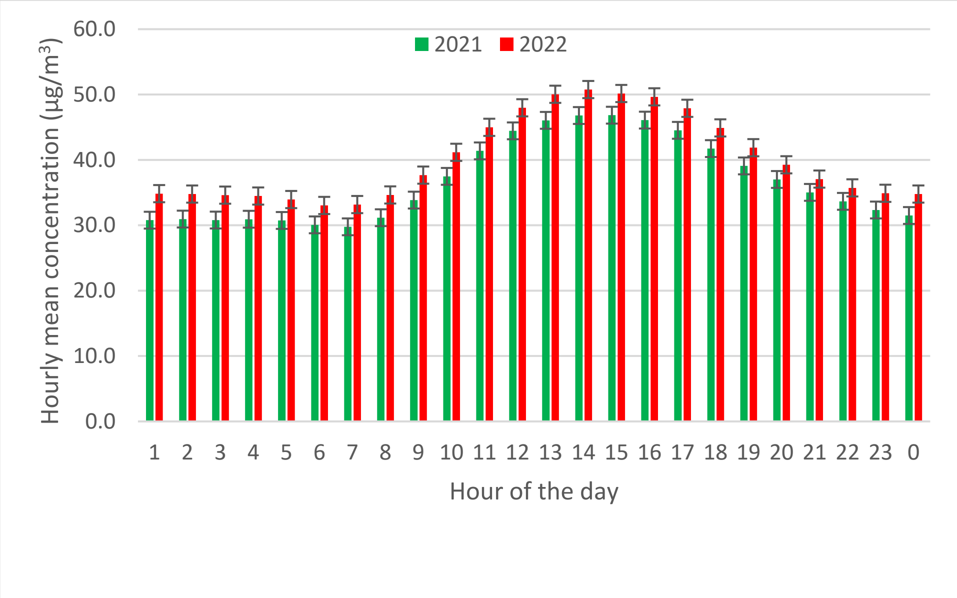

Figure 40. Time variations in ozone hourly mean concentrations. Error bars represent the standard errors of the mean.

3.2.7 Black carbon

The annual black carbon concentration measured at Customs Street in 2022 was significantly higher than the previous year (from 1,138 ± 1200 to 1,755 ± 3,559 ng/m³) (p<0.0.5). Conversely, the annual black carbon concentration recorded at Henderson was significantly lower than the previous year (from 617 ± 1,026 to 584 ± 737 ng/m³) (p<0.0.5). The reason for the different behaviours at the two sites is not clear. Further investigation is needed. When data from the two sites are combined, the mean annual black carbon concentration for 2022 significantly decreased by 14.3 % (from 866 ± 1,142 ng/m³ to 742 ± 884 ng/m³). Figures 41 and 42 present the variation and distribution of black carbon concentrations at the two sites.

Between 6th and 17th June 2022, there were spikes in black carbon levels at the Customs Street site (See Figure 43). This was caused by exhaust emissions from a diesel generator which was placed near the site. As indication at section 3.2.3, this resulted in NO_2 NESAQ exceedances.

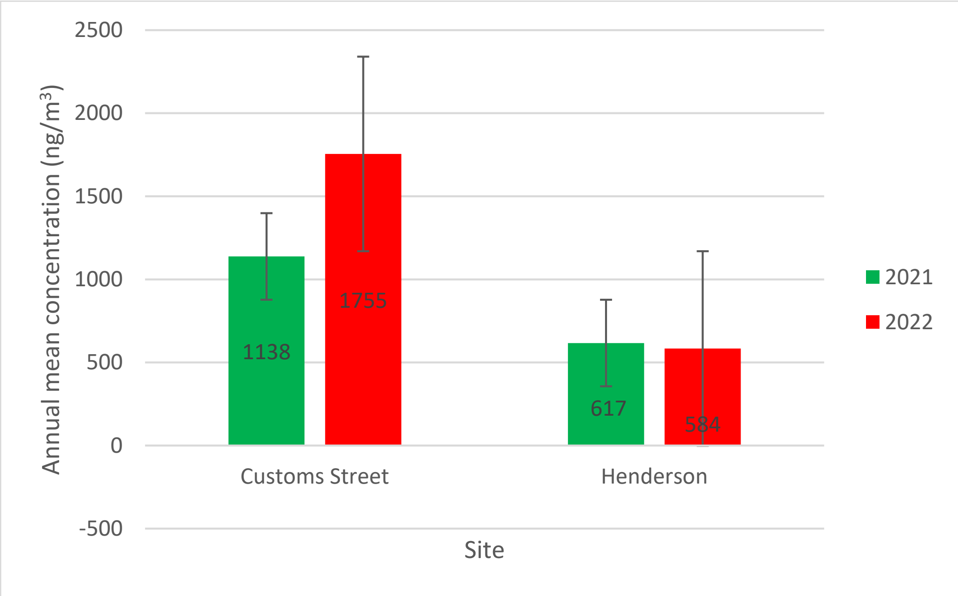

Figure 41. Black carbon annual mean concentrations for Henderson and Customs Street sites. Error bars represent the standard errors of the mean.

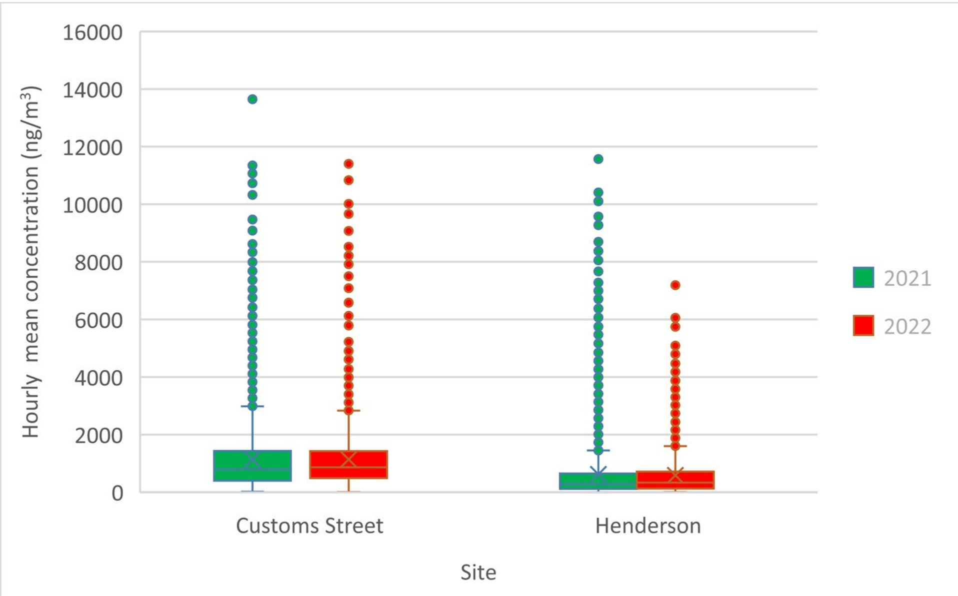

Figure 42. Boxplot of black carbon hourly mean concentration measured at two sites.

Boxes represent 25th (bottom of the box) and 75th (top of box) percentile, central line through the box is the median, bars outside the box (whiskers) represent the 1.5× interquartile range, × markers are the means, and circles are outliers.

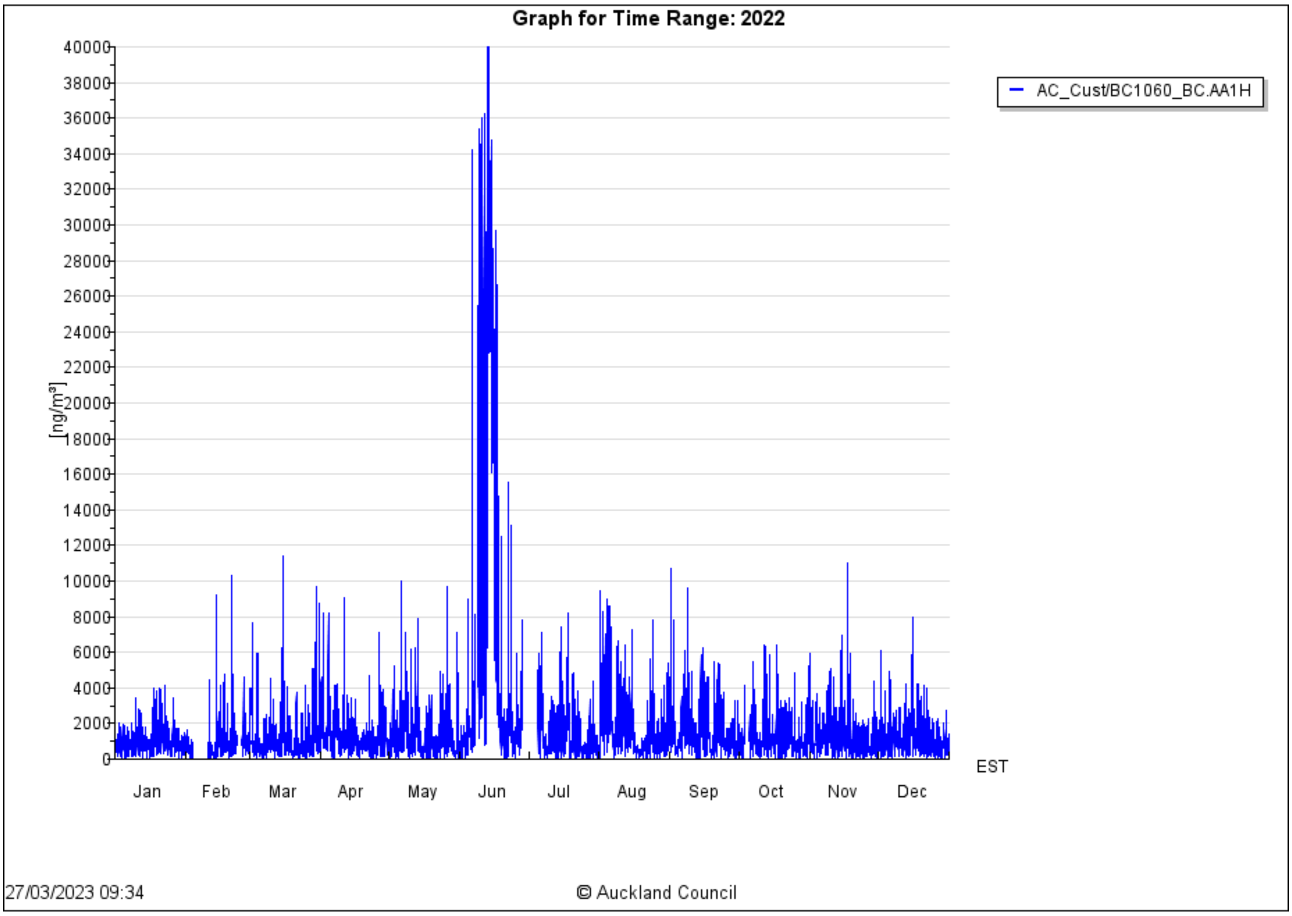

Figure 43. Variation in black carbon concentration at the Customs Street site showing spikes during the period between 6th and 17th June 2022, caused by exhaust emissions from a diesel generator which was placed near the site. As indication at section 3.2.3, this resulted in NO_2 NESAQ exceedances.

Overall, the highest black carbon concentrations were measured in the mornings (between 7am and 9am) and late afternoon (from 5pm to 9pm) likely due to increasing traffic volume (see Figure 44). Black carbon concentrations on weekdays are slightly higher than on weekends. The highest black carbon concentrations were recorded in winter (See Appendix L). Concentrations of black carbon tend to increase later in the week with the highest concentrations seen between Wednesday and Friday (Figure 45). Higher traffic volume is the likely contributing factor.

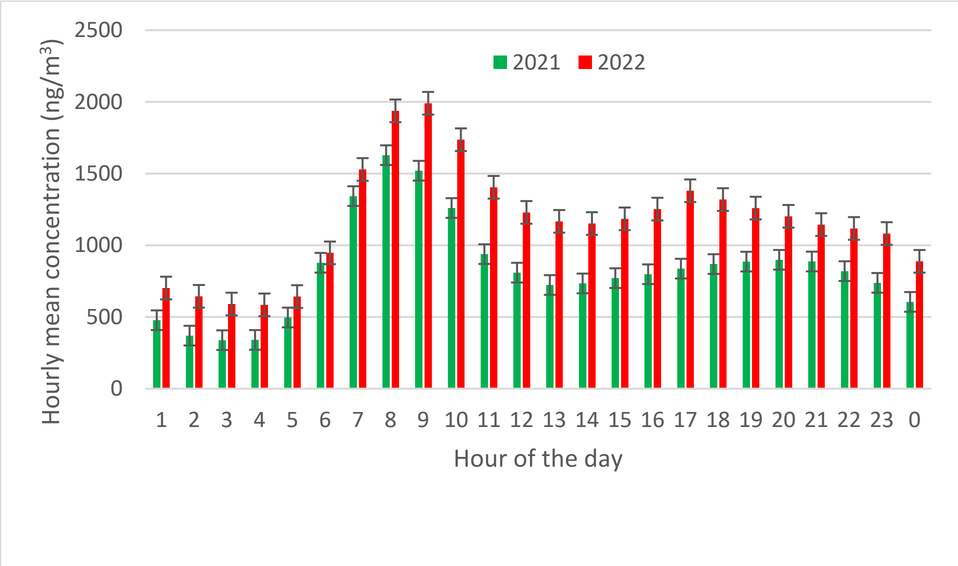

Figure 44. Time variations in black carbon hourly mean concentrations. Error bars represent the standard errors of the mean.

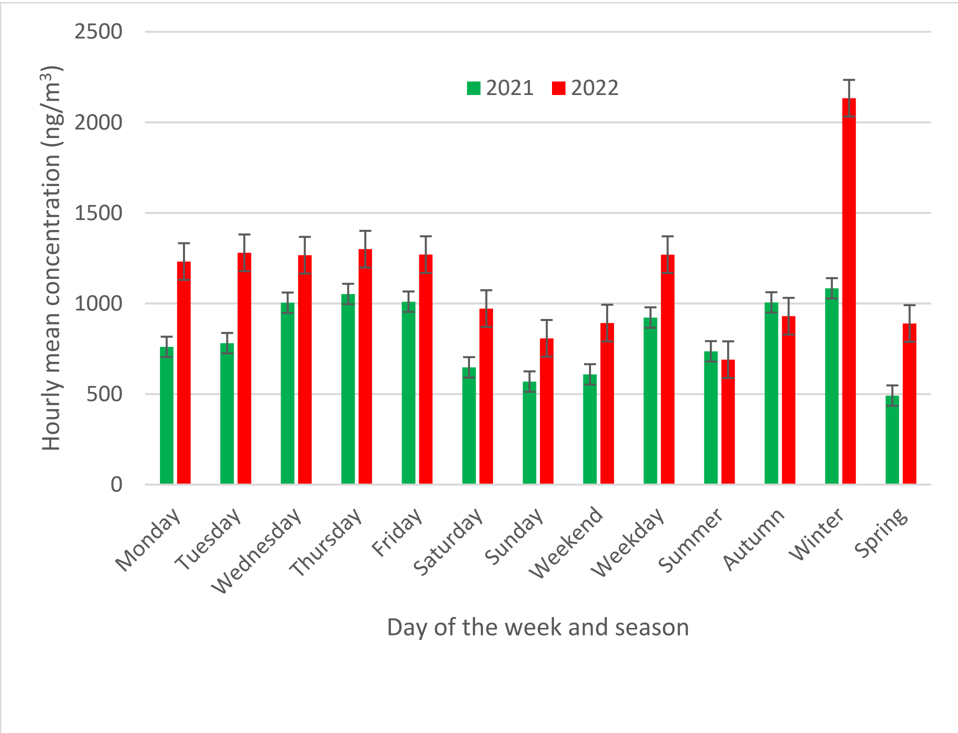

Figure 45. Temporal variations in black carbon annual mean concentrations. Error bars represent the standard errors of the mean.

3.2.8 Total Suspended particulate (TSP), lead (Pb), BTEX and VOCs

Penrose's TSP mean in 2022 decreased by 4.6% compared to 2021 (from 13.0 ± 1.7 to 12.4 ± 5.2 $\mu g/m^3$) ($p>0.05$). As expected, the corresponding mean lead (Pb) levels in TSP also decreased by 65% compared to 2021 (from 0.0023 ± 0.0007 $\mu g/m^3$ to 0.0008 ± 0.0008 $\mu g/m^3$) ($p<0.05$).

It is important to note that the levels of BTEX and other VOCs monitored at Penrose and Newmarket in 2022 were all below the limit of detection.

4 Conclusions

Key findings:

- The annual average PM_{10} concentration of Auckland in 2022 increased by 2.5% compared to 2021. However, this increase did not exceed the 2021 WHO air quality guideline of 15 $\mu g/m^3$. It is worth noting that on the individual sites level, Queen Street exceeded the WHO guideline by 28.7%. On 18 -19 August, the Queen Street site recorded two exceedances of NESAQ for PM_{10} (24-hour average). Our investigation indicated that these exceedances were due to marine aerosol (sea salt) following a high sea state and onshore easterly wind conditions.
- The annual average $PM_{2.5}$ concentration of Auckland in 2022 increased by 2.8% compared to 2021. This increase was over the 2021 WHO air quality guideline of 5 $\mu g/m^3$. The annual $PM_{2.5}$ averages for Penrose, Patumahoe, Takapuna and Queen Street sites were higher than the more stringent WHO air quality guideline. Auckland's target for 24-hour and annual average $PM_{2.5}$ were not exceeded.
- As in the previous year, overall concentrations of particulate matter peaked in the afternoon and night hours and mostly increased later in the week with the highest concentrations typically occurring on Wednesday to Friday.
- In general, Auckland's annual mean concentration of NO_2 marginally decreased by 0.2% compared to 2021. As expected, the highest NO_2 concentrations were measured at the city centre sites, although the concentrations were lower than the same period of the previous year. Auckland transport traffic volume data collected between 15-21 August 2022, shows that 24-hour traffic volume at the city centre screenline intersections are between 70% to 80% relative to normal (pre-covid levels). There were NO_2 national standard and WHO guideline breaches at the Customs Street and Khyber Pass Road sites. Our investigations indicated that these exceedances were not true representatives of the monitoring sites where these exceedances occurred.
- The average SO_2 concentration of Auckland in 2022 significantly increased by 40.8% compared to 2021. As found in 2021, the annual SO_2 mean concentration at Customs Street was higher than at the Penrose site. Further investigation is required.
- The average CO concentration at the Khyber Pass Road site decreased by 14.5% compared to 2021. There was no exceedance of NESAQ and the 2021 WHO air quality guideline for CO.
- The average O_3 concentration at Patumahoe in 2022 increased by 9.0% compared to 2021. Though there were occasional hourly spikes in O_3 mean concentrations, none was above the NESAQ and the 2021 WHO air quality guidelines for O_3.
- The levels of BTEX and other VOCs monitored at Penrose and Newmarket in 2022 were all below the limit of detection.
- In general, most air pollutants peaked in the morning and late afternoon due to traffic, with the increase between 7am and 9am, and 5pm and 9pm.
- All key air pollutants were highest in winter, most likely due to domestic fires.
- Weekday air pollutants concentrations were slightly higher than weekends due to increased traffic.

We are committed to continuously collecting air quality data to ensure compliance with national standards and aid policy development and evaluation. The data we collect provides a better understanding of ambient air quality in the region, including spatial and temporal variations.

Data and information from the Auckland air quality monitoring network is reported in multiple ways. Technical and monthly reports are regularly published on the Knowledge Auckland website (www.knowledgeauckland.org.nz). This report provides the 2022 data and assesses it against the relevant National Environmental Standard for Air Quality (NESAQ), Auckland Unitary Plan air quality target, and the 2021 WHO air quality guidelines.

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7 Appendices

Appendix A: HAPINZ 3.0: Auckland region factsheet.

This factsheet is taken from HAPINZ 3.0 documentations (https://www.ehinz.ac.nz/projects/hapinz3/).

A1 Summary

Clean healthy air contributes to New Zealand's quality of life – not only to people's health, but also to the natural functioning and beauty of the natural and physical environment. New Zealand has good air quality in most places – most of the time. However, solid fuel (wood and coal) used for domestic (home) heating and exhaust emissions from motor vehicles combine to produce unacceptable air quality in some locations – particularly during winter or along major roads. Despite the relatively low levels of pollution in New Zealand compared to many other countries, the adverse health effects of poor air quality on New Zealanders are still substantial.

The effects of air pollution are not experienced evenly in the community. The likelihood and magnitude of any health effects depend on the concentration of air pollution, the number of people exposed to that concentration where they live. Some population groups are also more vulnerable to the effects of air quality, e.g. children and asthmatics.

The health effects of air pollution in New Zealand (HAPINZ) were first assessed in HAPINZ 1.0 for a base year of 2001. This work was later updated in HAPINZ 2.0 for a base year of 2006. **HAPINZ 3.0** represents the latest update and assesses the air pollution health effects experienced by New Zealanders for 2016. 2016 was selected as the base year for HAPINZ 3.0 because when the study commenced in July 2019 this was the most recent year for which we had suitable population, health and air quality monitoring data.

A1.1 What did HAPINZ 3.0 find nationally?

HAPINZ 3.0 found **anthropogenic** (human-generated) air pollution in New Zealand in 2016 resulted in:

- the premature deaths of more than 3300 adult New Zealanders
- more than 13,100 hospital admissions for respiratory and cardiac illnesses, including 845 asthma hospitalisations for children
- over 13,200 cases of childhood asthma
- approximately 1.745 million restricted activity days (days on which people could not do the things they might otherwise have done if air pollution had not been present).

Of the more than 3300 deaths associated with anthropogenic air pollution, more than 60% (2000) were associated with nitrogen dioxide (**NO_2**) pollution – which is largely from motor vehicles – whilst the rest (nearly 1300) were associated with fine particulate (**$PM_{2.5}$**) pollution – largely from domestic fires. For context, StatsNZ reports that 31,179 New Zealanders died in 2016 from <u>all</u> causes.

The social costs associated with anthropogenic air pollution in New Zealand in 2016 alone were $15.6 billion.

HAPINZ 3.0 focusses on anthropogenic sources of air pollution because emissions from these sources can be controlled through a combination of central and local government legislation, rules, policies and interventions.

Anthropogenic air pollution means human (*anthro-*) generated (*-genic*) pollution. Examples of sources of anthropogenic air pollution include motor vehicles (e.g. cars, buses, and trucks), domestic fires (e.g. coal and wood burners used for home heating), windblown dust (e.g. from construction, land use activities and road dust) and industry.

A1.2 What did HAPINZ 3.0 find regionally across New Zealand?

Air pollution health impacts vary with region across New Zealand. The highest levels of fine particles ($PM_{2.5}$) are in areas in which a large proportion of households use domestic fires burning wood or coal for winter-time home heating. The highest levels of NO_2 are found in areas with a high density of roads and in 'hot spots' where there is high diesel traffic and/or close to intersections and inner-city areas, where there are tall buildings on either side of the road which can trap air pollutants.

In all regions, domestic fire impacts dominated the regional $PM_{2.5}$ social costs – with contributions ranging from 59% to 88%. **On average, domestic fire impacts were more than four times those of motor vehicles for $PM_{2.5}$ pollution from anthropogenic sources.**

However, for the total anthropogenic health costs ($PM_{2.5}$ and NO_2 combined), motor vehicles were the dominant source in most locations – except in areas where the amount of wood or coal burnt in domestic fires during winter was high. **On average, motor vehicle impacts were more than twice those of domestic fires for total pollution ($PM_{2.5}$ and NO_2) from anthropogenic sources.**

A1.3 What changes have occurred since the last HAPINZ study?

The body of evidence showing air pollution impact on human health has increased substantially. Since 2006, the understanding of air pollution impacts has improved greatly, with adverse health effects occurring at lower concentrations of $PM_{2.5}$ and NO_2 than known previously. In the case of NO_2, HAPINZ 3.0 was one of the first studies to find strong associations between mortality and low level exposure. The results were rigorously peer-reviewed before being published internationally and have now been referenced by other researchers who have found similarly strong NO_2 impacts in their countries.

More stringent global air quality guidelines were released. In response to better understanding, the World Health Organization (**WHO**) has **significantly reduced their recommended guideline values for PM and NO_2** (released in late 2021). For example, the guideline value for annual average $PM_{2.5}$ has dropped from 10 $\mu g/m^3$ to 5 $\mu g/m^3$ – a 50% reduction and for annual average NO_2 has dropped from 40 $\mu g/m^3$ to 10 $\mu g/m^3$ – a 75% reduction.

Regional councils have progressively introduced measures to improve air quality. In New Zealand, considerable improvements have occurred in domestic fire emissions following the introduction of the woodburner standards and programmes encouraging insulation and clean heat appliances. Most airsheds that were exceeding air quality PM_{10} standards in winter-time are now in compliance. However, the health benefits resulting from improvements in annual average $PM_{2.5}$ concentrations have been reduced due to more people being exposed (population growth in urban areas).

Significant and genuine improvements were made in fuel quality and vehicle emissions standard requirements between 2001 and 2006. However, little further regulation of motor vehicle emissions has occurred since. The number of diesel vehicles, which are the main source of NO_2, have increased significantly since 2006. Annual average NO_2 concentrations worsened by more than 13% between 2006 and 2016.

Despite improvements in $PM_{2.5}$, **the health burden due to anthropogenic air pollution overall increased by 10.2% between 2006 and 2016**.

Moving forward from HAPINZ 3.0, the good work being done by Councils to address domestic fire emissions needs to continue to ensure people's exposure reduces, especially with continued population growth. However more attention needs to go on addressing harmful emissions from motor vehicles. Many of options that improve air quality can also result in improved housing conditions and improved transport/accessibility for communities, thereby delivering a "trifecta" of air quality, climate change and increased activity (exercise) co-benefits.

A2 What does this mean for the Auckland region?

A2.1 What are the air pollution impacts for our region?

Table 1 shows the estimated health impacts due to $PM_{2.5}$ and NO_2 pollution from anthropogenic sources in the Auckland region in 2016. The associated **social costs are estimated at $4.45 billion** with $0.72 billion from domestic fires and $3.60 billion from motor vehicles.

Table A-3. Health impacts for the Auckland region in 2016 due to anthropogenic air pollution (in cases)

Health effect	Cases by source (number)				
	Domestic fires	Motor vehicles	Industry	Windblown dust	Total
Cases due to both $PM_{2.5}$ and NO_2					
Premature deaths (all adults)	149	763	0.2	26	**939**
Cardiovascular hospitalisations (all ages)	355	946	0.6	63	**1,365**
Respiratory hospitalisations (all ages)	303	2,911	0.5	53	**3,268**
Asthma prevalence (0-18 yrs)		6,144			**6,144**
Restricted activity days (all ages)	279,576	153,014	435	50,106	**483,132**

A2.2 How does Auckland compare relative to the national numbers?

While Auckland's population in 2016 was approximately 34% of New Zealand's (1.59 million vs 4.71 million), the Auckland region was responsible for 29% of the national anthropogenic air pollution social costs ($4.45 billion vs $15.61 billion).

Looking at sources, the Auckland region contributed 34% of the national costs associated with total air pollution from motor vehicles but only 16% of those associated with domestic fires. Motor vehicle costs in Auckland were approximately 5.0 times greater than those for domestic fires – compared with a national average of 2.3.

Looking at pollutants, the Auckland region contributed 34% of the national costs associated with NO_2 pollution from all sources but only 20% of those associated with $PM_{2.5}$ pollution. NO_2 pollution costs in Auckland were approximately 2.6 times greater than those for $PM_{2.5}$ pollution – compared with a national average of 1.5.

A2.3 How has air quality changed in Auckland since 2006?

Between 2006 and 2016, the New Zealand population increased by nearly 13%. While national annual average $PM_{2.5}$ concentrations due to anthropogenic sources improved (reduced) by 21%, national annual average NO_2 concentrations worsened (increased) by more than 13%. As a result, **overall social costs increased by just over 10% across New Zealand**.

Over the same period, Auckland's population increased by nearly 16% and **anthropogenic air pollution social costs increased similarly by nearly 16%.**

A2.4 What have we done in Auckland to improve air quality?

The Auckland region manages air quality across 13 gazetted airsheds – Urban Airshed, Rural Airshed, and 11 Rural Towns Airsheds (Beachlands, Helensville, Kumeu, Maraetai, Pukekohe, Riverhead, Snells Beach, Waiheke Island, Waiuku, Warkworth and Wellsford)

Airsheds are air quality management areas. They typically combine areas within them that have a similar mix of sources, population density, meteorological conditions and topographical features.

Since 2006, the Auckland region has taken many steps to improve air quality, including:

- requiring all domestic heating appliances to meet the emission limit specified in the National Environmental Standards for Air Quality (**NESAQ**).
- limiting the moisture content of wood and the sulphur content of fuels used in domestic heating appliances
- banning the burning of green waste and hazardous materials, including treated timber
- supporting more compact urban form
- supporting cleaner public transport – electric trains and low emissions buses.

A2.5 What more do we need to do to improve Auckland's air quality?

Even small improvements in air quality can deliver significant health benefits. For example, reducing current (2016) levels of $PM_{2.5}$ and NO_2 air pollution by just 5% across the Auckland region would:

- reduce the number of premature deaths by 52
- reduce the number of cardiovascular and respiratory hospitalisations by 249
- reduce the number of asthma hospitalisations in children by 18
- reduce the number of restricted activity days by more than 40,800.

While Auckland's airsheds meet current ambient air quality guidelines and standards, the World Health Organization (**WHO**) has recently released new guidance on acceptable levels, based on the latest science (WHO, 2021). For many pollutants, the new guidelines are much tighter. For example, the guideline for annual average NO_2 concentrations has reduced by 75% from 40 $\mu g/m^3$ to 10 $\mu g/m^3$.

With Auckland's population projected to grow to more than two million by 2033 (Stats NZ, 2022) more people will be exposed to air pollution so reducing the associated health burden is going to be challenging. Some of the ways in which we could reduce Auckland's air pollution levels further, include:

- Reducing the amount we travel overall
- Shifting some of our trips to active modes (walking and cycling)
- Improving home insulation so we don't need to burn as much fuel to heat our homes
- Upgrading existing domestic fires to cleaner home heating methods.

Auckland's biggest challenge going forward will be in addressing motor vehicle air pollution impacts. Auckland has many arterial transport routes with people living or working close by and these people will be being more adversely affected by motor vehicle emissions than the average Aucklander.

Initiatives that encourage more walking and cycling can deliver a "trifecta" of air quality, climate change and increased activity (exercise) co-benefits.

A3 HAPINZ 3.0 key messages

Clean air matters to Kiwis

New Zealanders value clean and healthy water, oceans and air. No matter where we live, all of us deserve clean air to breathe and the opportunity to live in healthy neighbourhoods. For Māori, clean air is a *taonga* and keeping our air healthy for all is part of *kaitiakitanga*.

In New Zealand, air pollution harms are caused mainly by the type of transport we use and the fuel we burn to heat our homes

Motor vehicles are the largest contributor to air pollution health effects in New Zealand with domestic fires in second place. However, we need to address effects from both PM (dominated by domestic fires) and NO_2 (dominated by motor vehicles).

Since 2006, despite significant improvements in domestic fire emissions, growth in the vehicle fleet (especially diesel vehicles) and the number of people exposed has resulted in the social costs associated with air pollution increasing by more than 10%. So more still needs to be done to reflect the value we place on clean air and good health.

Air pollution is hurting people, especially children

Air pollution does significant harm to many New Zealanders, especially children. It is unacceptable.

Levels of particulate matter (**PM**) in New Zealand's air have improved steadily since 2006 in response to people taking action to reduce the impact of woodburners used to heat homes in winter-time. However, we now know much more about the harms associated with gases emitted from motor vehicles – in particular nitrogen dioxide (**NO_2**). Not only are the impacts more significant than we expected, exposure to even low levels can be harmful. This is a new finding for New Zealand and one that is now being confirmed in other places around the world.

Some communities have a greater burden of harm

The effects of air pollution are not experienced evenly in the community across New Zealand. Not everyone lives in a place where they can breathe clean air in New Zealand but our findings (and especially the HAPINZ model) will help us to identify where best to focus on air quality improvements. Many of the options that will improve air quality can deliver co-benefits like improved housing conditions and improved transport/accessibility to communities.

Improvements in air quality make a difference to people's health

Making improvements in air quality, even small ones, significantly improves the health of many New Zealanders, including many children.

There are solutions and they can build on what people in government have already started

There are concrete things that can be done to improve air quality in all communities, especially those where air pollution is high. Improvements by people in government, especially in relation to helping us change our systems of transport and improve the built environment will give everyone the opportunity to breathe clean air and experience good health.

Local government has been working hard to clean up pollution from domestic fires and has delivered cleaner air to many local communities. However, the good work needs to continue to ensure people's exposure continues to reduce, especially with populations increasing in many urban areas.

Over the past two years, COVID-19 changed the way New Zealanders work and travel. Lockdowns and increased flexible working significantly reduced transport emissions, thereby improving air quality at least in the short term. Some of these changes are likely to be permanent, thereby improving New Zealand's air quality and associated health costs in future.

The government has already identified a raft of climate change initiatives (e.g. increasing public transport, walking and cycling) to address vehicle-related greenhouse gas emissions which will deliver air quality benefits. Initiatives that encourage more walking and cycling can deliver a "trifecta" of air quality, climate change and increased activity (exercise) co-benefits.

Appendix B: Sources of air contaminants in Auckland.

Pollutant	Source	Site(s) impacted	References
PM, black carbon, CO, SO_2, NOx, VOCs	Domestic activities – dominated by emissions from solid fuel fires (biomass burning) used for domestic heating during cold days, lawn mowing	All sites	Davy et al. (2017), Metcalfe et al. (2018), Xie et al. (2019), Sridhar and Metcalfe (2019), Talbot and Crimmins (2020)
PM, CO, NO_2, black carbon, SO_2, VOCs	Land and air transport – motor vehicles, aviation, rail, road dust (sealed and unsealed), off-road vehicles and road laying	All sites	Davy et al. (2017), Metcalfe et al. (2018), Crimmins (2018), Sridhar and Metcalfe (2019), Xie et al. (2019), Talbot and Crimmins (2020)
PM	Local wind-blown soil or road dust sources	All sites	Davy et al. (2017)
PM	Katabatic wind flows down the Wairau Valley	Takapuna	Davy et al. (2017)
PM	Marine aerosol (Sea spray)	All sites	Davy et al. (2017), Talbot and Crimmins (2020)
PM	Secondary particulate matter resulting from atmospheric gas-to-particle conversion processes (sulphate and nitrate species, organic particle species resulting from photochemical reactions)	All sites	Davy et al. (2017), Talbot and Crimmins (2020)
PM	Long range transport of industrial emissions	Takapuna, Penrose, Queen Street, Khyber Pass Road	Davy et al. (2017)
PM	Fireworks displays and other special events	All sites	Davy et al. (2017)
PM, NO_2	Short-term road works and demolition/construction activities	All sites	Font et al. (2014), Davy et al. (2017), Talbot and Crimmins (2020)

Pollutant	Source	Site(s) impacted	References
PM, SO_2, CO, NOx, VOCs	Sea transport – ocean going vessels, harbour vessels, ferries and port cargo handling equipment	Queen Street, Takapuna, Customs Street	Davy et al.(2017), Peeters (2018), Talbot and Crimmins (2020)
PM, SO_2, NOx, CO, VOCs	Local commercial/industrial activities	Khyber Pass Road, Penrose, Henderson, Takapuna	Davy et al. (2017), Crimmins (2018), Talbot and Crimmins (2020)
PM	Trans-boundary events such as bush fires or dust storms in Australia	All sites	Davy et al.(2017), Talbot and Crimmins (2020)
SO_2	White Island volcano	Penrose	Davy et al.(2017)

Appendix C: Meteorological parameters descriptive statistics.

Ambient temperature					
Site	Year	Annual mean (°C)	Std. Deviation	Significant?*	Change**
Glen Eden	2021	15.6	4.3	Yes	↑
	2022	16.0	3.2		
Penrose	2021	16.7	3.9	Yes	↑
	2022	17.0	3.3		
Queen Street	2021	17.2	3.7	Yes	↑
	2022	17.7	3.7		
Pakuranga	2021	15.4	5.0	No	↗
	2022	15.6	3.4		
Papatoetoe	2021	16.1	4.3	Yes	↑
	2022	16.6	4.4		
Takapuna	2021	16.2	3.9	Yes	↑
	2022	17.0	3.6		
Henderson	2021	16.0	4.3	Yes	↑
	2022	16.5	3.3		
Auckland	2021	16.2	4.2	Yes	↑
	2022	16.8	3.3		
Ambient relative humidity					
Site	Year	Annual mean(%)	Std. Deviation	Significant? *	Change**
Glen Eden	2021	72.6	13.0	No	↗
	2022	72.9	4.3		
Penrose	2021	69.8	12.3	No	↗
	2022	70.5	4.2		
Queen Street	2021	64.7	12.5	No	↗
	2022	65.2	3.9		
Pakuranga	2021	70.4	12.9	Yes	↗
	2022	71.7	4.6		
Papatoetoe	2021	71.5	12.8	Yes	↑
	2022	73.7	14.3		
Takapuna	2021	70.4	11.9	No	↗
	2022	71.0	5.0		
Henderson	2021	71.3	13.4	No	↗
	2022	71.7	4.7		
Auckland	2021	69.4	13.0	No	↗
	2022	71.0	5.0		

↗ Increased but not significant

↑ Increased

* Mean difference

Appendix D: Mean difference comparison between 2022 and 2022: t-test results.

Site	Pollutant	p-value	t/F	Significant?	Change*
Penrose	SO_2	0.102	1.7	No	↗
Customs Street		0.035	1.9	Yes	↑
Auckland		0.043	684	Yes	↑
Customs Street	Black carbon	0.000	15.1	Yes	↓
Henderson		0.000	4.4	Yes	↑
Auckland		0.000	250.1	Yes	↑
Khyber Pass Road	CO	0.000	-5.8	Yes	↓
Patumahoe	O_3	0.000	14.2	Yes	↑
Patumahoe	NO_2	0.000	36.7	Yes	↑
Penrose		0.006	2.8	Yes	↑
Queen Street		0.000	-49.7	Yes	↓
Customs Street		0.000	-4.2	Yes	↓
Glen Eden		0.000	27.4	Yes	↑
Khyber Pass Road		0.000	-8.2	Yes	↓
Henderson		0.000	16.9	Yes	↑
Takapuna		0.000	5.3	Yes	↑
Auckland		0.085	-8.7	Yes	↘
Patumahoe	PM_{10}	0.176	-1.4	No	↘
Penrose		0.463	0.7	No	↗
Queen Street		0.032	2.1	Yes	↑
Glen Eden		0.104	-1.6	No	↘
Pakuranga		0.000	7.5	Yes	↑
Papatoetoe		0.000	-15.3	Yes	↓
Khyber Pass Road		0.000	22.4	Yes	↑
Henderson		0.113	-1.6	Yes	↘
Takapuna		0.000	8.9	Yes	↑
Auckland		0.000	33.1	Yes	↑
Queen Street	$PM_{2.5}$	0.000	8.2	Yes	↑
Penrose		0.000	5.6	Yes	↓
Patumahoe		0.000	3.6	Yes	↑
Takapuna		0.017	2.4	Yes	↓
Auckland		0.026	2.2	Yes	↑
Penrose	TSP	0.722	0.357	No	↘
Penrose	Pb in TSP	0.000	4.8	Yes	↓
*	↓	Decreased			
	↑	Increased			
	↗	Increased but not significant			
	↘	Decreased but not significant			

Appendix E: Calendar plots for PM_{10} 24-hr mean concentration.

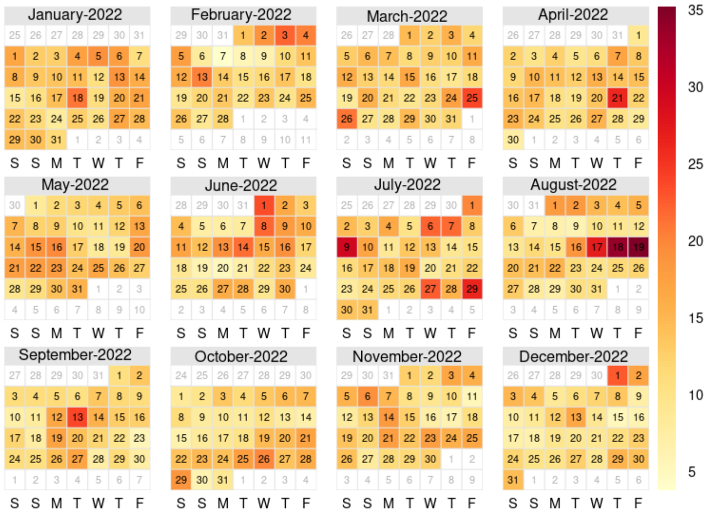


Figure E1. Calendar plot for PM_{10} concentrations in 2022 – nine sites combined.

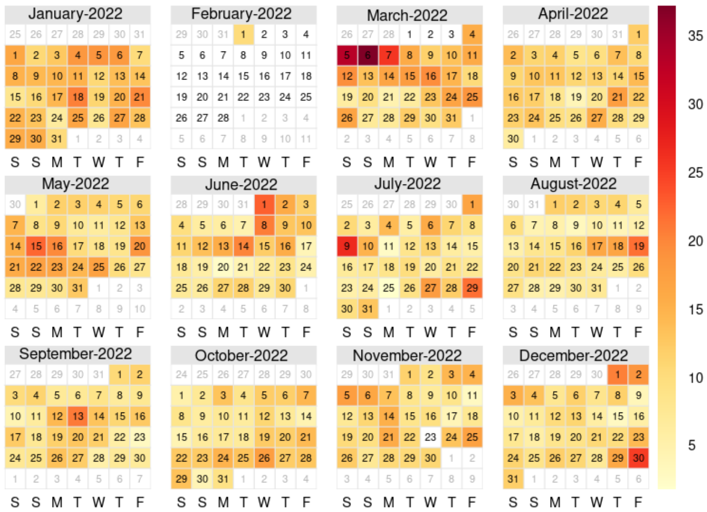


Figure E2. Calendar plot for PM_{10} concentrations in Patumahoe.

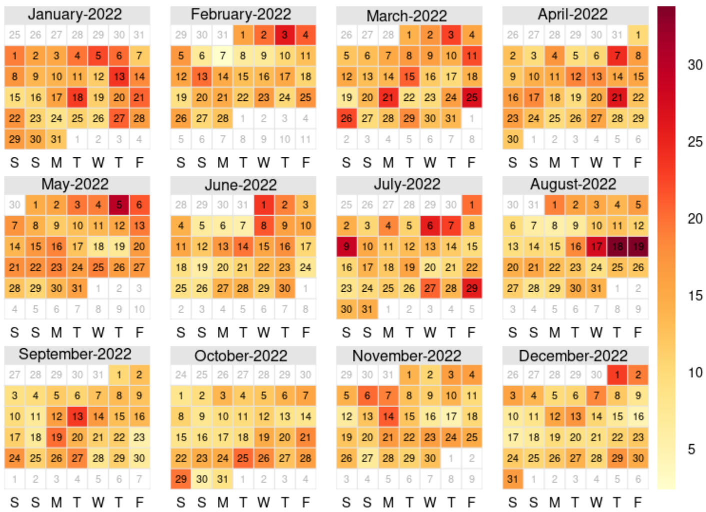


Figure E3. Calendar plot for PM_{10} concentrations in Penrose.

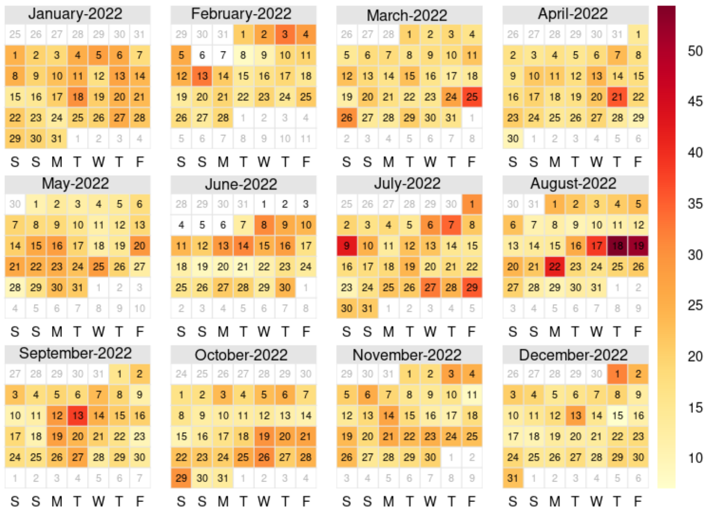


Figure E4. Calendar plot for PM_{10} concentrations in Queen.

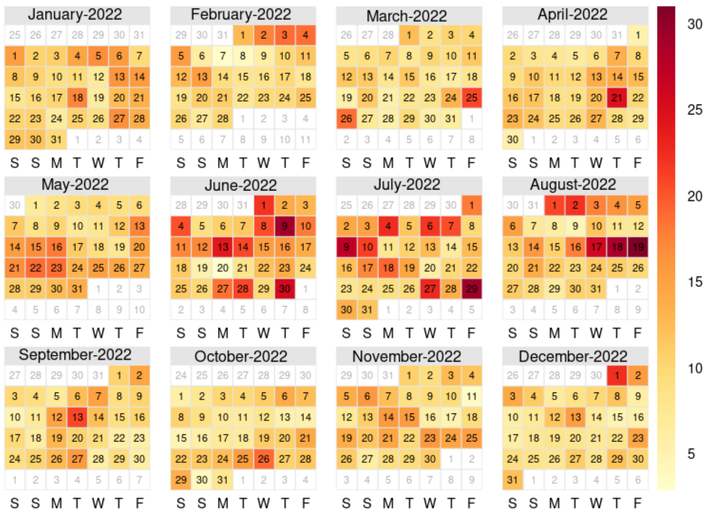


Figure E5. Calendar plot for PM_{10} concentrations in Glen Eden site.

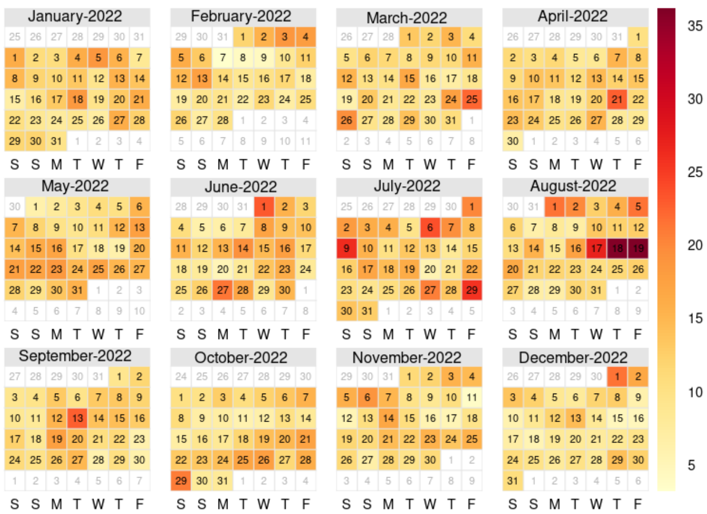


Figure E6. Calendar plot for PM_{10} concentrations in Pakuranga.

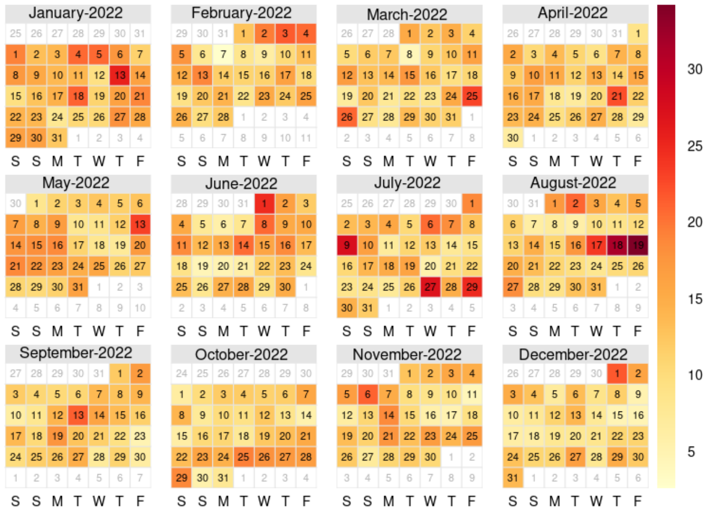


Figure E7. Calendar plot for PM_{10} concentrations in Papatoetoe

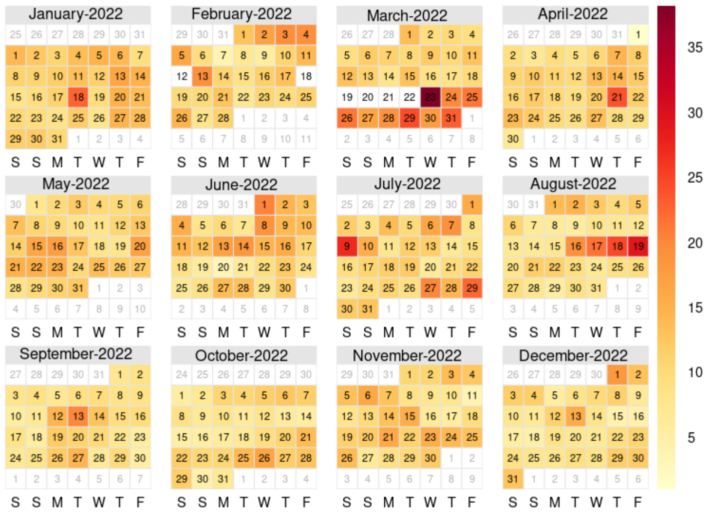


Figure E8. Calendar plot for PM_{10} concentrations in Henderson.

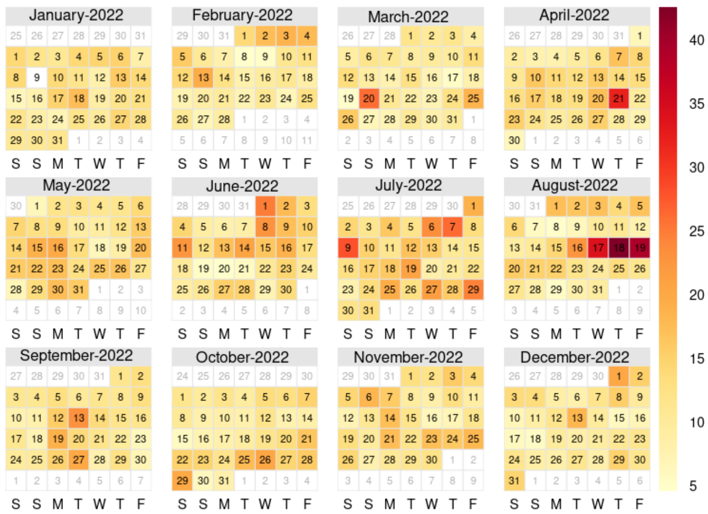


Figure E9. Calendar plot for PM_{10} concentrations in Takapuna.

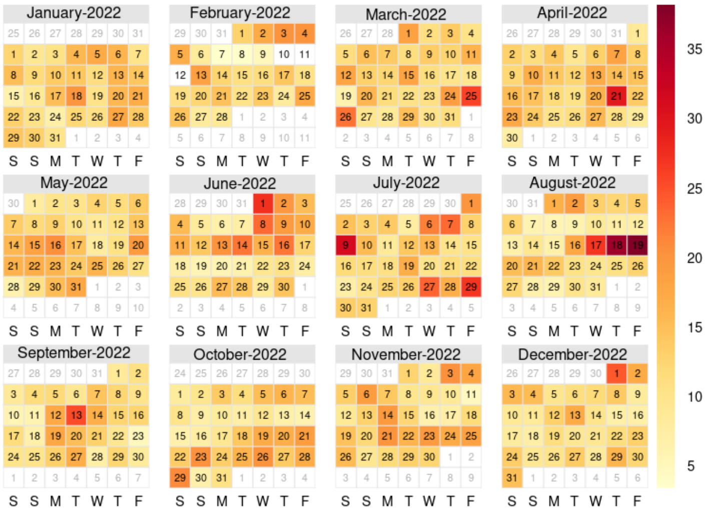


Figure E10. Calendar plot for PM_{10} concentrations in Khyber Pass Road.

Appendix F: Calendar plots for $PM_{2.5}$ 24-hr mean concentration.

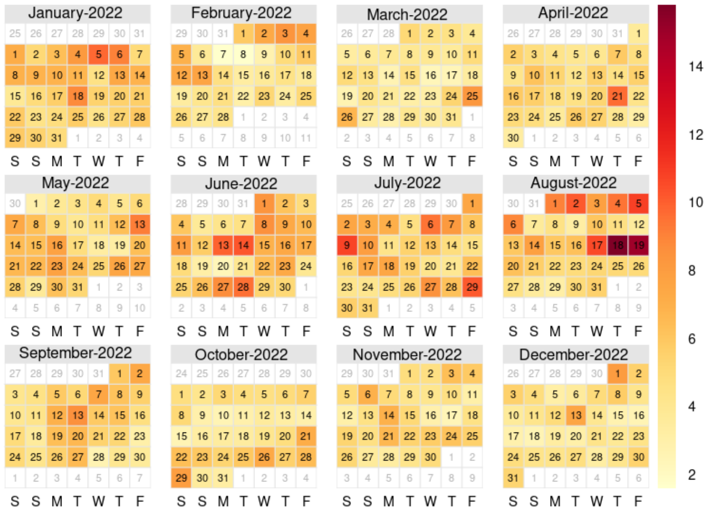


Figure F1. Calendar plot for Auckland $PM_{2.5}$ concentrations in 2022 (seven sites combined).

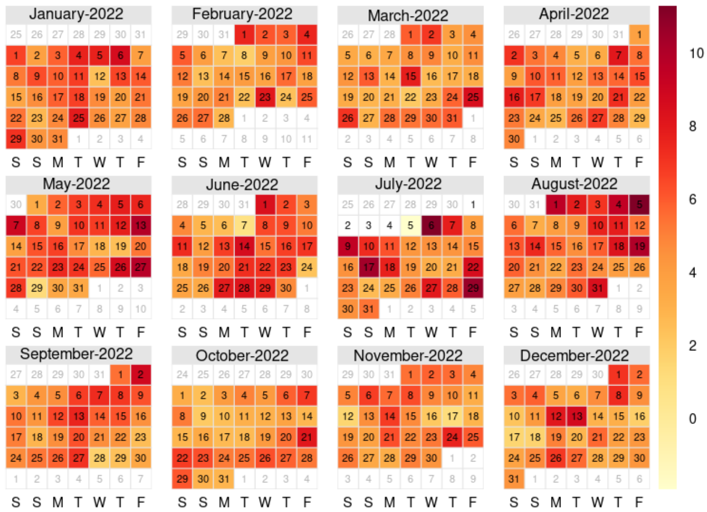


Figure F2. Calendar plot for $PM_{2.5}$ concentrations in Penrose.

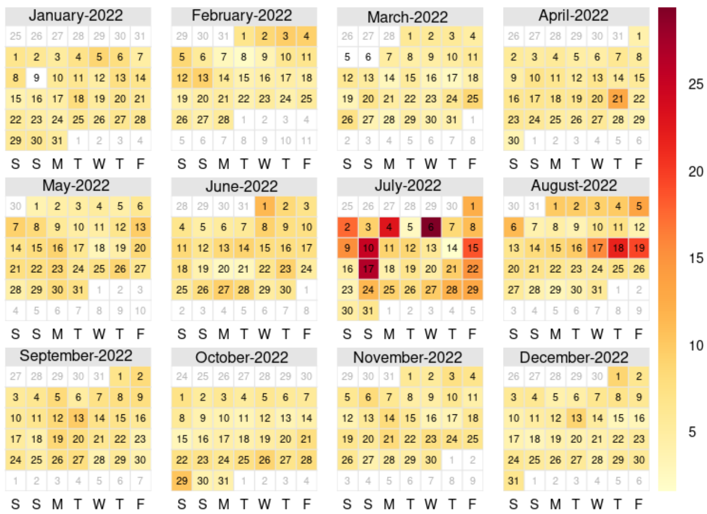


Figure F3. Calendar plot for $PM_{2.5}$ concentrations in Takapuna.

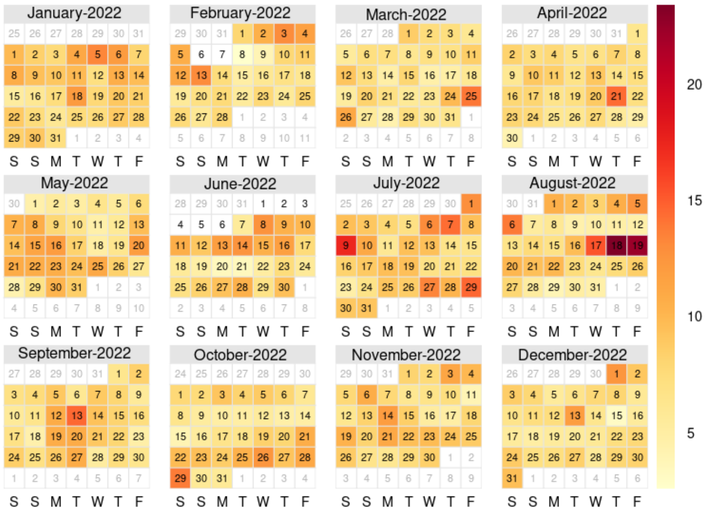


Figure F4. Calendar plot for $PM_{2.5}$ concentrations in Queen Street.

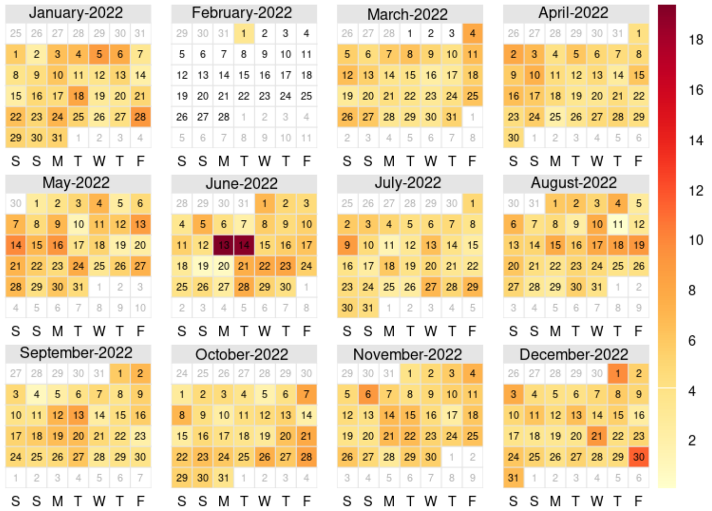


Figure F5. Calendar plot for $PM_{2.5}$ concentrations in Patumahoe.

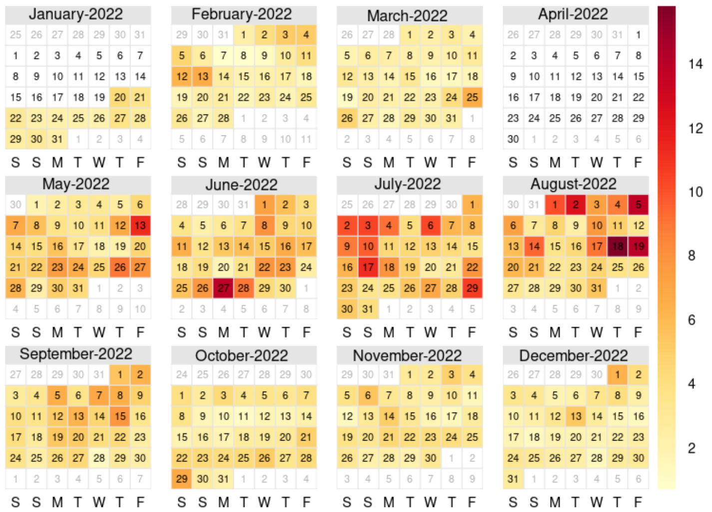


Figure F6. Calendar plot for $PM_{2.5}$ concentrations in Pakuranga.

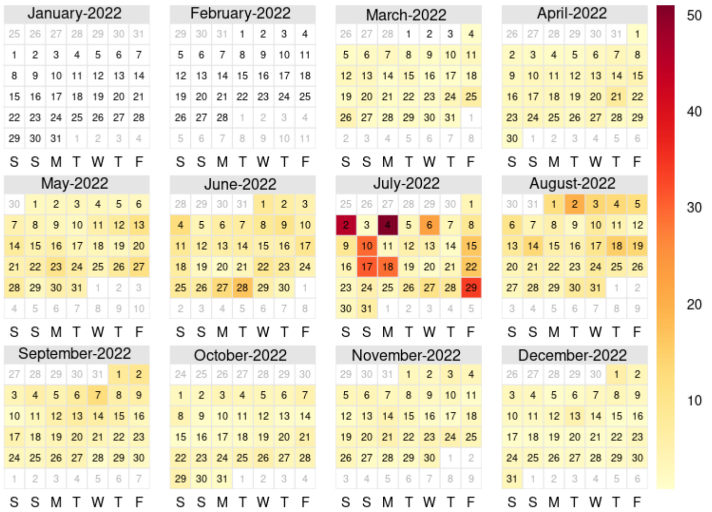


Figure F7. Calendar plot for $PM_{2.5}$ concentrations in Glen Eden.

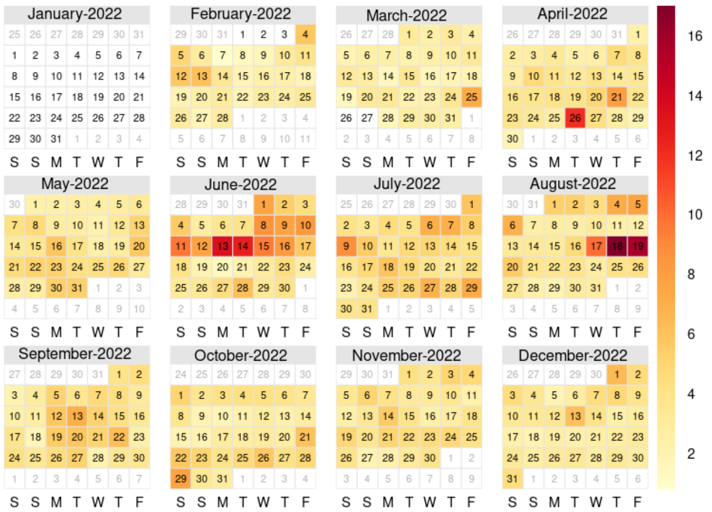


Figure F8. Calendar plot for $PM_{2.5}$ concentrations in Customs Street.

Appendix G: Calendar plots for NO_2 1-hour mean concentration.

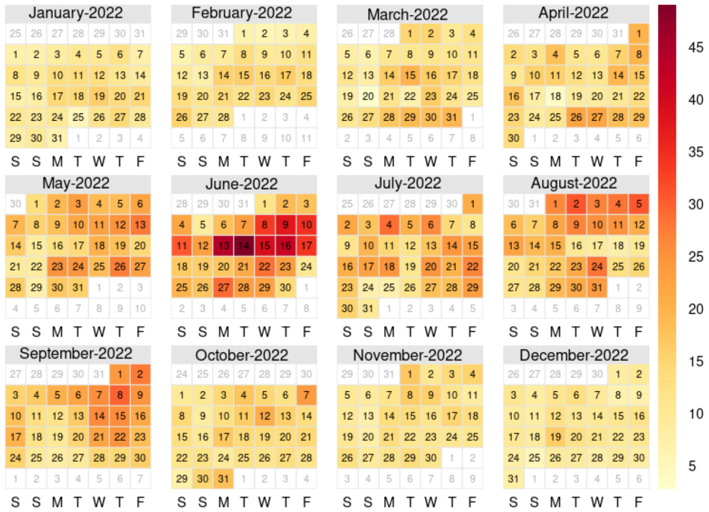


Figure G1. Calendar plot for NO_2 concentrations in 2022 – eight sites combined.

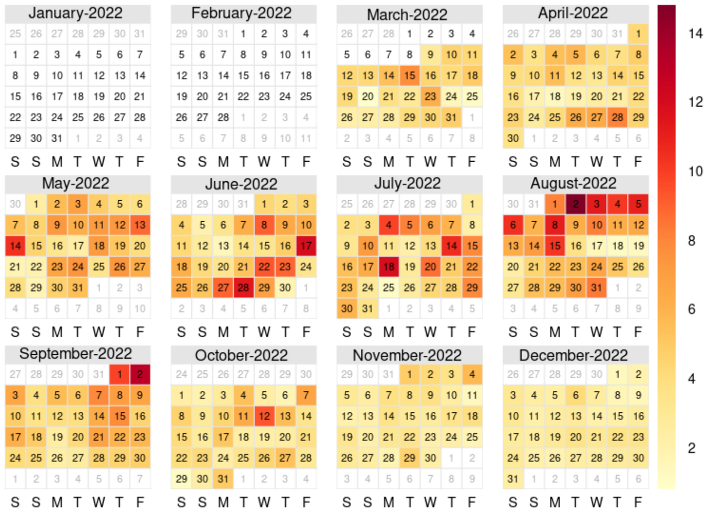


Figure G2. Calendar plot for NO_2 concentrations in Patumahoe.

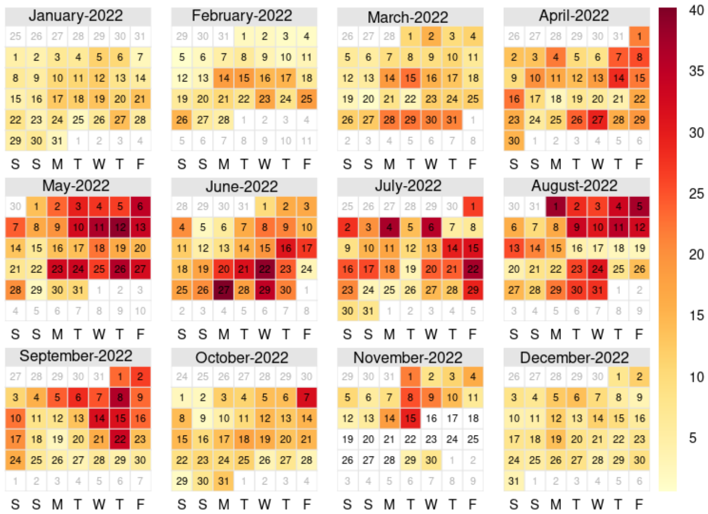


Figure G3. Calendar plot for NO_2 concentrations in Penrose.

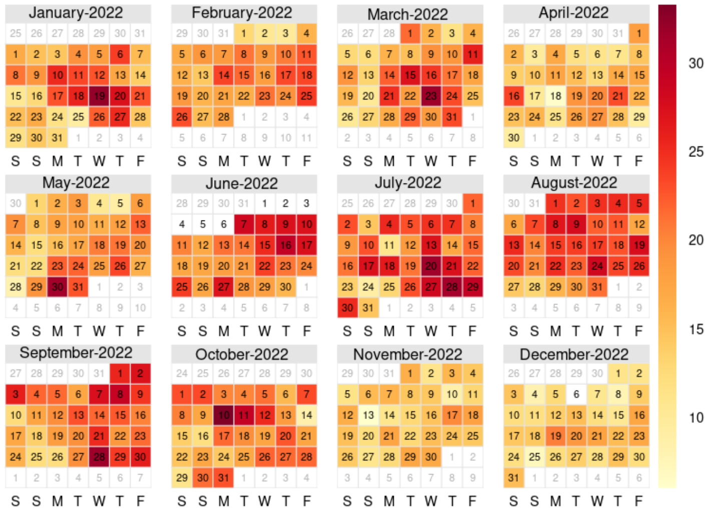


Figure G4. Calendar plot for NO_2 concentrations in Queen Street.

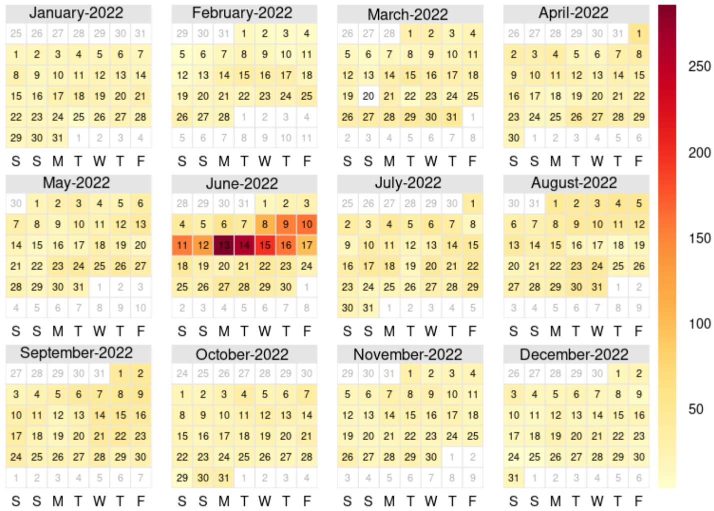


Figure G5. Calendar plot for NO_2 concentrations in Customs Street.

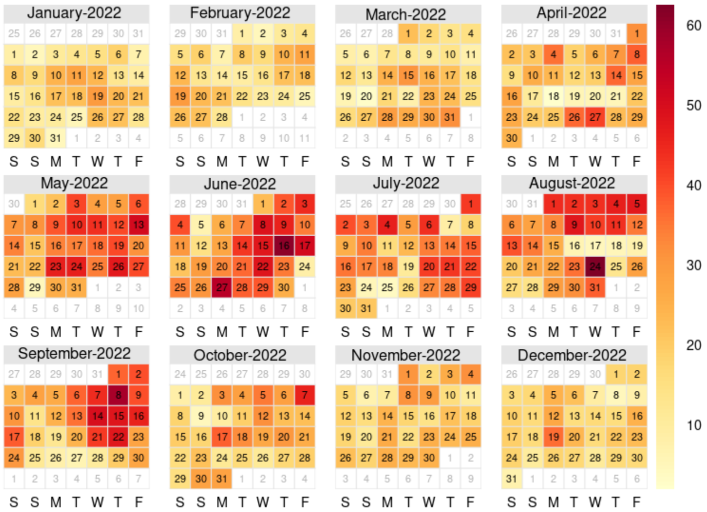


Figure G6. Calendar plot for NO_2 concentrations in Khyber Pass Road.

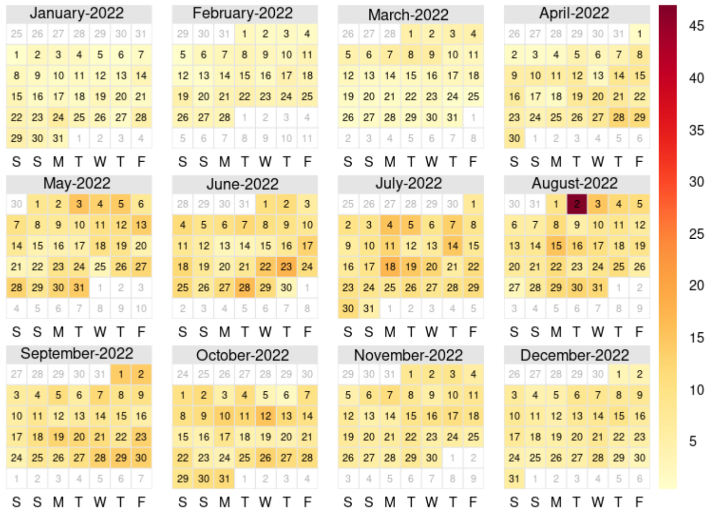


Figure G7. Calendar plot for NO_2 concentrations in Glen Eden.

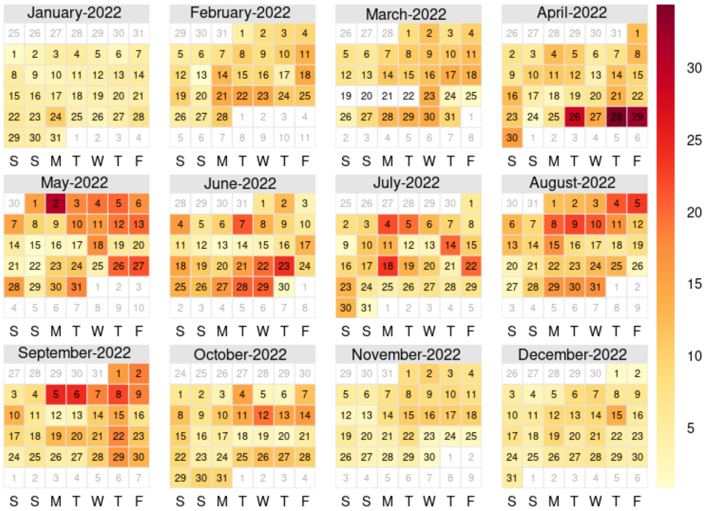


Figure G8. Calendar plot for NO_2 concentrations in Henderson.

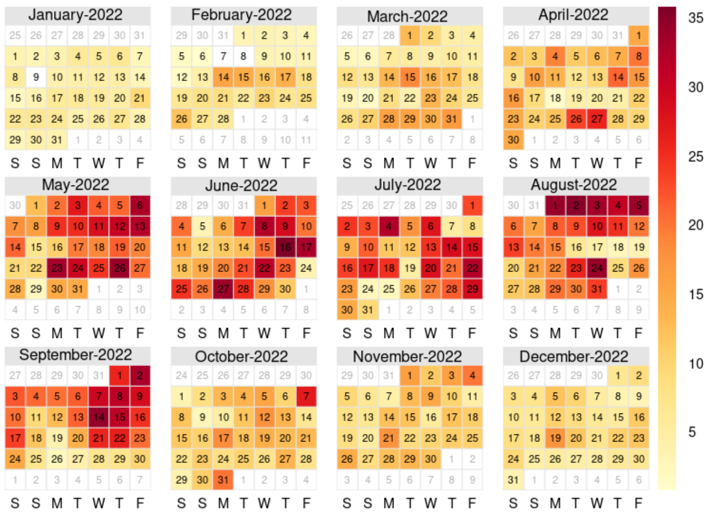


Figure G9. Calendar plot for NO_2 concentrations in Takapuna.

Appendix H: NZTA measurement of NO_2 by passive diffusion tubes.

Table H1. Auckland sites description, annual averages(µg/m³) and percentage data coverage

Site ID	Coordinates (NZTM)		Area	Site name	Annual average		% valid data	
	Easting	Northing			2021	2022	2021	2022
AUC004	1750133	5949359	Orewa	Grand Dr / Tauranga Pl	14.0	12.8	70%	75%
AUC005	1753095	5935106	Albany	Oteha Valley Rd / Fairview Ave	18.6	18.1	70%	92%
AUC007	1756065	5923935	Northcote	Northern Motorway / Sulphur Beach Rd	21.4	21.6	70%	92%
AUC008	1755662	5921138	St Mary's Bay	Northern Motorway / St Mary's Bay Rd	20.4	22.2	60%	67%
AUC009	1756848	5919273	Newton	CMJ / Canada St	39.0	36.9	70%	92%
AUC011	1758969	5917106	Remuera	Southern Motorway / Mt Hobson Rd	27.4	25.3	70%	83%
AUC013	1761757	5914171	Penrose	Southern Motorway / Gavin St b	24.0	22.3	90%	100%
AUC014	1761757	5914171	Penrose	Southern Motorway / Gavin St c	24.4	21.5	90%	100%
AUC015	1761757	5914171	Penrose	Southern Motorway / Gavin St d	24.1	21.4	90%	100%
AUC018	1767509	5905866	Flat Bush	Southern Motorway / Waimate St	24.8	21.7	60%	75%
AUC019	1767713	5903803	Manukau	Southern Motorway / Liggett Dr	20.1	23.1	70%	50%
AUC020	1744702	5921634	Massey East	North Western Motorway / Redwood Dr	14.6	12.3	70%	92%
AUC021	1751667	5917766	Waterview	Waterbank Cres	18.3	18.3	70%	83%
AUC022	1755717	5918398	Arch Hill	North Western Motorway / Niger St	22.0	19.7	60%	83%
AUC025	1756246	5912958	Hillsborough	Hugh Watt Dr / Melrose Rd	17.7	17.5	70%	75%
AUC026	1759570	5909661	Mangere	South Western Motorway / Hastie Ave	21.3	23.6	70%	92%
AUC027	1760143	5908270	Mangere	South Western Motorway / Ashmore Pl	21.3	18.8	70%	50%
AUC039	1752074	5930540	Unsworth Heights	Albany Highway / Ashby Pl	14.6	13.4	70%	83%
AUC040	1749755	5928069	Greenhithe	Upper Harbour Dr / William Pitcher Pl	15.2	13.7	60%	67%
AUC041	1753390	5929775	Glenfield	Glenfield Rd / Sunset Rd	20.1	19.4	60%	92%
AUC042	1758078	5927136	Takapuna	Lake Rd / Service Ln	20.9	19.9	90%	100%
AUC043	1756069	5928070	Takapuna	Northern Motorway / Wairau Rd	20.7	17.3	80%	100%
AUC044	1756069	5928070	Takapuna	Northern Motorway / Wairau Rd	20.3	21.0	90%	67%
AUC045	1756069	5928070	Takapuna	Northern Motorway / Wairau Rd	19.8	17.7	80%	100%
AUC046	1758428	5926591	Takapuna	Lake Rd / Esmonde Rd	20.1	20.4	90%	67%
AUC047	1753696	5927375	Marlborough	Woodcote Dr	7.7	8.2	70%	92%
AUC049	1747171	5926306	Hobsonville	Hobsonville Rd / Carnegie Cres	21.5	23.5	70%	83%
AUC050	1742288	5926712	Whenuapai	SH16 / Kennedys Rd	22.5	20.5	90%	100%
AUC051	1744980	5921293	Massey East	North Western Motorway / Taitapu St	17.2	16.9	60%	92%
AUC052	1745187	5916791	Henderson	Henderson Valley Rd / Hickory Ave	14.4	13.9	90%	100%
AUC053	1746833	5918830	Te Atatu Sth	Te Atatu Rd / Edmonton Rd	25.3	25.0	90%	75%
AUC054	1745135	5918515	Henderson	Lincoln Rd / Henderson Intermediate	12.5	11.9	90%	100%
AUC055	1745135	5918515	Henderson	Lincoln Rd / Henderson Intermediate	12.0	11.7	90%	100%
AUC056	1745135	5918515	Henderson	Lincoln Rd / Henderson Intermediate	12.8	12.3	80%	100%
AUC057	1747149	5912480	Glen Eden	AC Glen Eden	6.9	6.1	90%	92%
AUC058	1747149	5912480	Glen Eden	AC Glen Eden	6.8	6.0	90%	92%
AUC059	1747149	5912480	Glen Eden	AC Glen Eden	6.6	6.1	90%	92%
AUC060	1752890	5916596	Mt Albert	New North Rd / Mount Albert Rd	25.1	24.1	70%	83%
AUC061	1759938	5915778	Greenlane	Great South Rd / Green Ln East	25.5	24.1	70%	75%
AUC062	1764307	5914946	Mt Wellington	Ellerslie Panmure Highway / Mountain Rd	20.3	18.4	90%	100%
AUC063	1749443	5913945	New Lynn	Great North Rd / Rata St	25.8	23.7	90%	100%
AUC064	1755692	5917809	Kingsland	Sandringham Rd / Kowhai Intermediate	17.1	15.9	90%	100%
AUC067	1761844	5906521	Mangere East	Southwestern Motorway / Ensor Pl	24.8	23.7	60%	83%
AUC069	1766535	5908095	Otara	Bairds Rd / Otara Rd	24.5	23.0	70%	83%
AUC070	1774740	5896065	Papakura	Dominion Rd / Settlement Rd	14.9	15.6	80%	50%
AUC071	1763755	5908915	Otahuhu	Mangere Rd / Walmsley Rd	24.8	23.2	60%	67%
AUC072	1768412	5913942	Pakuranga	Pakuranga Rd / Bell Reserve	16.6	15.9	90%	83%
AUC073	1771370	5912359	Botany	AC Botany	10.0	8.9	80%	67%

Site ID	Coordinates (NZTM)		Area	Site name	Annual average		% valid data	
	Easting	Northing			2021	2022	2021	2022
AUC115	1747004	5919893	Te Atatu	Northwestern Motorway / Titoki St 1	15.2	15.1	70%	75%
AUC170	1755482	5928973	Westlake	Northern Motorway / Tristram Ave	30.0	27.8	70%	75%
AUC171	1720175	6049513	Tikipunga	Korau Rd	8.3	9.5	80%	50%
AUC187	1718687	6045757	Avenues	Western Hills Dr / Central Ave	26.9	27.3	80%	50%
AUC190	1759358	5906628	Mangere	George Bolt Memorial Dr / Desford Pl	21.2	18.6	70%	75%
Auckland					19.3	18.4	77%	83%

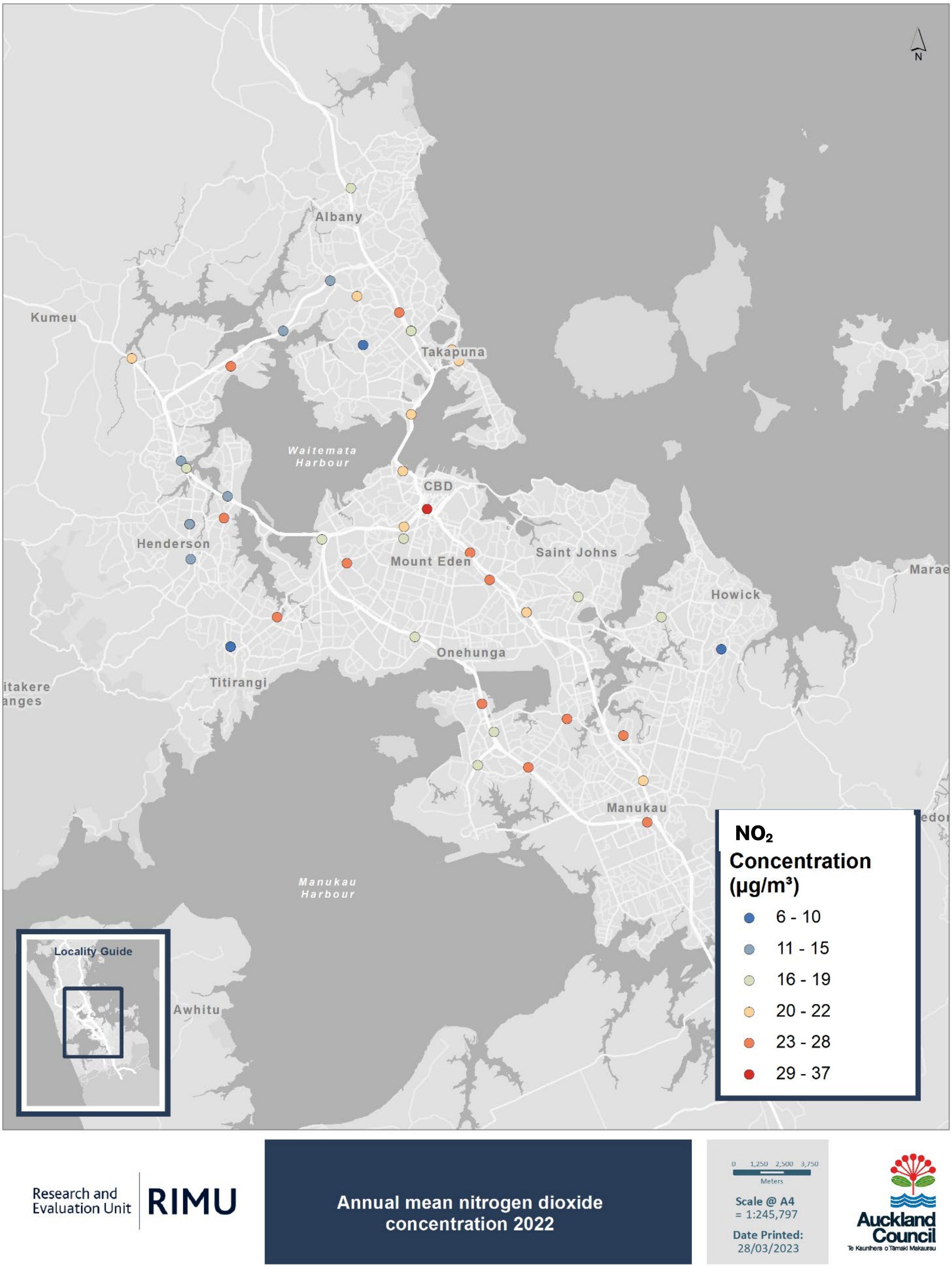


Figure H1. NZTA – Air quality monitoring network measurement of NO_2 by passive diffusion tubes: annual mean concentration across Auckland sites.

Appendix I: Calendar plots for SO_2 24-hr mean concentration.

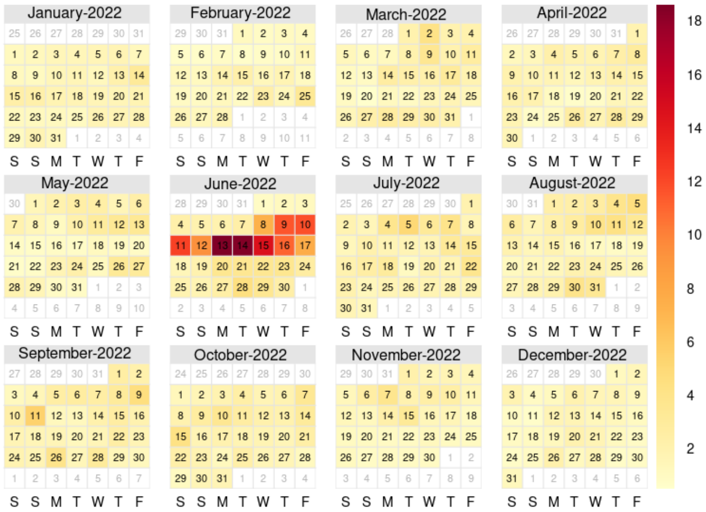


Figure I1. Calendar plot for SO_2 concentrations in 2022 – two sites combined.

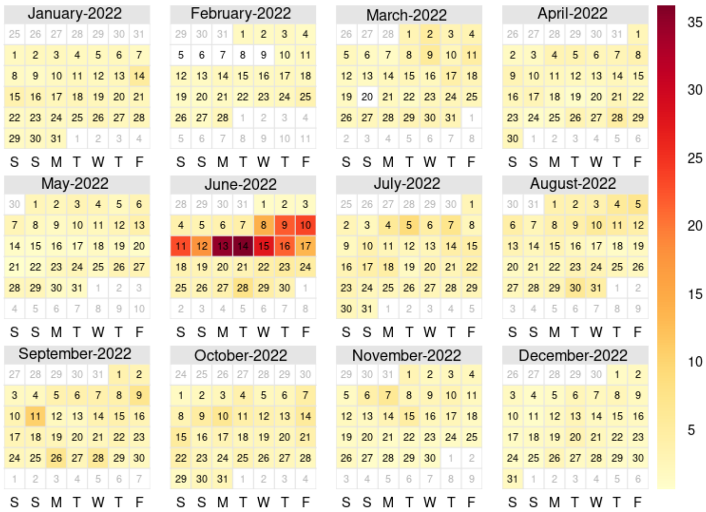


Figure I2. Calendar plot for SO_2 concentrations in Customs Street.

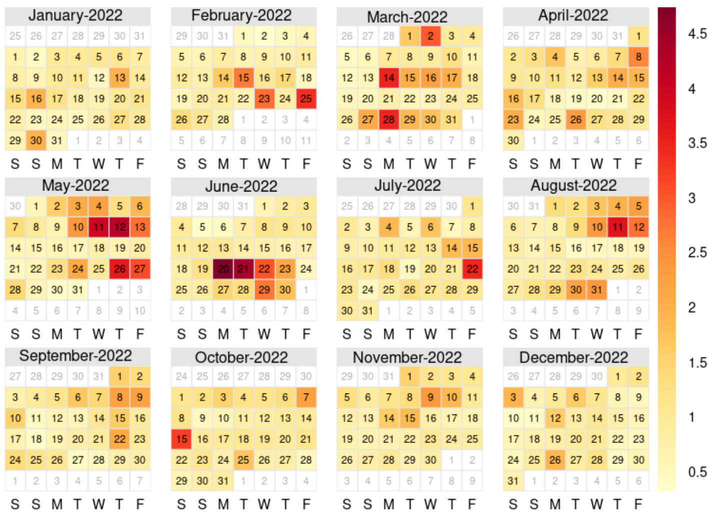


Figure I3. Calendar plot for SO_2 concentrations in Penrose.

Appendix J: Calendar plots for CO 24-hr mean concentration.

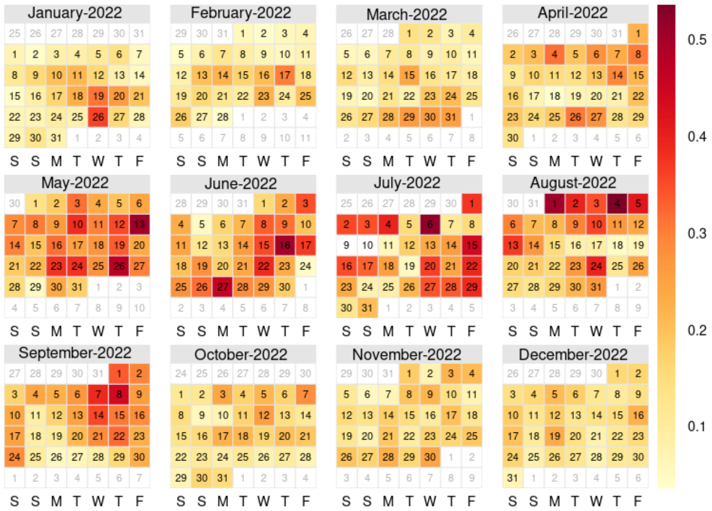


Figure J1. Calendar plot for CO concentrations in Khyber Pass Road.

Appendix K: Calendar plots for O_3 24-hr mean concentration.

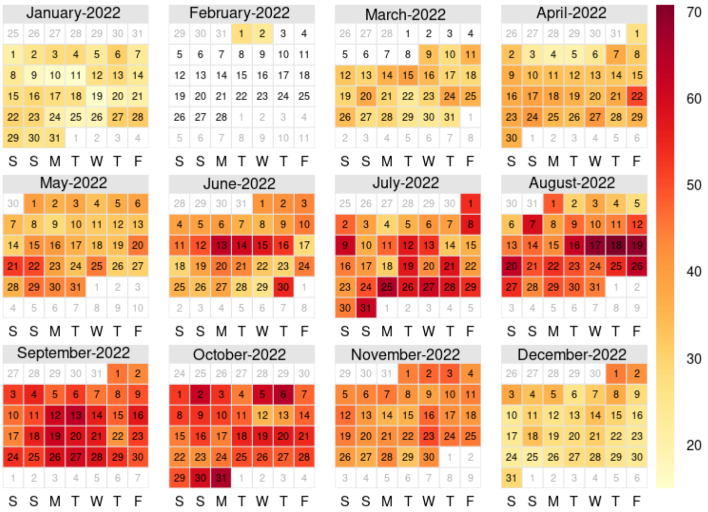


Figure K1. Calendar plot for ozone concentrations in Patumahoe.

Appendix L: Calendar plots for black carbon 24-hr mean concentration.

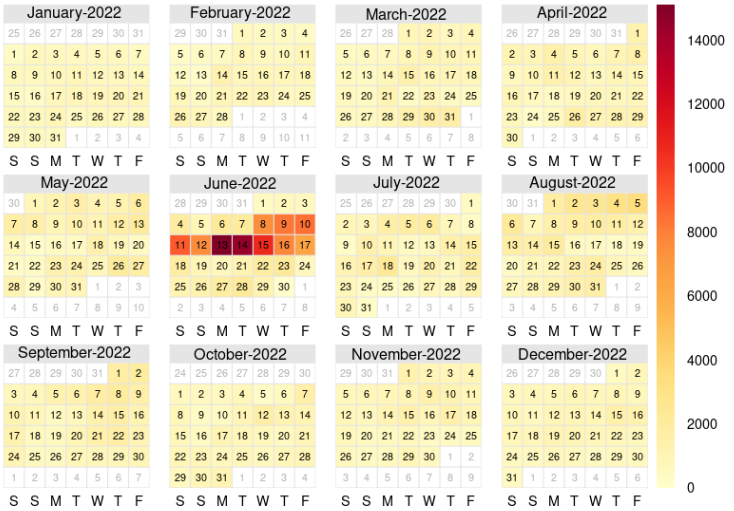


Figure L1. Calendar plot for black carbon concentrations in 2022 – two sites combined.

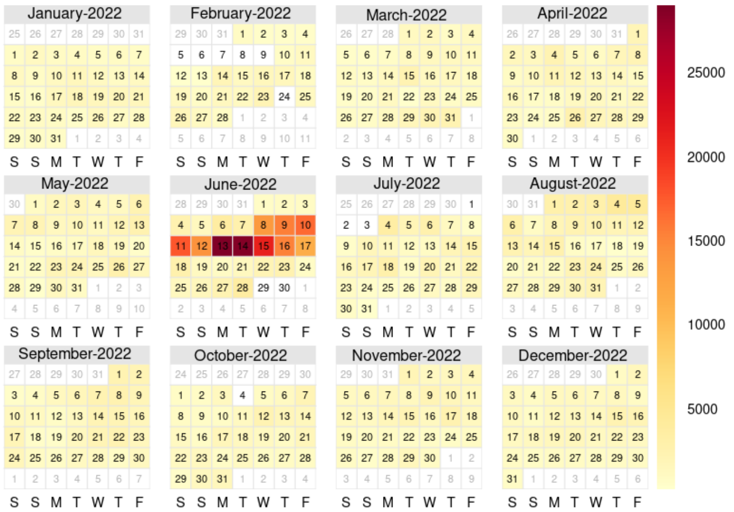


Figure L2. Calendar plot for black carbon concentrations in Customs Street.

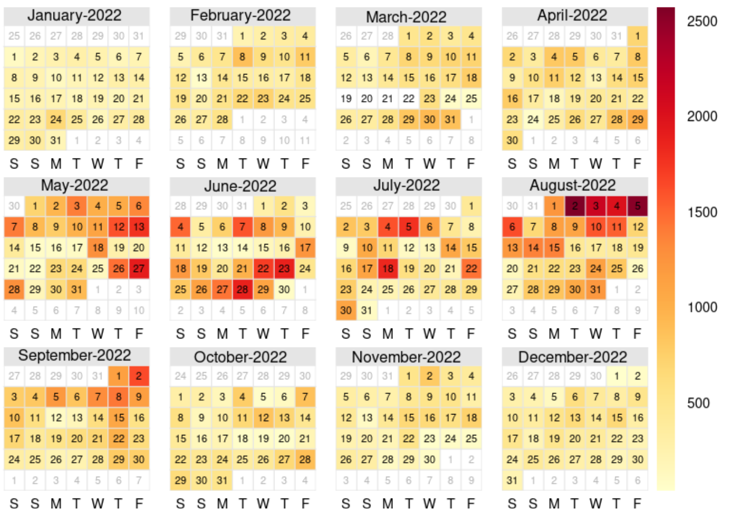


Figure L3. Calendar plot for black carbon concentrations in Henderson.

Appendix M: Data coverage across the sites – 2021 and 2022.

Pollutant	Site	Year	Data coverage (%)
PM_{10}	Glen Eden	2022	99.4
		2021	95.0
	Henderson	2022	94.5
		2021	93.0
	Khyber Pass Road	2022	97.0
		2021	97.5
	Pakuranga	2022	82.3
		2021	96.0
	Papatoetoe	2022	98.8
		2021	97.0
	Patumahoe	2022	88.7
		2021	92.6
	Penrose	2022	98.8
		2021	95.2
	Queen Street	2022	96.8
		2021	99.6
	Takapuna	2022	**98.9**
		2021	95.3
$PM_{2.5}$	Customs Street	2022	89.5
		2021	56.0
	Glen Eden	2022	82.8
		2021	55.1
	Pakuranga	2022	50.0
		2021	62.2
	Patumahoe	2022	84.7
		2021	89.0
	Penrose	2022	94.8
		2021	90.0
	Queen Street	2022	96.8
		2021	100.0
	Takapuna	2022	98.3
		2021	86.9
NO_2	Customs Street	2022	95.5
		2021	97.0
	Glen Eden	2022	97.3
		2021	94.9
	Henderson	2022	96.1
		2021	97.6
	Khyber Pass Road	2022	97.1
		2021	98.7
	Patumahoe	2022	78.9
		2021	93.8

Pollutant	Site	Year	Data coverage (%)
	Penrose	**2022**	91.6
		2021	92.0
	Queen Street	**2022**	94.7
		2021	97.0
	Takapuna	**2022**	96.0
		2021	94.8
SO_2	**Customs Street**	**2022**	93.8
		2021	96.0
	Penrose	**2022**	95.0
		2021	95.1
O_3	**Patumahoe**	**2022**	89.0
		2021	94.1
CO	**Khyber Pass Road**	**2022**	96.4
		2021	96.6
Black carbon	**Customs Street**	**2022**	95.0
		2021	95.5
	Henderson	**2022**	**97.4**
		2021	**96.2**

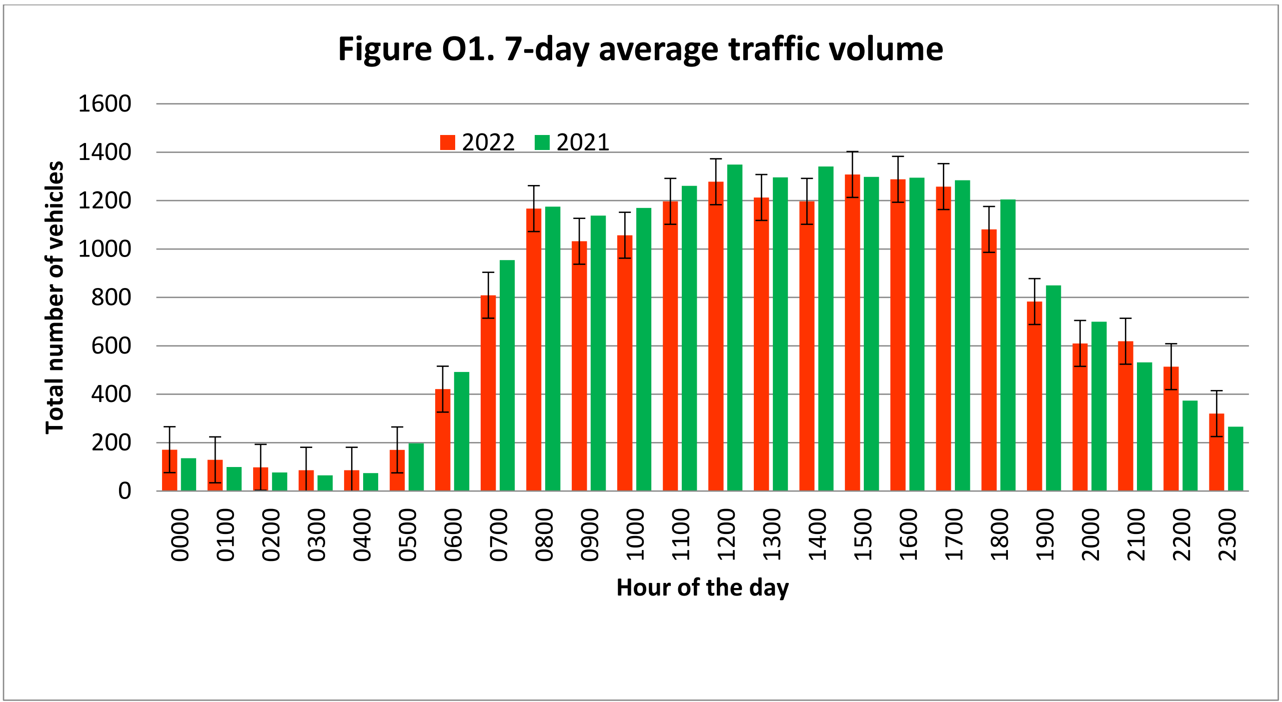
Appendix N: Monthly averages: 2022 and past 2-5 years.

Pollutant	Site	Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PM_{10} (µg/m^3)	Glen Eden	2022	11.7	10.5	9.6	10.6	12.3	15.0	14.6	13.6	10.3	9.7	11.0	9.7
		Past 5 years	12.6	11.1	9.4	11.0	13.5	15.4	15.8	13.8	11.8	10.6	11.7	13.2
	Henderson	2022	12.2	11.7	13.8	11.1	11.7	11.9	12.3	10.7	9.3	9.4	11.0	9.2
		Past 5 years	12.7	11.4	10.4	11.6	12.8	13.3	13.2	12.5	11.6	11.1	12.2	13.2
	Khyber Pass Road	2022	13.0	12.3	13.4	13.7	13.1	13.7	14.6	13.0	11.7	12.0	13.4	11.9
		Past 5 years	16.2	14.5	13.5	13.6	14.2	13.2	13.7	13.1	13.1	12.9	14.5	14.4
	Pakuranga	2022	12.2	10.6	11.8	11.9	13.0	12.8	14.7	14.5	11.6	11.7	11.5	10.0
		Past 5 years	13.2	11.8	9.9	10.5	12.7	14.0	14.0	12.6	11.4	11.1	12.4	13.1
	Papatoetoe	2022	15.1	12.8	12.3	12.3	13.6	13.1	13.5	13.8	12.0	12.0	12.1	10.5
		Past 4 years	15.1	13.8	12.4	13.4	14.1	14.3	16.2	14.4	13.9	13.2	15.1	15.8
	Patumahoe	2022	13.9	10.1	14.6	11.1	11.9	10.3	10.3	8.7	9.7	10.0	10.9	10.6
		Past 5 years	15.0	13.7	11.5	11.9	11.3	9.7	10.0	11.0	11.7	11.7	13.3	15.4
	Penrose	2022	15.5	13.7	15.5	14.3	16.0	13.0	14.6	14.0	12.4	12.1	13.0	12.0
		Past 5 years	15.9	15.1	13.4	14.2	15.4	14.9	14.6	13.9	13.7	13.1	15.0	16.2
	Queen Street	2022	21.4	19.4	18.4	17.9	18.4	19.2	21.7	20.6	19.2	19.2	19.3	16.7
		Past 5 years	16.5	16.0	15.1	15.8	16.7	16.1	17.0	17.3	17.3	17.4	18.1	19.0
	Takapuna	2022	11.8	11.0	10.5	12.8	13.4	13.5	15.5	14.5	11.9	11.7	12.5	10.8
		Past 5 years	13.9	12.7	11.2	12.2	13.0	13.5	13.8	12.7	11.8	11.5	12.7	13.7
$PM_{2.5}$ (µg/m^3)	Customs Street	2022	ND	2.9	2.6	3.8	3.8	5.7	4.9	4.9	4.1	3.8	3.8	3.4
		Past 2 years	4.4	4.1	3.6	3.9	4.1	4.1	4.7	6.5	6.8	4.0	3.7	4.0
	Glen Eden	2022	ND	ND	2.0	2.8	5.0	6.9	7.4	7.6	4.6	2.9	2.9	2.3
		Past 3 years	2.7	2.5	2.0	3.2	6.0	10.8	10.6	7.8	5.1	3.4	3.8	3.8
	Pakuranga	2022	2.7	2.8	2.4	ND	4.8	5.3	6.3	6.3	4.4	3.2	3.2	2.7
		Past 3 years	3.1	2.9	2.5	3.5	5.5	6.7	10.2	5.4	4.4	3.2	4.4	4.0
	Patumahoe	2022	5.1	3.3	4.6	4.9	5.4	5.8	4.5	5.2	4.7	4.9	5.3	5.4
		Past 5 years	5.5	4.7	4.2	4.9	5.6	5.0	5.0	4.8	5.0	4.7	5.7	5.9
	Penrose	2022	5.5	4.6	4.5	5.0	6.1	5.8	6.1	6.1	5.2	4.4	4.7	4.6
		Past 5 years	7.0	5.6	5.0	5.7	6.8	8.0	7.5	6.5	5.9	6.1	7.0	6.5
	Queen Street	2022	8.8	7.8	7.1	7.4	8.0	8.4	9.4	8.8	7.9	7.7	8.2	7.3
		Past 5 years	6.7	6.1	5.8	6.6	7.0	7.2	7.5	7.3	7.1	7.2	7.3	7.6
	Takapuna	2022	6.0	5.7	4.9	5.7	6.5	7.0	8.6	8.1	6.5	5.6	5.9	5.3
		Past 5 years	5.9	5.4	4.9	5.6	6.9	8.5	8.8	7.4	6.7	6.3	6.7	6.3
NO_2 (µg/m^3)	Customs Street	2022	20.0	18.8	26.7	26.3	26.5	80.4	31.5	33.9	33.7	24.1	21.8	17.5
		Past 2 years	42.1	45.7	45.1	33.1	42.4	39.0	40.5	36.4	29.4	31.9	25.6	27.2
	Glen Eden	2022	2.3	2.7	2.6	5.3	8.9	9.2	9.9	10.2	9.4	8.6	7.1	6.0
		Past 5 years	2.0	3.4	4.4	4.6	7.3	8.1	7.6	5.8	3.5	3.4	3.0	2.2
	Henderson	2022	4.4	8.9	9.4	11.2	12.5	10.9	9.9	12.4	11.8	8.4	6.0	5.8
		Past 5 years	3.6	7.3	8.2	9.0	12.7	14.1	12.8	8.1	6.1	5.9	6.1	4.4
	Khyber Pass Road	2022	15.5	16.0	17.3	22.8	33.2	35.0	29.3	30.6	30.2	22.4	20.5	17.5
		Past 5 years	24.1	21.6	27.8	28.3	37.4	36.1	40.5	34.7	32.0	28.5	33.5	22.0
	Patumahoe	2022	ND	ND	3.9	4.2	5.3	5.6	5.4	6.5	5.4	3.9	3.1	2.6
		Past 5 years	1.5	2.3	3.3	2.8	3.8	4.2	4.2	3.0	1.9	1.9	2.2	1.9
	Penrose	2022	7.7	7.5	11.4	15.7	21.8	19.1	18.3	19.9	16.6	10.8	12.5	7.8
		Past 5 years	9.5	11.9	14.5	17.2	23.1	24.6	25.4	19.2	17.0	13.4	13.2	9.1
	Queen Street	2022	18.5	18.5	18.5	15.0	17.4	21.9	21.8	22.5	21.1	19.6	14.2	13.4
		Past 5 years	31.4	32.3	34.7	37.6	43.0	43.3	49.4	48.8	45.0	42.0	36.8	32.2
	Takapuna	2022	4.8	6.9	8.7	12.7	20.3	20.0	19.1	19.9	18.9	11.4	10.9	7.7
		Past 5 years	7.6	9.5	11.9	15.4	21.2	22.4	23.9	18.7	14.9	12.5	11.5	8.1
SO_2 (µg/m^3)	Customs Street	2022	2.1	1.7	2.6	2.3	2.0	10.3	3.3	3.3	3.3	3.0	2.1	1.7
		Past 2 years	1.4	1.6	2.2	1.1	1.6	1.5	2.2	2.6	1.7	1.7	1.3	1.4
	Penrose	2022	1.0	1.0	1.2	1.2	1.4	1.3	1.1	1.3	1.1	1.1	1.1	0.8
		Past 5 years	0.4	0.9	1.1	0.9	1.3	1.4	1.1	0.8	0.9	0.8	1.0	0.5
O_3 (µg/m^3)	Patumahoe	2022	24.4	26.1	31.0	33.4	37.4	41.2	47.6	48.4	52.5	50.8	42.6	29.2
		Past 5 years	27.4	28.9	32.9	38.9	41.6	42.2	46.3	52.1	51.3	46.2	40.1	32.2
CO (mg/m^3)	Khyber Pass Road	2022	0.015	0.012	0.018	0.036	0.137	0.120	0.135	0.106	0.080	0.012	0.006	0.003
		Past 5 years	0.199	0.262	0.281	0.357	0.509	0.425	0.540	0.336	0.229	0.226	0.232	0.160
Black carbon (ng/m^3)	Customs Street	2022	1001	1005	1055	1265	1322	7818	1303	1807	1444	1156	1238.0	1156
		Past 2 years	1675	1740	1456	1009	1375	1357	1372	1076	818	945	1061	992
	Henderson	2022	254	452	502	530	825	802	699	1055	729	419	364	343
		Past 5 years	236	444	577	603	1105	1337	1272	890	476	391	413	302

ND = No data measured due to faulty sensor

Appendix O: Traffic volume – Khyber Pass Road (2021 and 2022).

According to Auckland Transport's 7-day traffic count data, the traffic volume in 2022 decreased compared to 2021, from 130,388 to 125,249 vehicles. The count was conducted at Khyber Pass Road, between Mountain Rd and Maungawhau Rd (both directions). The 2021 count took place between May 24th and 30th, while the 2022 count occurred between June 13th and 19th.



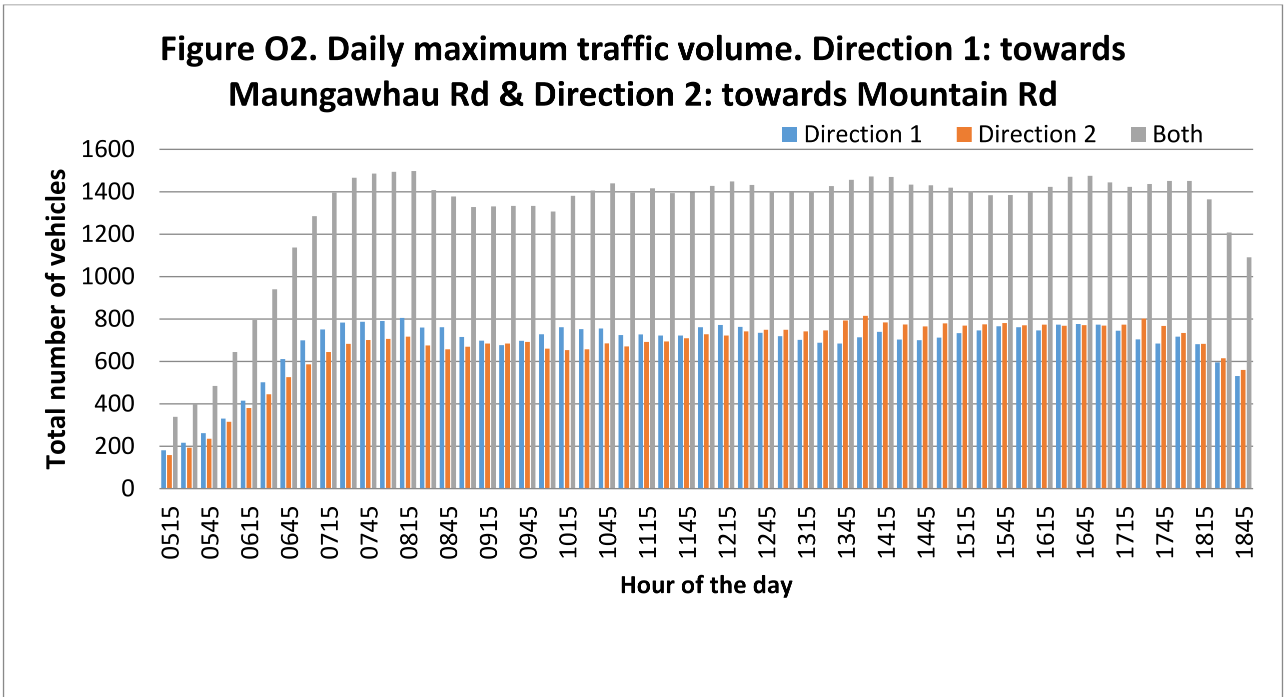


Table 01. 7-day peak traffic volume: Direction 1: towards Maungawhau Rd and Direction 2: towards Mountain Rd

2021

Peaks Summary	Direction 1							Direction 2						
	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun
AM PEAK														
60 Minutes beginning	0745	0730	**0815**	0800	0800	0900	0900	0745	0745	0800	0745	**0815**	0900	0900
Volume	717	783	**805**	787	758	522	324	679	694	703	675	**717**	473	331
MID PEAK														
60 Minutes beginning	1200	0915	1115	1115	1400	1015	**1215**	1400	1245	1315	1245	1330	**1400**	1400
Volume	604	698	724	727	714	761	**772**	676	695	742	749	746	**815**	787
PM PEAK														
60 Minutes beginning	1715	1630	1545	1800	**1645**	1430	1500	1745	1715	1700	**1730**	1415	1415	1415
Volume	675	729	668	717	**776**	660	712	723	677	762	**802**	731	784	764

2022

Peaks Summary	Direction 1							Direction 2						
	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun
AM PEAK														
60 Minutes beginning	0800	0800	0815	0800	**0745**	0900	0900	0800	**0815**	0800	0800	0815	0900	0900
Volume	709	731	745	726	**784**	549	319	688	**728**	711	685	663	457	287
MID PEAK														
60 Minutes beginning	1145	1130	1245	1200	1115	**1100**	1200	1330	1400	1330	1215	1400	**1345**	1330
Volume	575	601	608	658	669	**763**	648	627	642	658	670	724	**810**	667
PM PEAK														
60 Minutes beginning	1600	1430	**1630**	1630	1545	1600	1500	1730	1700	1645	1700	1630	**1545**	1515
Volume	613	582	**654**	652	650	541	605	769	717	755	739	793	**854**	743

Find out more: email
rimu@aucklandcouncil.govt.nz
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