Auckland Air Quality – 2023 Annual Data Report

Louis Boamponsem

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Executive summary

Air quality is a major environmental issue in urban centres worldwide, with adverse effects on both human health and local visibility. The repercussions of compromised air quality span from functional impairments to a spectrum of health symptoms, leading to reduced life expectancy and death. Globally, air pollution causes over seven million deaths annually. In New Zealand, the societal costs attributed to anthropogenic air pollution in 2016 amounted to $15.6 billion. In Auckland, air pollution was responsible for an estimated 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 home 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 council's Environmental Data Portal, www.environmentauckland.org.nz and technical reports are produced in specific reporting years. This is the annual data report for 2023 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 2023 increased by 1.8% compared to 2022. 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 37.1%. On 27th July 2023, the Queen Street site recorded one exceedance of NESAQ for PM_{10} (24-hour average). Our investigation indicated that this exceedance was likely due to the construction activities in the city centre.
- The annual average $PM_{2.5}$ concentration of Auckland in 2023 increased by 1.6% compared to 2022. This increase was 26% 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. The Auckland Unitary Plan ambient air quality targets of 25 $\mu g/m^3$ for the 24-hour average and 10 $\mu g/m^3$ for the annual average of $PM_{2.5}$ were not exceeded.
- In general, Auckland's annual mean concentration of NO_2 in 2023 decreased by 8.4% compared to 2022. This is statistically significant ($P<0.05$). As expected, the highest NO_2 concentrations were measured at the city centre sites. There were no NO_2 national standard exceedance in Auckland. However, on 27 occasions (7%), the 24-hour average NO_2 concentrations exceeded the 2021 WHO air quality guideline of 25 $\mu g/m^3$.
- The average SO_2 concentration of Auckland in 2023 marginally increased by 0.7% compared to 2022. As found in 2022, the annual SO_2 mean concentration at Customs Street was higher than at the Penrose site. This could be attributed to the higher traffic volume on Customs Street and its proximity to the Port of Auckland, where shipping emissions are likely to be a contributing factor. There was no exceedance of NESAQ and the 2021 WHO air quality guideline for SO_2.
- The average CO concentration at the Khyber Pass Road site increased by 3.5% compared to 2022. This increase is likely due to the 2% increase in traffic volume on Khyber Pass Road. There was no exceedance of NESAQ and the 2021 WHO air quality guideline for CO.
- The average ground level O_3 concentration at Patumahoe in 2023 decreased by 1.7% compared to 2022. 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.
- In 2023, Penrose's Total Suspended Particulate (TSP) mean decreased by 24.2% compared to 2022, accompanied by a slight reduction in Pb levels, while benzene levels at Khyber Pass Rd and Penrose remained undetectable, and the Crowhurst St site recorded an annual average benzene concentration below the Auckland Unitary Plan threshold, with traces of various VOCs detected at some sites.
- 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.
- Overall, weekday air pollutants concentrations were slightly higher than weekends due to increased traffic and activities.

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.

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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
NO_X	Oxides of nitrogen (NO_2 + NO). NO_X is principally formed by the oxidation of nitrogen contained in air at high combustion temperatures. It is a significant tracer for the impact of traffic pollution.
NZTA	New Zealand Transport Agency
Pb	Lead
PM	Particulate matter. It 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 correlated at a particular site.
Relative humidity	Is a ratio, expressed in percent, 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. The World Health Organization (WHO) estimates 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 an estimated 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; Boamponsem et al. 2024). 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 council's 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 2023 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; Boamponsem et al. 2024).

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

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 and Stats NZ, 2021). The Auckland Council's air quality monitoring network measures particulate matter using two metrics (PM_{10} and $PM_{2.5}$). PM_{10} refers to 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 particles with an aerodynamic diameter of 2.5 micrometres or less (a subset of PM_{10}), 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 and 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 and Stats NZ, 2021). There is considerable evidence that inhaling PM is harmful to human health, particularly smaller particle sizes that can become trapped in the small airways deep in the lungs and, for very small particles, enter the bloodstream and penetrate organs in the body (EFCA, 2019; Talbot and Crimmins, 2020; MfE and 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). From temporary effects such as shortness of breath, coughing, or chest pain to increased risk of life-threatening conditions like heart attacks, strokes, or emphysema (MfE and Stats NZ, 2021).

Research has found that exposure to PM, and the subsequent inflammatory response, can also lead to lung cancer, exacerbate asthma, increased risk of diabetes and (WHO, 2013; MfE and Stats NZ, 2021).

Finally, 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 (NO_X)

Nitrogen monoxide (NO) and nitrogen dioxide (NO_2), collectively referred to as nitrogen oxides (NO_X), are primarily produced when nitrogen in the air is oxidised at high combustion temperatures. These high temperature combustions occur typically in fossil fuel powered vehicles (cars, trucks and marine vessels), therefore, the main source of anthropogenic NO_X emissions in Auckland is vehicle traffic. Approximately 95% of NO_X is emitted as nitric oxide

(NO) at the point of discharge, which is generally considered harmless to human health. However, the remaining 5% of NO_X 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 and 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). Over the past few decades, vehicle 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 and 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 and it can 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 and 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 and 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 and 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 and 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 and 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 and 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 and 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 and 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 and 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 and 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 and 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; Boamponsem et al., 2024). 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 and 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 and Stats NZ, 2021). In ecosystems, SO_2 can damage vegetation, acidify water and soil, and affect biodiversity (US EPA, 2017; MfE and Stats NZ, 2021).

f. Black carbon

Soot generated from combustion processes is a common type of particulate matter 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 and 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 and Stats NZ, 2014). Benzo(a)pyrene (BaP) can irritate the eyes, nose, and throat, and is associated with lung cancer (MfE and 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 and 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 and 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 and 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 26 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.

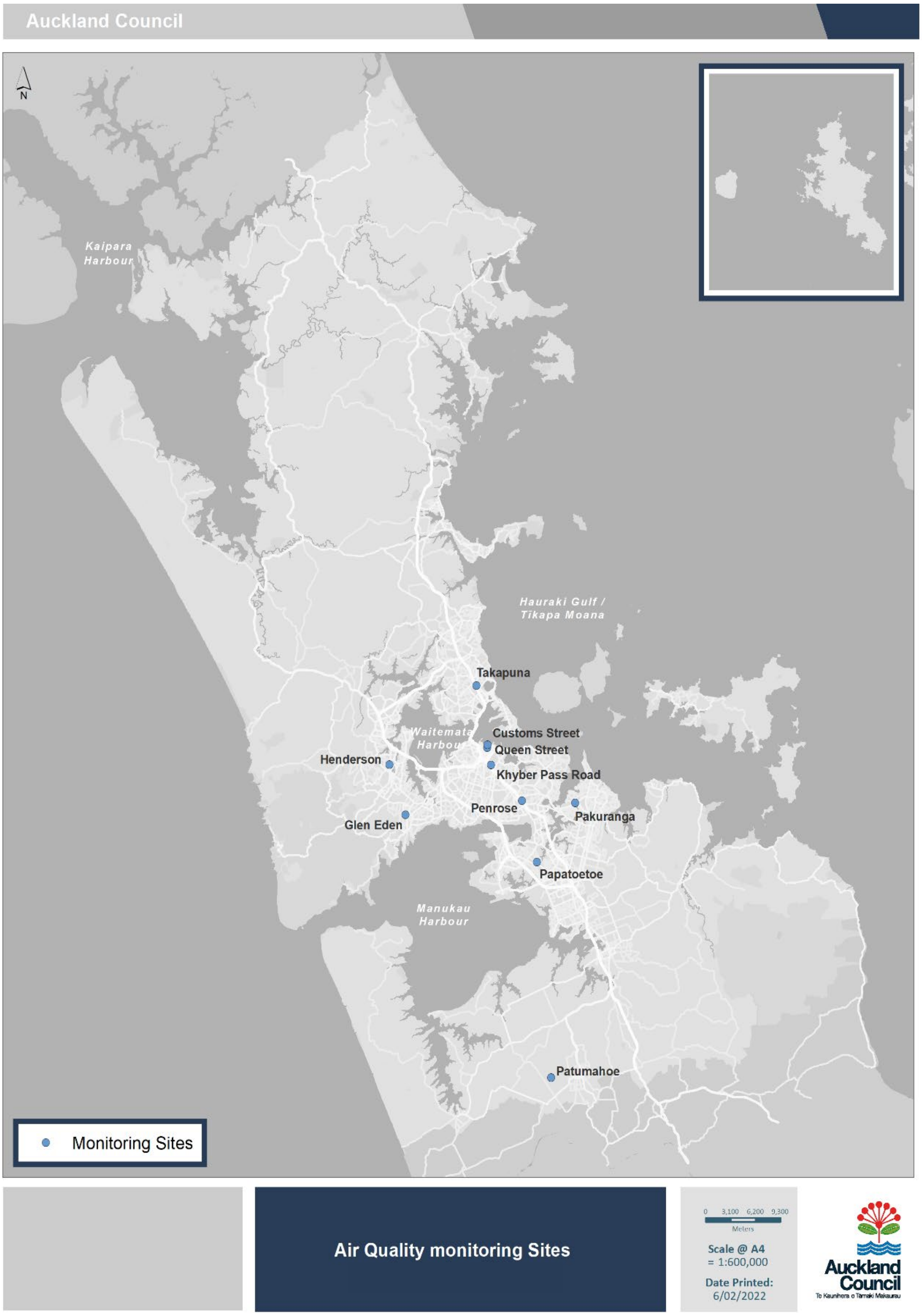

Figure 1. Auckland Council air quality monitoring sites.

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	NO_X – 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 NO_X – 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 NO_X – 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	NO_X – 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	NO_X – 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 NO_X – API 200E Gas Analyser
Henderson[b]	1993	PM_{10}, black carbon, and NO_2	WS, WD, AT, RH	NO_X – 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	NO_X – 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 IBM SPSS (v28), MS Excel and the Openair R package (Carslaw & Ropkins 2012). Inferential statistical analysis was conducted using IBM SPSS. 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 (2022 and 2023). 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 2022 and 2023 is given by Appendix L. The Queen Street station has been temporarily closed due to the renovation of the building hosting the site. Due to this, data from this site in this report is up to August 22, 2023.

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 2023 and 2022. 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 annual average ambient temperature of the Auckland air quality monitoring sites in 2023 decreased by 3.1% compared to 2022 (from 16.3 ± 3.9 ^{O}C to 15.8 ± 4.2 ^{O}C) ($p<0.05$). As shown by Figure 2, the pattern of temperature variations in 2023 was similar to the previous year. Except for Pakuranga, all the average annual ambient temperatures across the five monitored sites significantly decreased compared to 2022 ($p<0.05$). Appendix B presents the temperature descriptive statistics for each site.

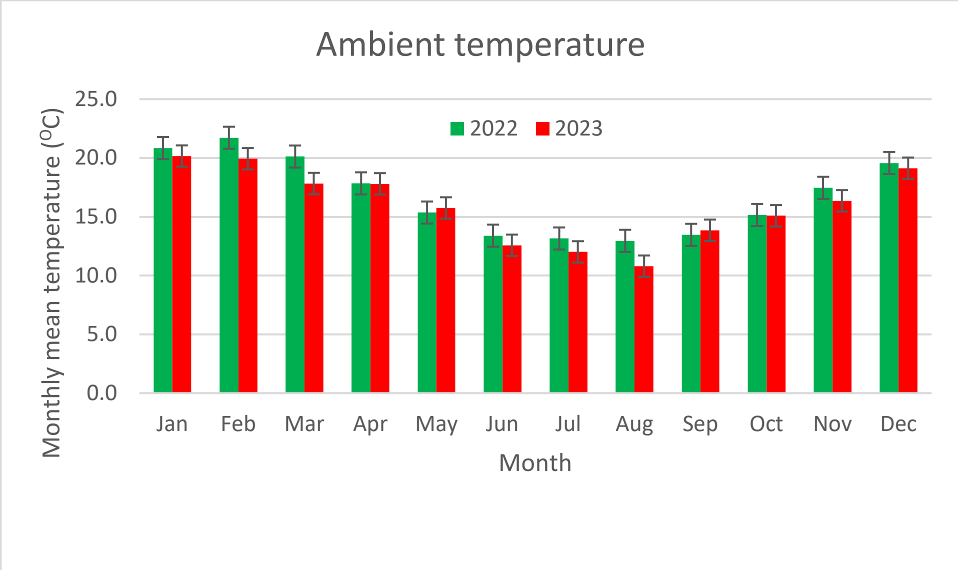

Figure 2. Monthly average ambient temperature measured at seven monitoring sites – 2023 compared to 2022. Error bars represent the standard errors of the mean.

b. Relative humidity

The overall annual average relative humidity of Auckland air quality monitoring sites in 2023 significantly increased by 4.6% compared to 2022 (from 72.3 ± 15.9% to 75.6 ± 13.0%) ($P<0.05$). The pattern of ambient relative humidity variations in 2023 was similar to the previous year (Figure 3). All the monitoring sites recorded an increase in relative humidity. Appendix B presents the relative humidity descriptive statistics for each site.

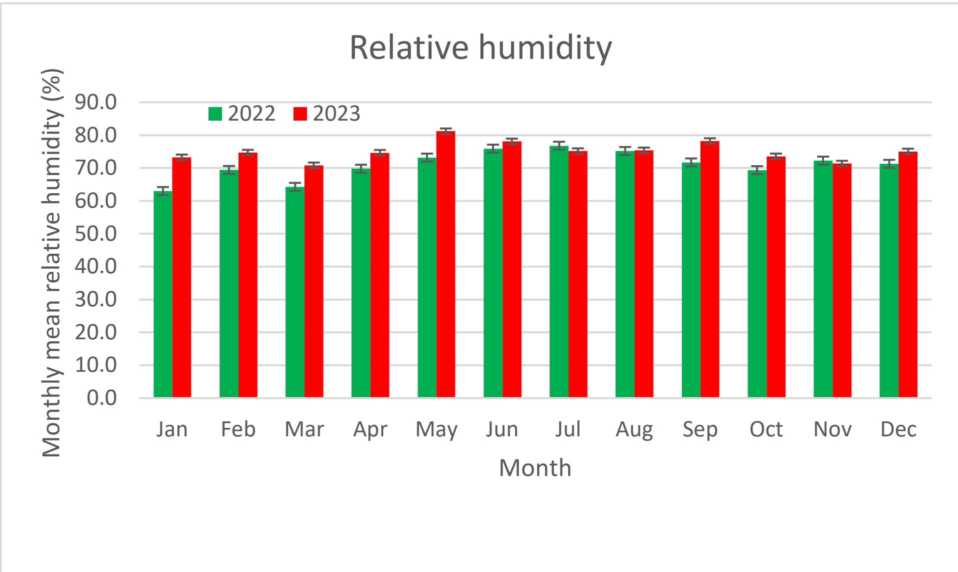

Figure 3. Monthly average relative humidity measured at six monitoring sites – 2023 compared to 20222. Error bars represent the standard errors of the mean.

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 summarising 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 2023 were similar to those of the previous year. Wind rose diagrams showing the general frequency distribution of the wind speed and direction during 2023 and 2022 for seven sites are provided in figures 4 to 7.

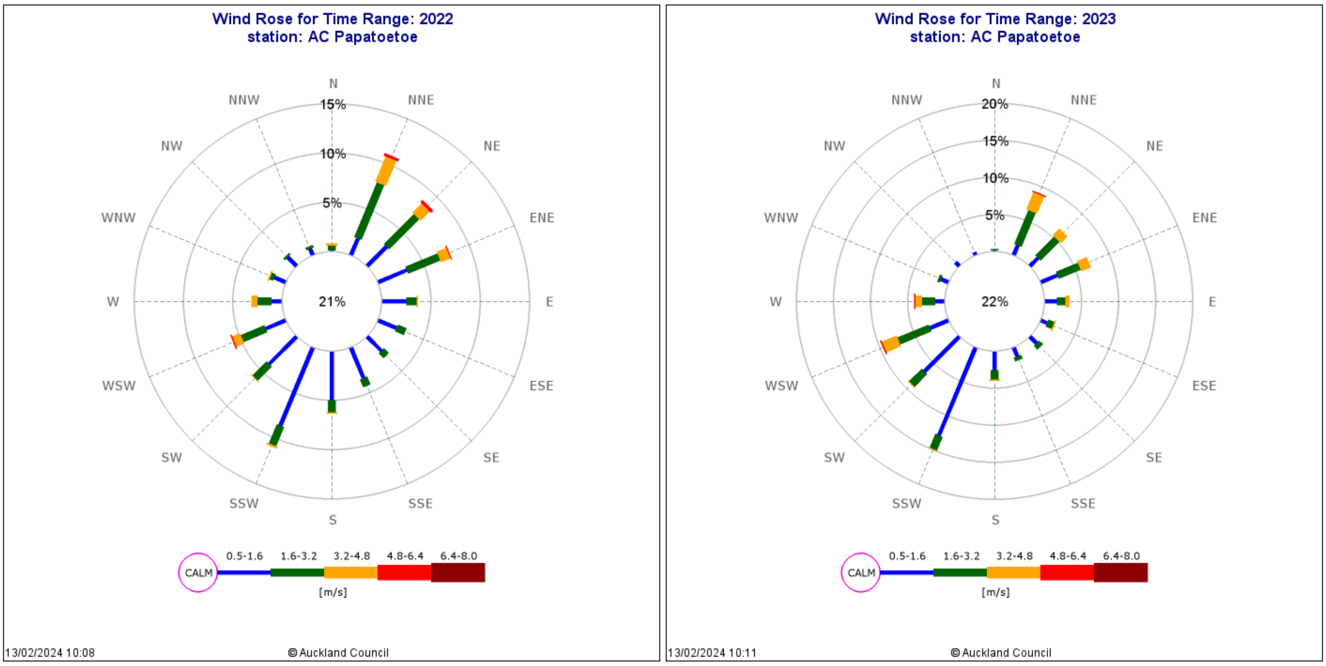

Figure 4. Wind roses for Papatoetoe.

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 2022 data while the right plot is for the 2023 data.

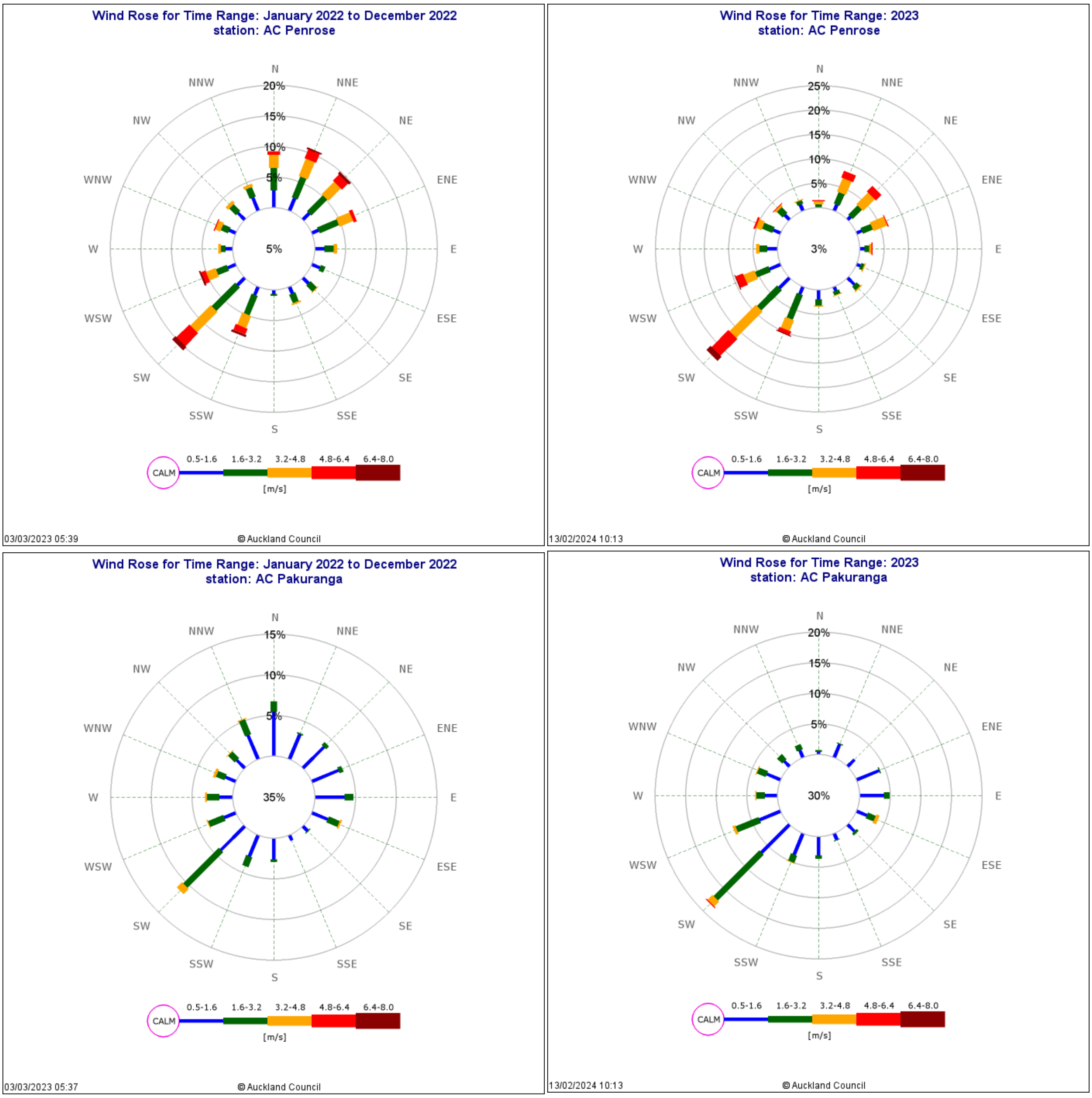

Figure 5. Wind roses for Penrose and Pakuranga.

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 2022 data while the right plots are for the 2023 data.

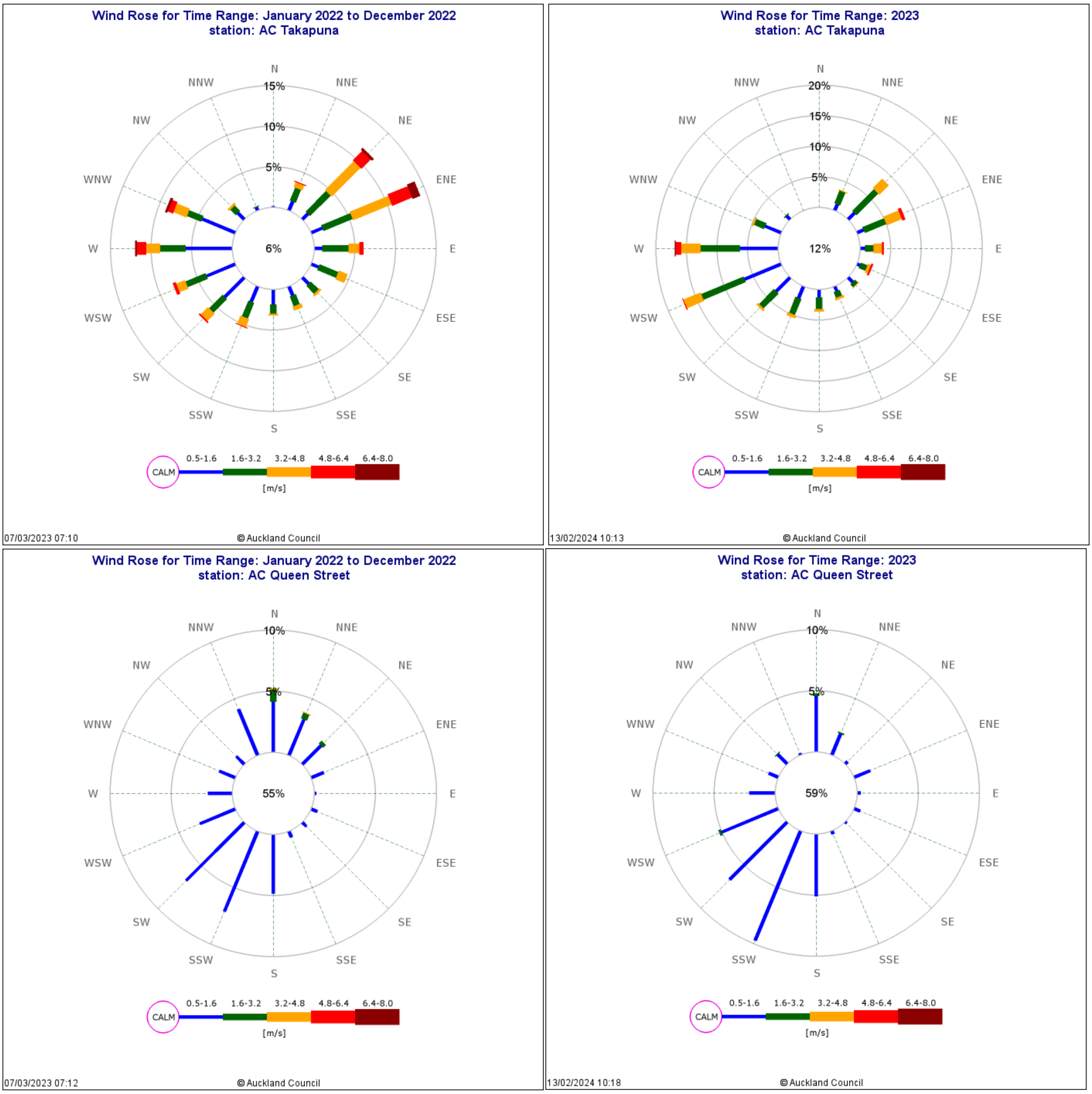

Figure 6. Wind roses for Takapuna and Queen Street.

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 2022 data while the right plots are for the 2023 data.

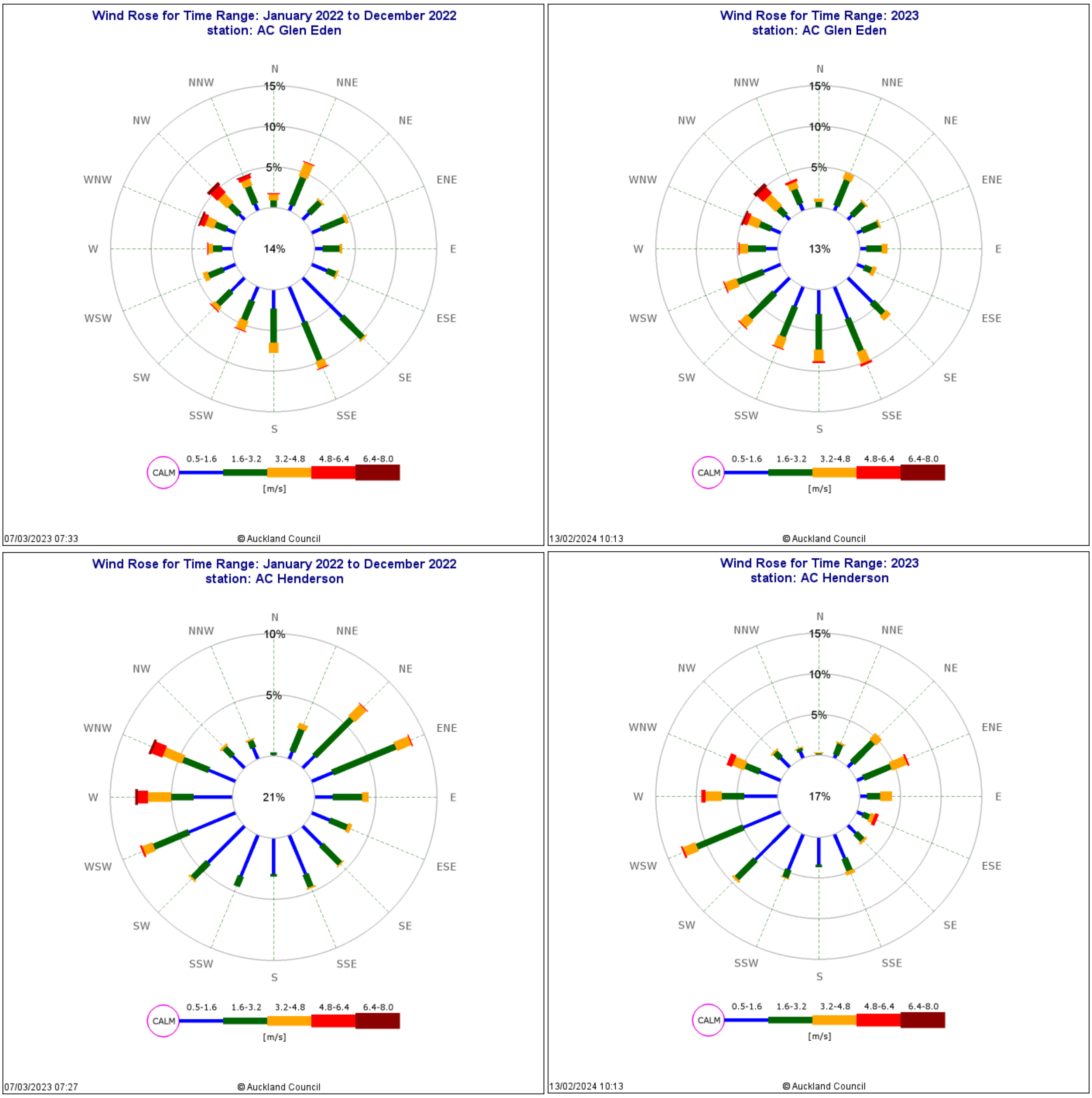

Figure 7. Wind roses for Glen Eden and Henderson.

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 2022 data while the right plots are for the 2023 data.

3.2 Auckland's air quality data – 2023

Auckland is not regarded as a polluted airshed under the National Environmental Standard for air quality (NESAQ), in fact, the most recent state of Auckland's environment report indicated that overall air quality is good and improving (Auckland Council Research and Evaluation Unit, 2021). 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.

Air pollutant concentrations in Auckland sometimes exceed the NESAQ or Auckland target limits due to exceptional events. For example, in December 2019, the Australian dust storms and bushfires resulted in a PM_{10} exceedance detected at three locations (Papatoetoe, Penrose, and Patumahoe). Also, in August 2022, the Queen Street site recorded two exceedances of NESAQ for PM_{10} (24-hour average). Our investigation indicated that these exceedances were due to sea salt following a high sea state and onshore easterly wind conditions. For a list of air pollution sources specific to Auckland, please refer to Appendix A. Appendix M provides monthly averages for 2023 and the past three to five years of pollutant concentrations (when data is available).

3.2.1 Particulate matter (PM_{10})

Overall, the annual average PM_{10} concentration of Auckland in 2023 was 13.3 µg/m³, which is an increase of less than 2% compared to 2022. This average concentration was below the 2021 WHO air quality guideline of 15 µg/m³. In fact, only the Queen Street site reported an annual mean PM_{10} concentration higher than the WHO guideline. On the other extreme, the rural site of Patumahoe recorded the lowest annual PM_{10} mean concentration of 10.4 µg/m³. Figure 8 presents the annual mean PM_{10} concentration across the nine monitoring sites.

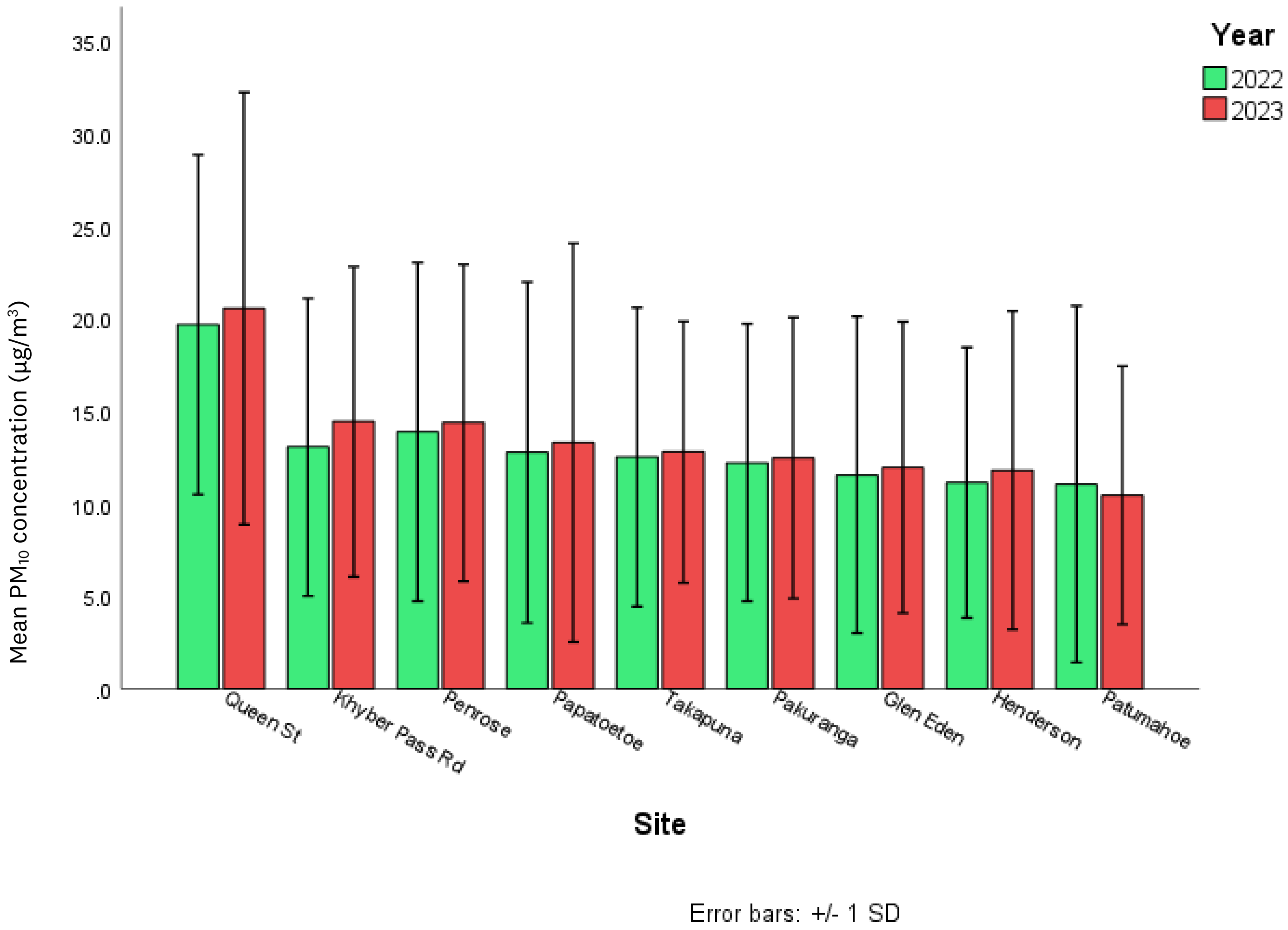

Figure 8. PM_{10} annual mean concentrations at nine sites – arranged in increasing order from left to right. Error bars represent the standard errors of the mean.

The annual PM_{10} concentration recorded at Patumahoe site was statistically significantly ($p<0.05$) lower than the previous year (See Appendix C). Conversely, the annual PM_{10} concentrations measured at all the other monitored sites were significantly higher than the previous year ($p<0.05$).

As indicated in Table 1, the 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 2023, the Auckland Urban Airshed exceeded this standard on one occasion. This PM_{10} exceedance event occurred at the Queen Street air quality monitoring site on 27th July 2023. This exceedance is likely due to the construction activities in the city centre, such as the City Rail project and the Queen Street modifications.

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

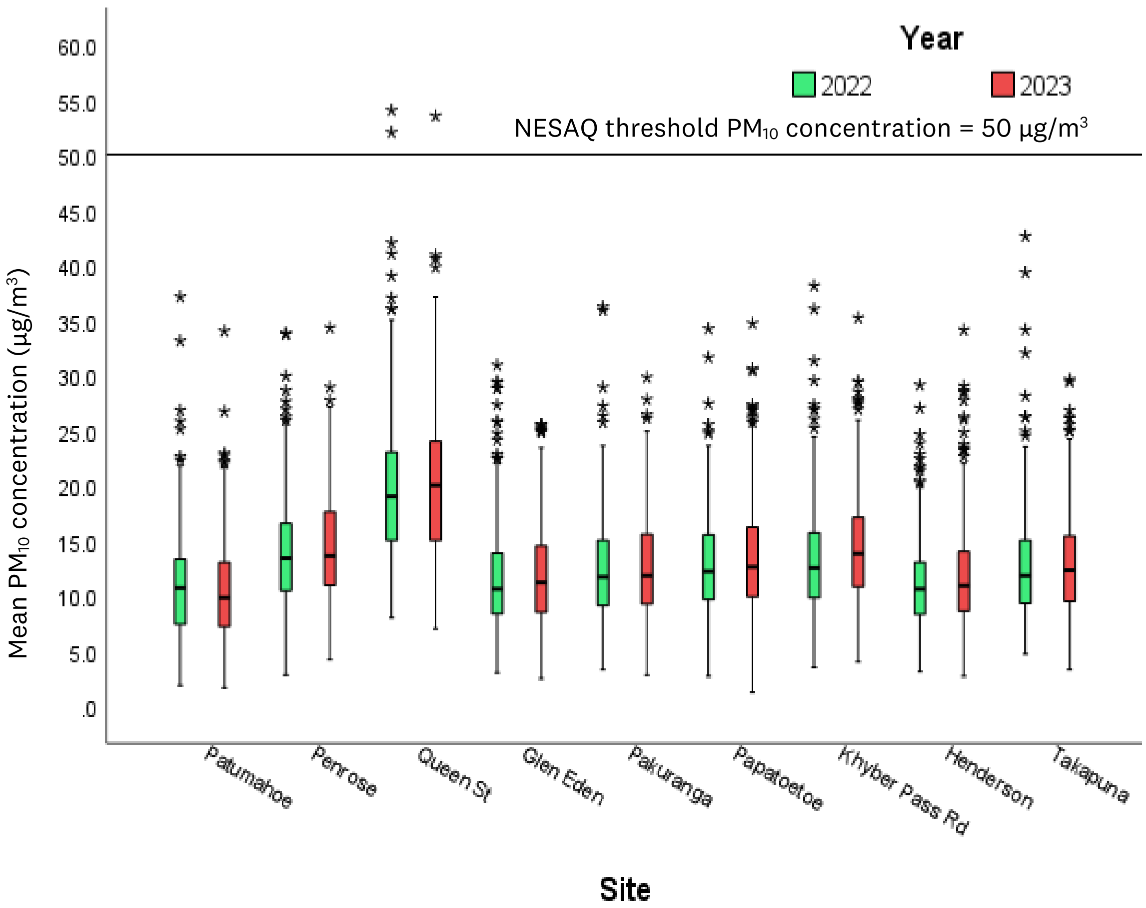

Figure 9. Boxplot of PM_{10} 24-hour mean concentration measured at nine sites.

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, asterisks represent outliers.

Most daily average PM_{10} levels increased in 2023 compared to 2022, with the highest increases observed on Sundays and Autumn. Notable decreases occurred on Thursdays, Fridays, and during the summer season. Both weekdays and weekends saw increases, with weekends showing the highest increase in PM_{10} levels (Figure 10).

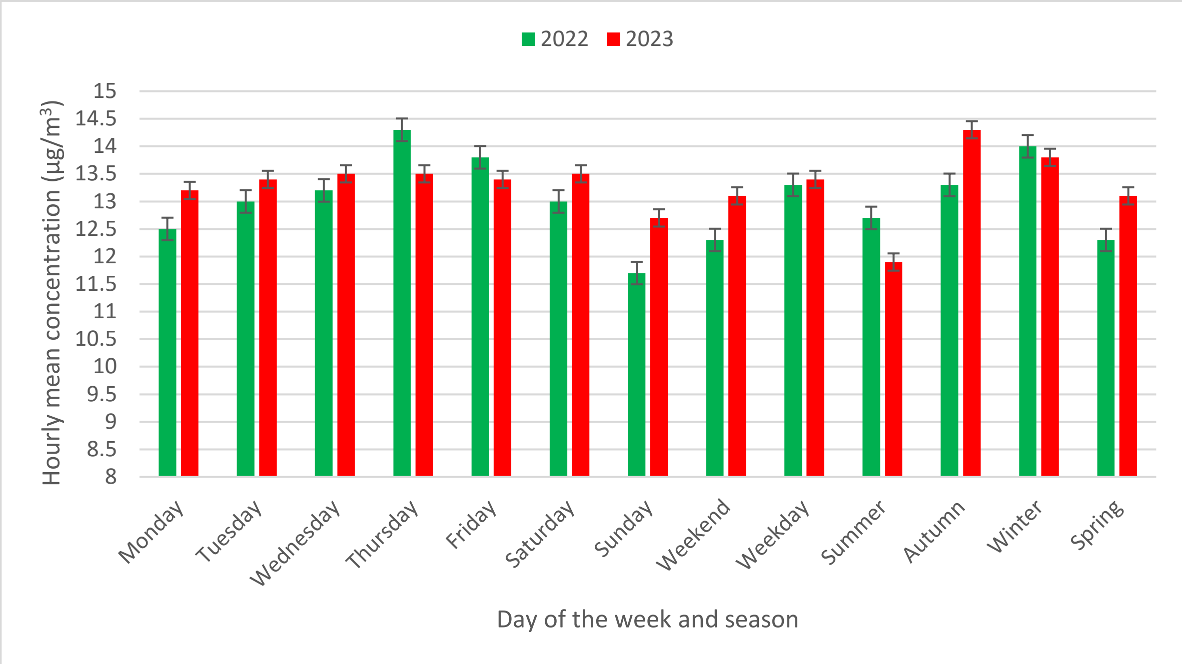

Figure 10. Temporal variations in Auckland PM_{10} annual mean concentrations. Error bars represent the standard errors of the mean.

Most hourly average PM_{10} levels increased in 2023 compared to 2022, with the highest increases observed during the early morning hours (1 and 2) and midday (10, 11, and 12). Notable stability or minor changes in PM_{10} levels occurred during early morning hours 3 and 4, and late evening hours 19 to 23 showed minimal increases. Both morning and midday hours exhibited increases, with early morning hours showing the highest increase in PM_{10} levels (Figure 11).

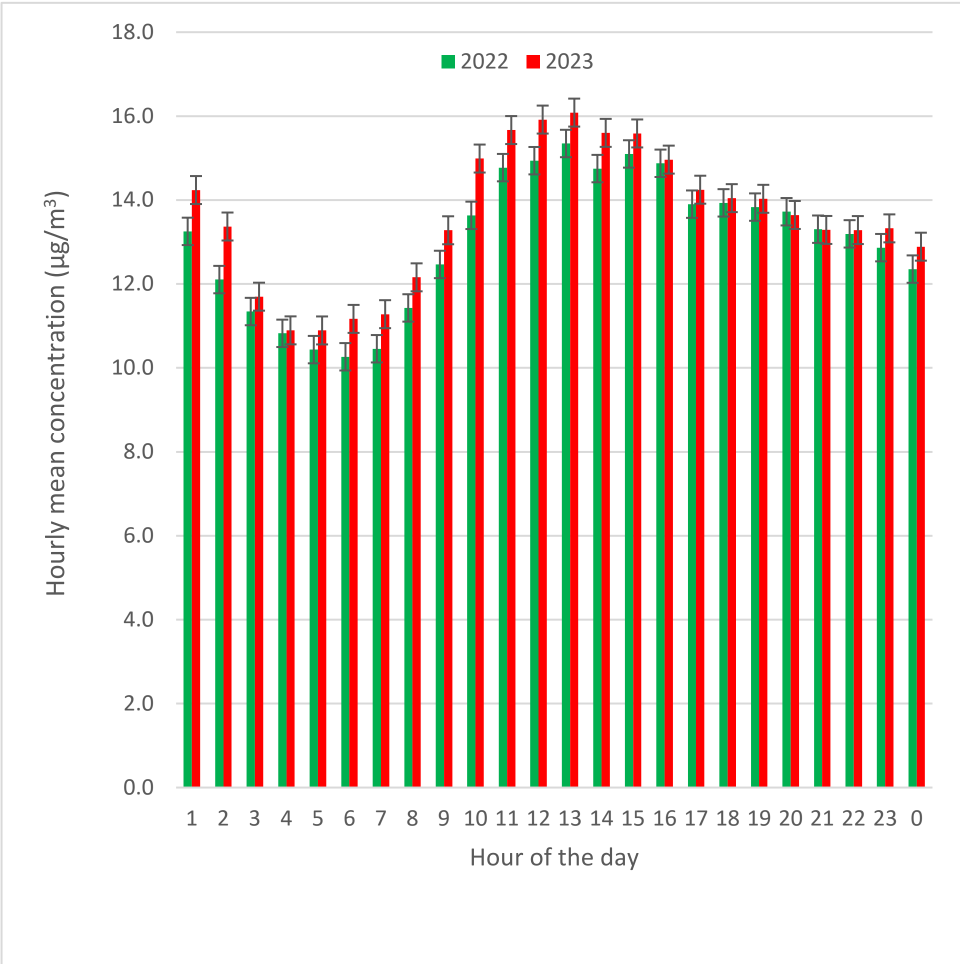

Figure 11. Time variations in Auckland PM_{10} hourly mean concentrations. Time variations in Auckland PM_{10} hourly mean concentrations. Error bars represent the standard errors of the mean.

As indicated in section 3.1, PM_{10} concentrations can 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 - 14 indicate that different dominant wind speeds and directions occur at each monitoring site. For example, Figure 12 shows that in 2023, 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 the Queen Street site, the patterns of PM_{10} pollution roses at all the sites in 2022 and 2023 were identical.

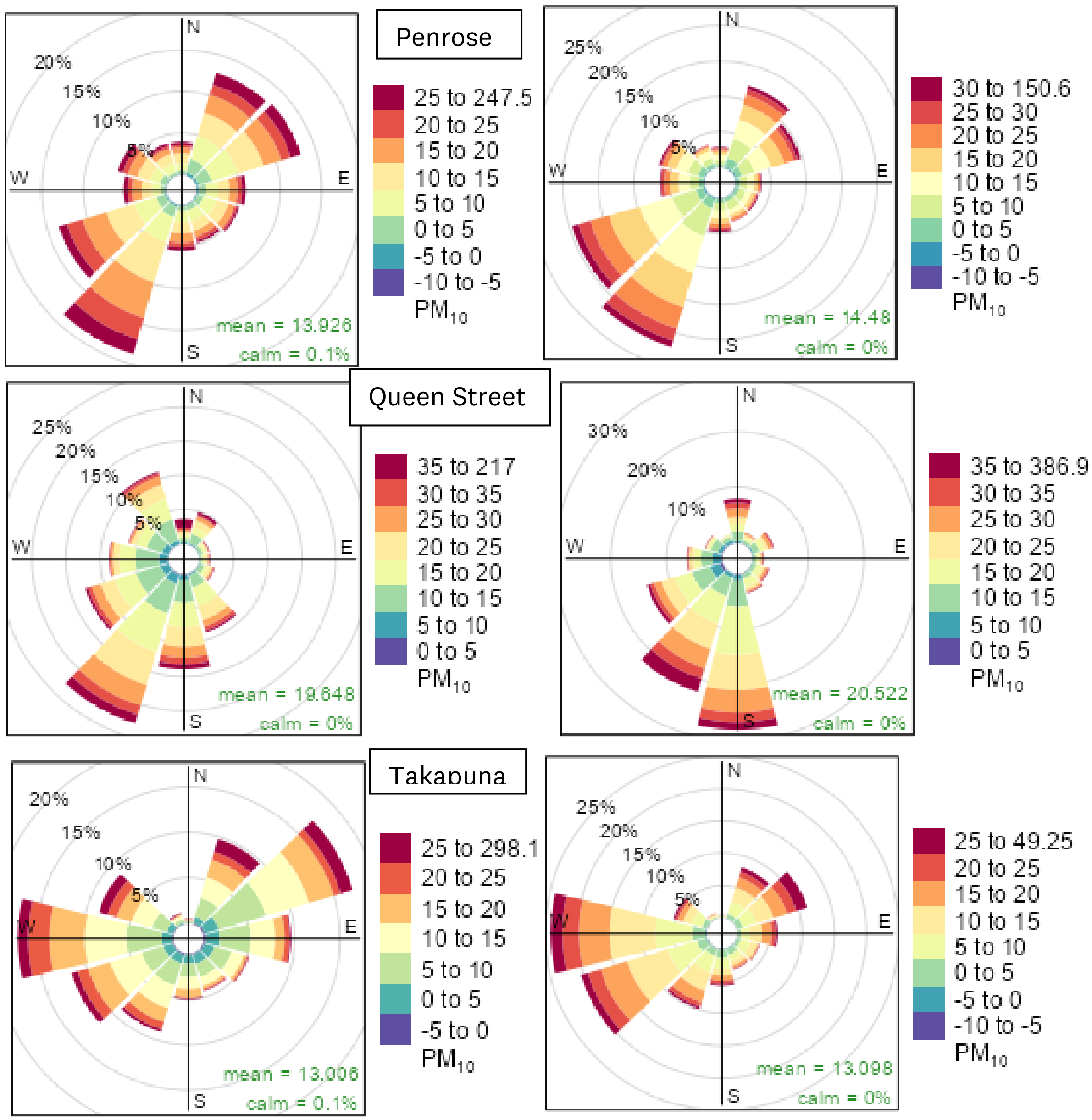

Figure 12. PM_{10} pollution roses for Penrose, Queen Street and Takapuna

Higher PM_{10} concentrations are associated with predominant prevailing wind direction as follows: Penrose: south-west, Queen Street: south-west, and Takapuna: south-westerly. The plots on the left are for 2022 data while the right plots are for 2023 data. Frequency of counts by wind direction (%).

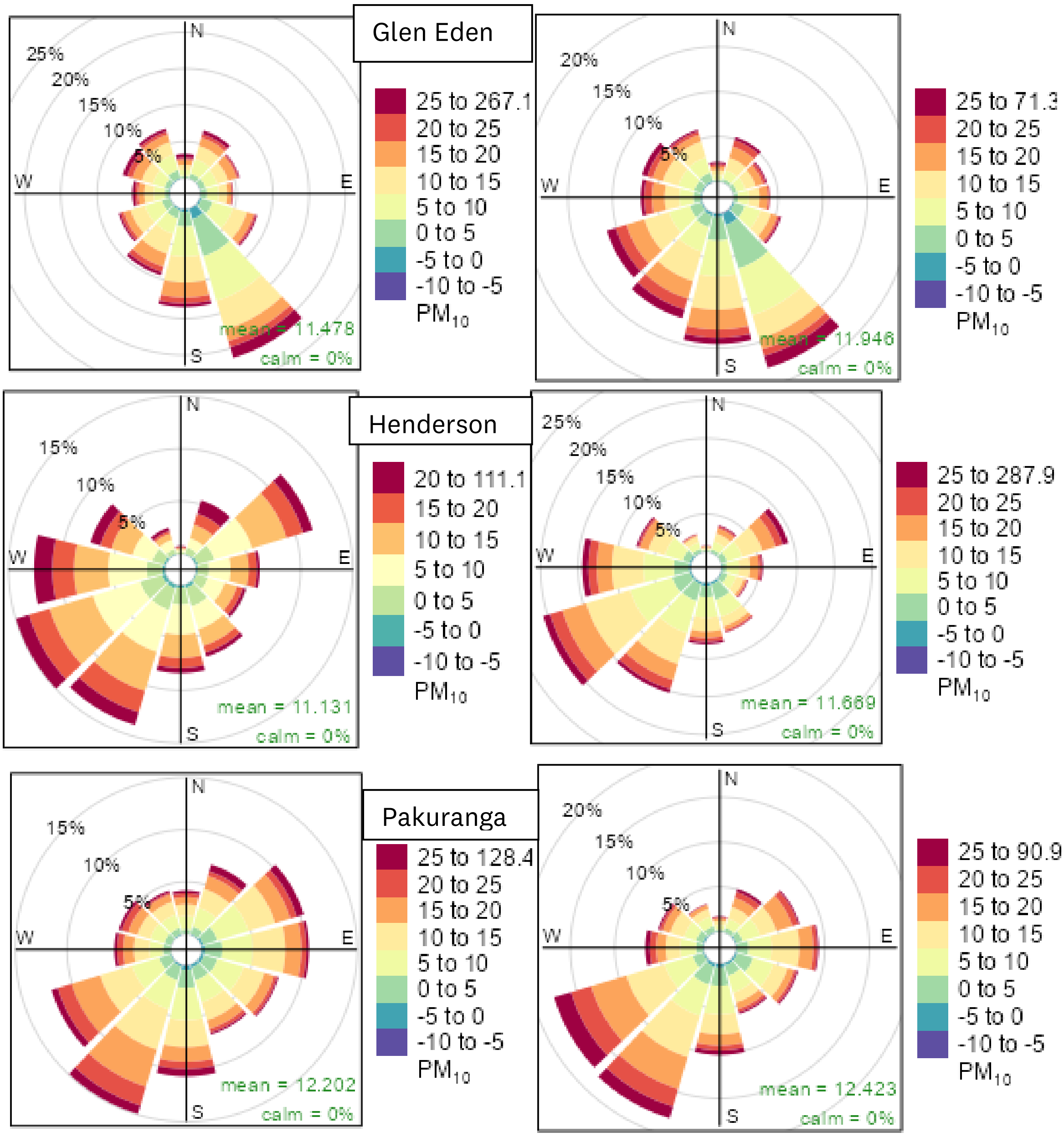

Figure 13. PM_{10} pollution roses for Glen Eden, Henderson, and Pakuranga sites.

Higher PM_{10} concentrations are associated with predominant prevailing wind direction as follows: Glen Eden: south-east, Henderson and Pakuranga: south-west. The plots on the left are for 2022 data while the right plots are for 2023 data. Frequency of counts by wind direction (%)

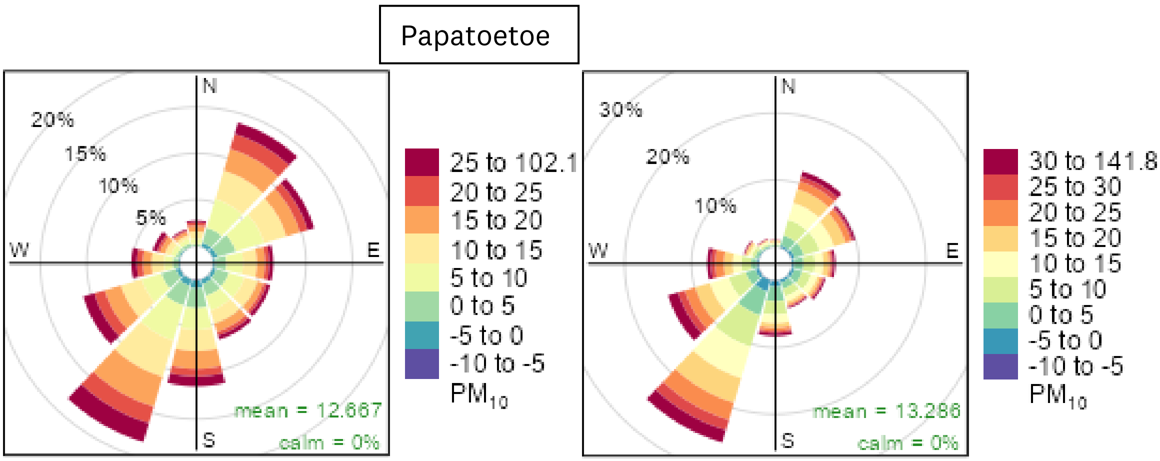

Figure 14. PM_{10} pollution roses for Papatoetoe site.

Higher PM_{10} concentrations are associated with predominant prevailing wind direction as follows: Papatoetoe: south-west. The plot on the left is for 2022 data while the right plot is for 2023 data. Frequency of counts by wind direction (%).

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 biomass burning, and soils. Emissions from transport and home heating are the main anthropogenic sources of PM in Auckland (Davy et al., 2017; Boamponsem et al. 2024).

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).

Soil 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, sea salt significantly contributes to PM_{10} concentration (approximately 50%). This natural background concentration is challenging to manage (Davy, 2021; Talbot and Crimmins, 2020, Boamponsem et al. 2024).

3.2.2 Particulate matter ($PM_{2.5}$)

The average $PM_{2.5}$ concentration of Auckland in 2023 was 6.3 μg/m³ which is a slight increase (less than 2%) compared to 2022. This is 26% higher than the 2021 WHO air quality guideline of 5 μg/m³. In contrast to PM_{10}, all sites reported annual mean $PM_{2.5}$ concentrations equal or higher than the 2021 WHO guideline. Penrose monitoring site had the lowest annual $PM_{2.5}$ mean concentration of 5.0 μg/m³, while Queen Street recorded the highest mean of 8.6 μg/m³. Patumahoe, Takapuna and Queen Street monitoring sites registered annual mean concentrations higher than the previous year. Penrose monitoring site recorded annual mean concentrations lower than the previous year. Apart from Patumahoe site, 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.

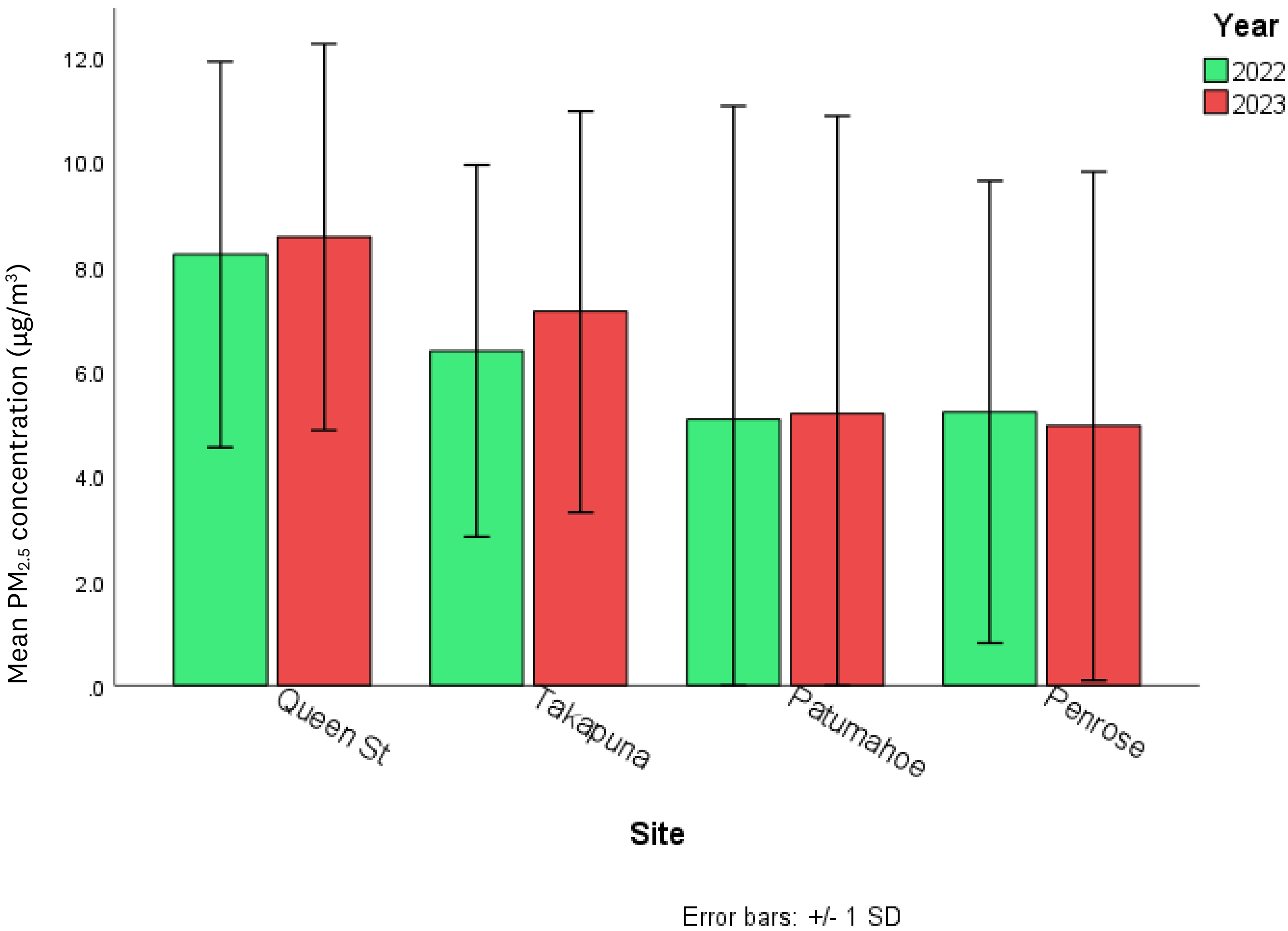

Figure 15. $PM_{2.5}$ annual mean concentrations at nine sites – arranged in increasing order from left to right. Error bars represent the standard errors of the mean.

As with PM_{10}, there were occasional hourly spikes in $PM_{2.5}$ mean concentrations in all the sites (See Appendix E) but there were no observed breaches of the Auckland 24-hour target of 25 µg/m³. On the other hand, all sites breached, at least once, the more stringent 24-hour WHO air quality guideline of 15 µg/m³. A box and whisker diagram showing the distribution of hourly mean concentrations across the sites is presented in Figure 16.

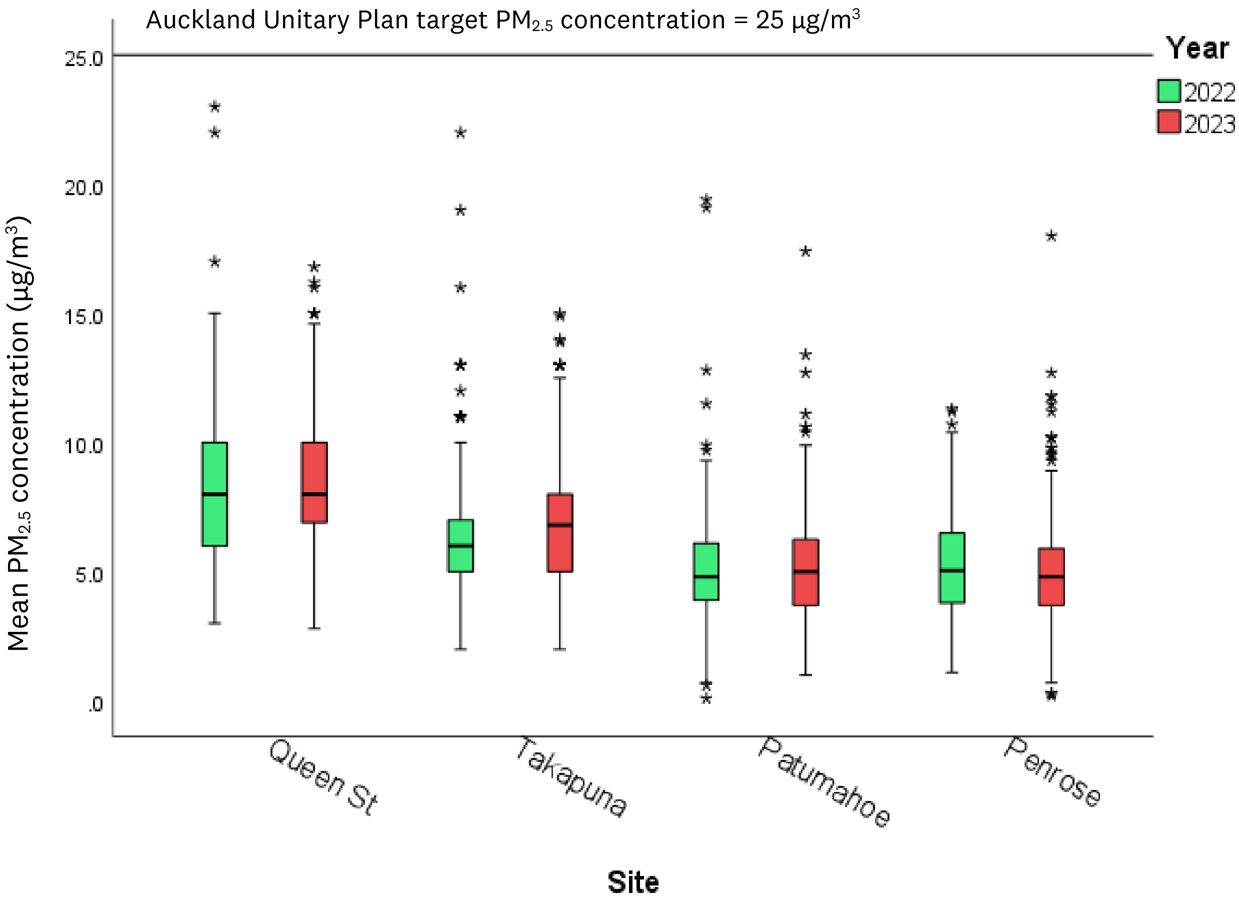

Figure 16. Boxplot of $PM_{2.5}$ 24-hour mean concentration measured at four sites.

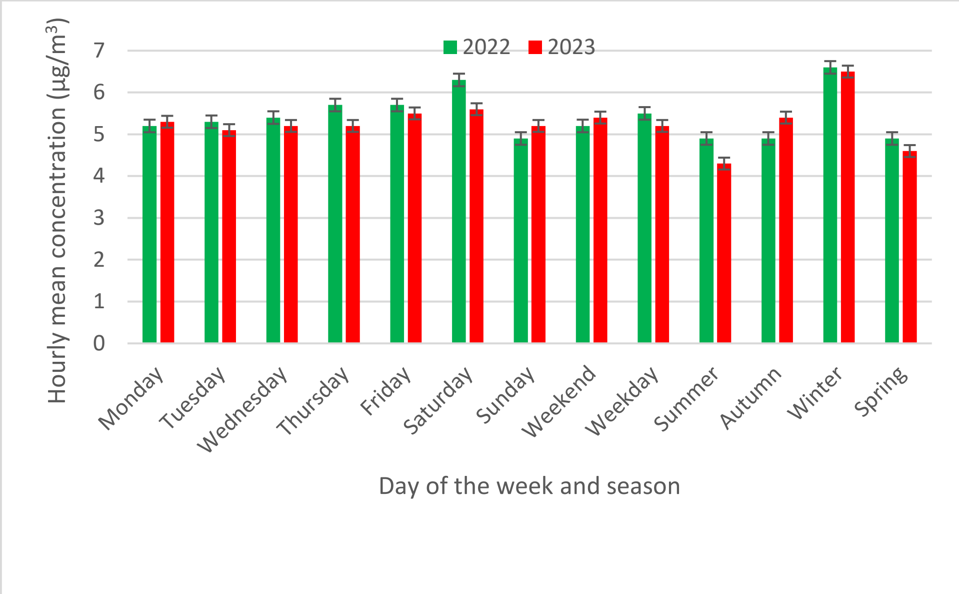

Figure 17. Temporal variations in Auckland $PM_{2.5}$ annual mean concentrations. Error bars represent the standard errors of the mean.

Concentrations of $PM_{2.5}$ tend to increase later in the week with the highest concentrations typically occurring on Wednesday to Saturday (Figure 17). $PM_{2.5}$ concentrations were higher in winter most likely due to domestic fires from home heating. Unlike in 2022, weekday average $PM_{2.5}$ concentrations are slightly lower than weekends. Overall, between the hours 12 noon and 6 pm, higher average $PM_{2.5}$ values were recorded in 2023 than in 2022. $PM_{2.5}$ average concentrations peak in the afternoon and night hours (See Figure 18).

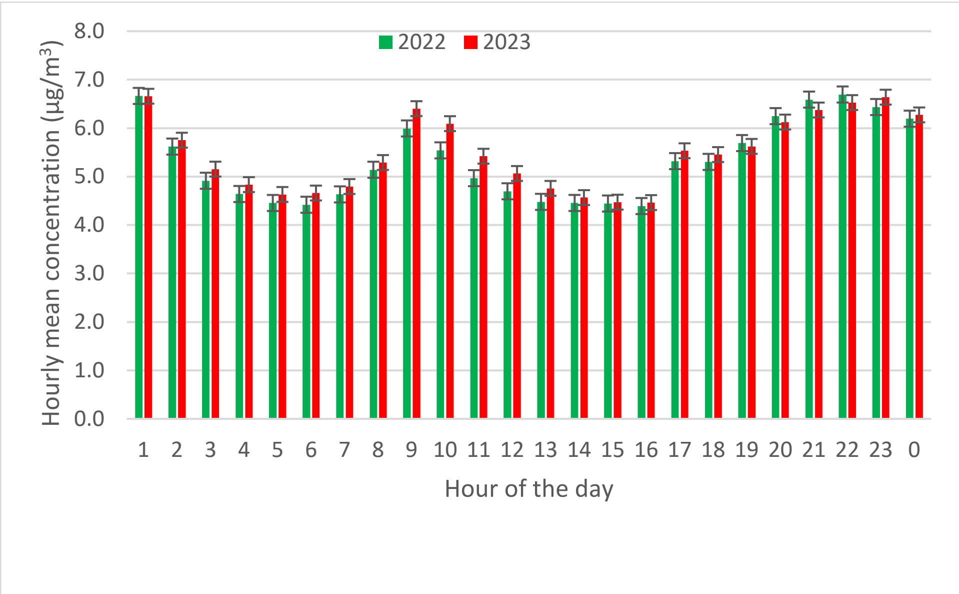

Figure 18. Time variations in Auckland $PM_{2.5}$ hourly mean concentrations. Error bars represent the standard errors of the mean.

Unlike PM_{10}, anthropogenic emissions dominate $PM_{2.5}$ concentrations (approximately 70%) (Davy, 2021; Boamponsem et al. 2024). 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). 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 motor vehicles, biomass burning, secondary sulphate, marine aerosol (sea spray), and soil. Motor vehicle and biomass burning emissions are the main anthropogenic sources of $PM_{2.5}$ across all sites in Auckland (Davy et al., 2017; Talbot et al., 2017; Boamponsem et al. 2024). 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; Boamponsem et al. 2024).

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.

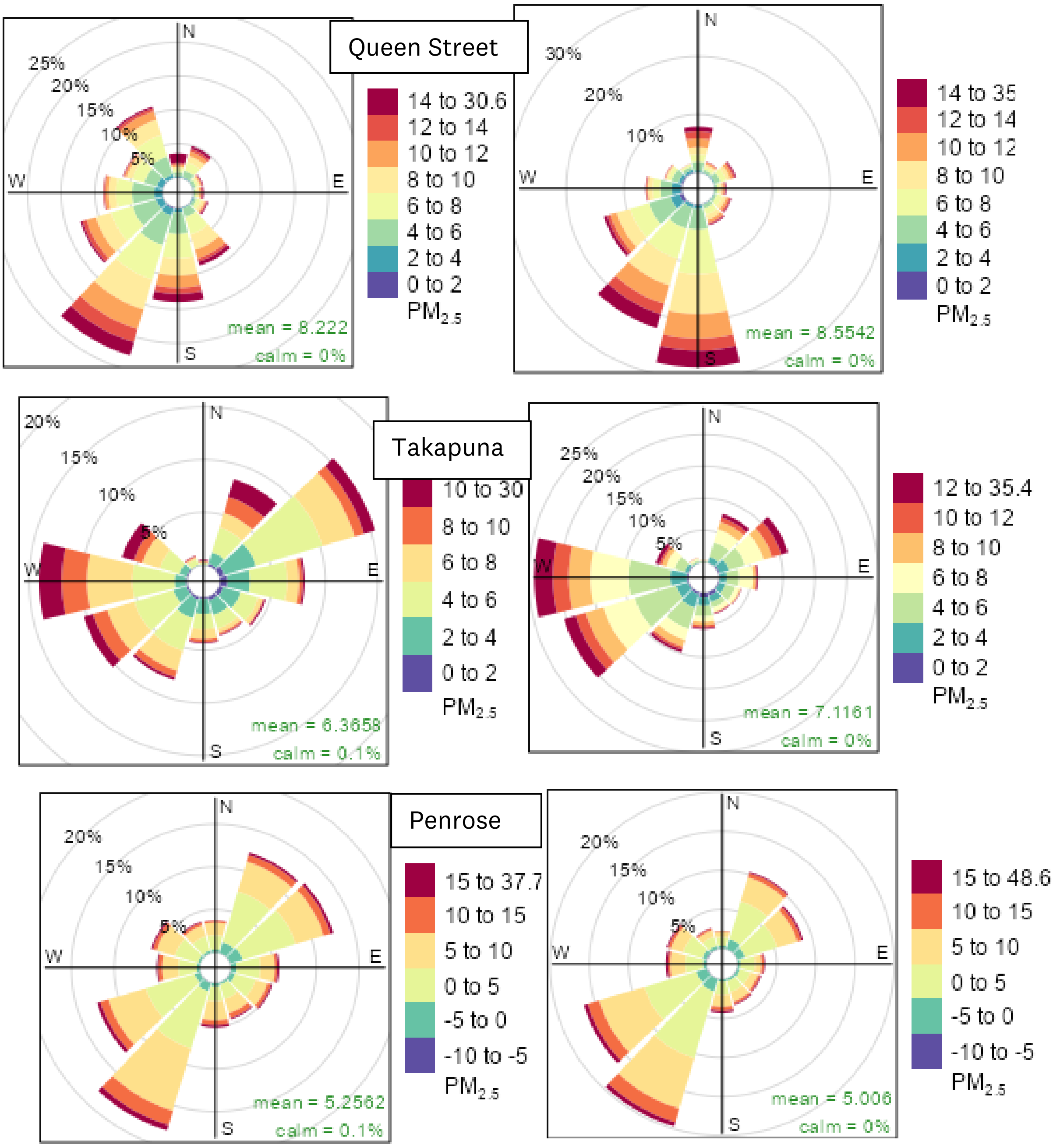

Figure 19. $PM_{2.5}$ pollution roses for Queen Street, Takapuna, and Penrose sites.

Higher $PM_{2.5}$ concentrations are associated with predominant prevailing wind direction as follows: Queen Street: south, Takapuna: west, and Penrose: south-west. The plots on the left are for 2022 data while the right plots are for the 2023 data. Frequency of counts by wind direction (%).

3.2.3 Nitrogen dioxide (NO_2)

The mean annual NO_2 concentration for 2023 decreased more than 8% to 14.1 µg/m^3 compared to 2022. Even though the average annual NO_2 concentration was lower than Auckland's target of 40 µg/m^3, it was more than 40% higher than the more demanding 2021 WHO air quality guideline of 10 µg/m^3. Furthermore, even though all sites reported values below the Auckland target, only Patumahoe, Henderson and Glen Eden observed annual NO_2 concentrations lower than the WHO guideline. As in the previous year, the Patumahoe monitoring site recorded the lowest annual NO_2 mean concentration of 3.1 µg/m^3, while city centre site, Queen 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 mean concentrations of NO_2 recorded at Queen Street and Takapuna were found to be statistically significantly higher than the previous year ($p < 0.05$), as detailed in Appendix D. Conversely, there was a statistically significant decrease ($p < 0.05$) in the annual mean concentration of NO_2 at the remaining sites. As expected, the highest NO_2 concentrations were measured at the city centre sites.

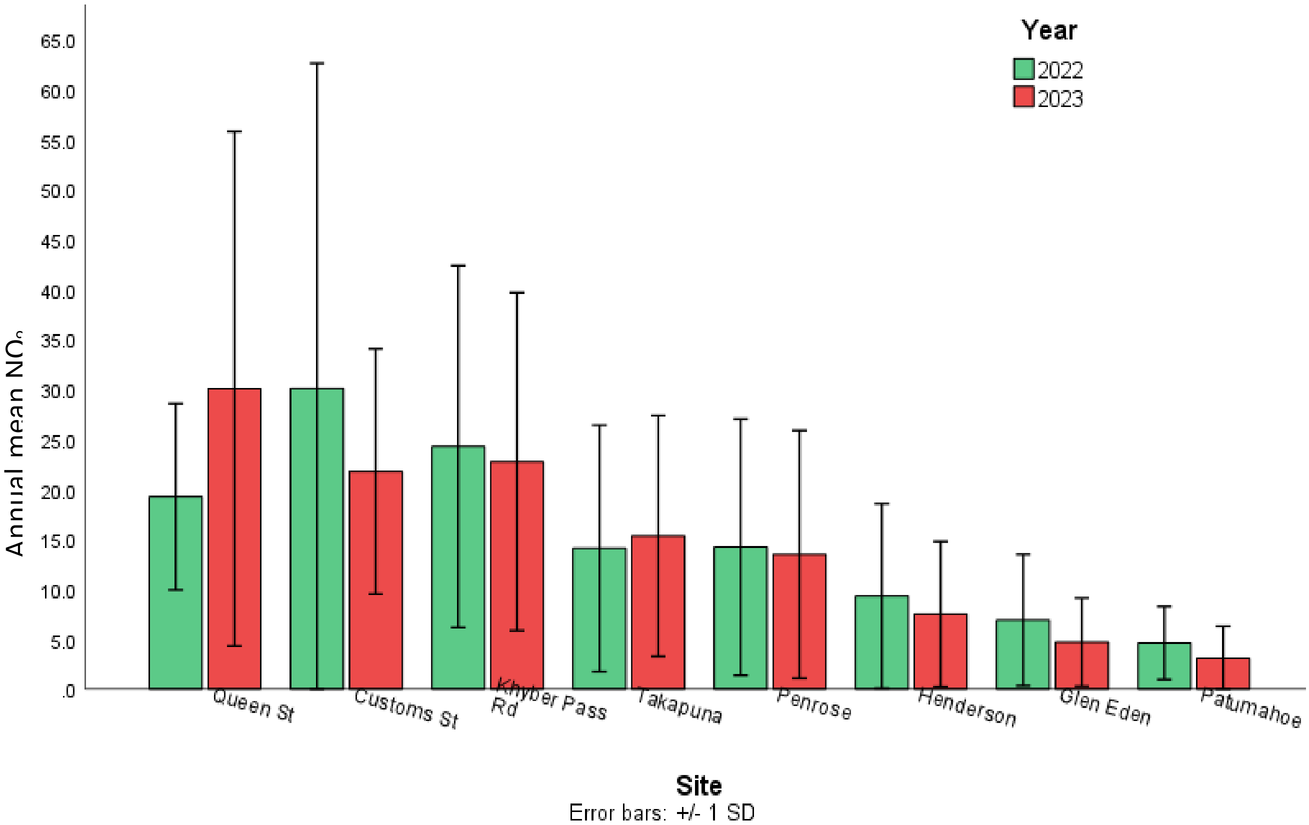

Figure 20. NO_2 annual mean concentrations at eight sites – arranged in increasing order from left to right. Error bars represent the standard errors of the mean.

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 2023, the Auckland Urban Airsheds did not breach this standard.

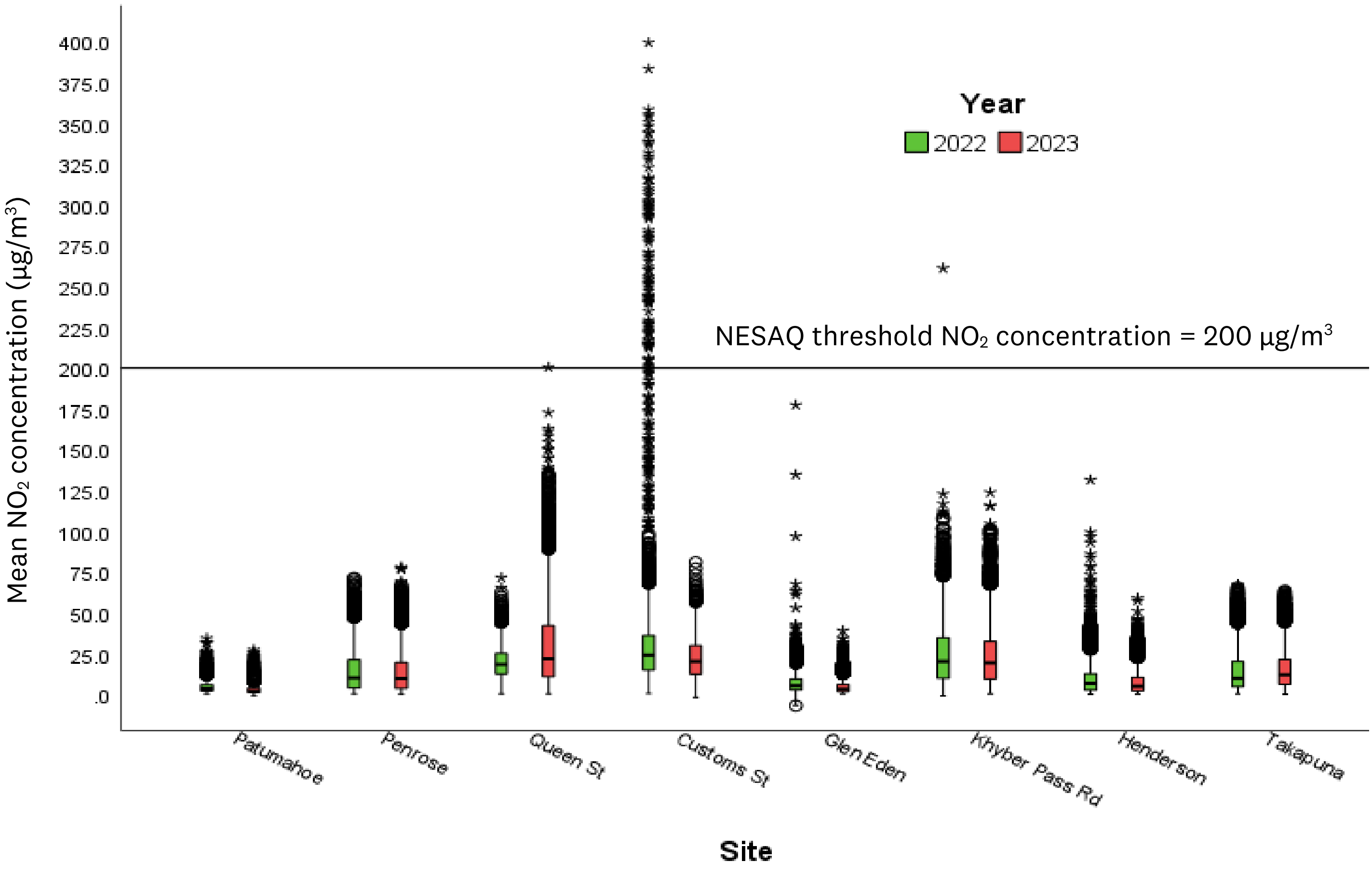

Figure 21. Boxplot of NO_2 hourly mean concentration measured at eight sites.

Figure 22 presents the annotated calendar plot of the 24-hour NO_2 mean concentrations indicating the days where the measured values reached or exceeded the WHO guideline of 25 µg/m³. In more than half of the days in 2023, the three Auckland city centre sites recorded 24-hour average NO_2 concentrations more than the 2021 WHO guideline (See Appendix F; Figures F4, F5, and F6).

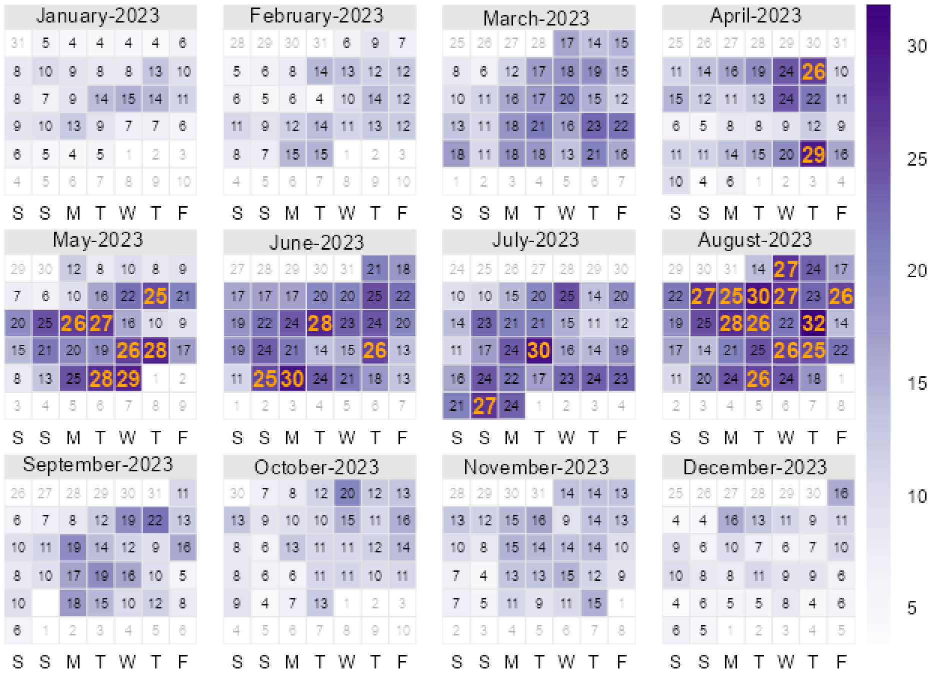

Figure 22. Calendar plot for NO_2 overall Auckland concentrations in 2023 with annotations highlighting those days where the concentration of NO_2 were equal or greater than the 2021 WHO guideline of 25 µg/m^3. The numbers show the NO_2 24-hour mean concentration in µg/m^3.

Like in 2022, 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 higher than weekends most likely due to increased traffic volume.

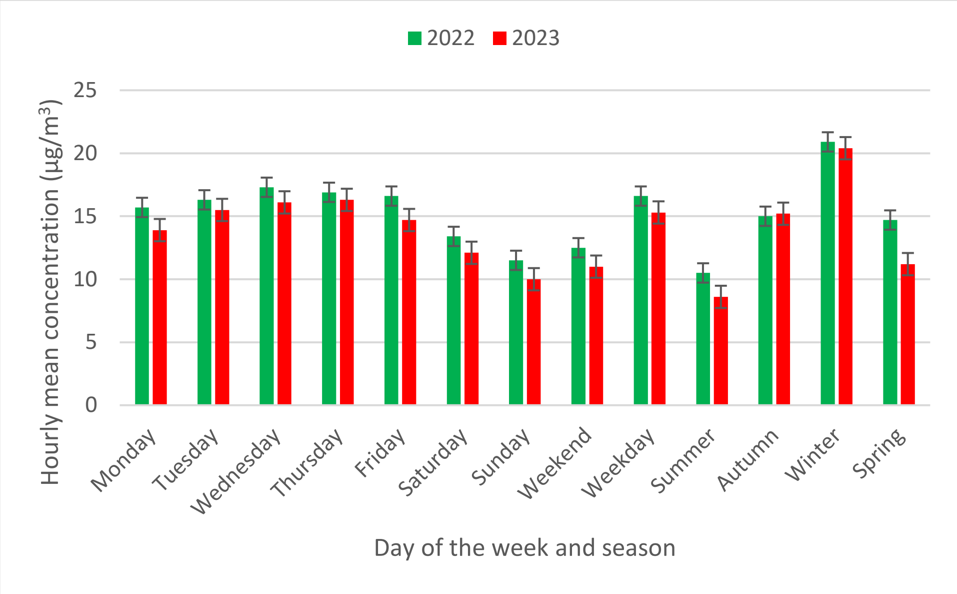

Figure 23. Temporal variations in Auckland NO_2 annual mean concentrations. Error bars represent the standard errors of the mean.

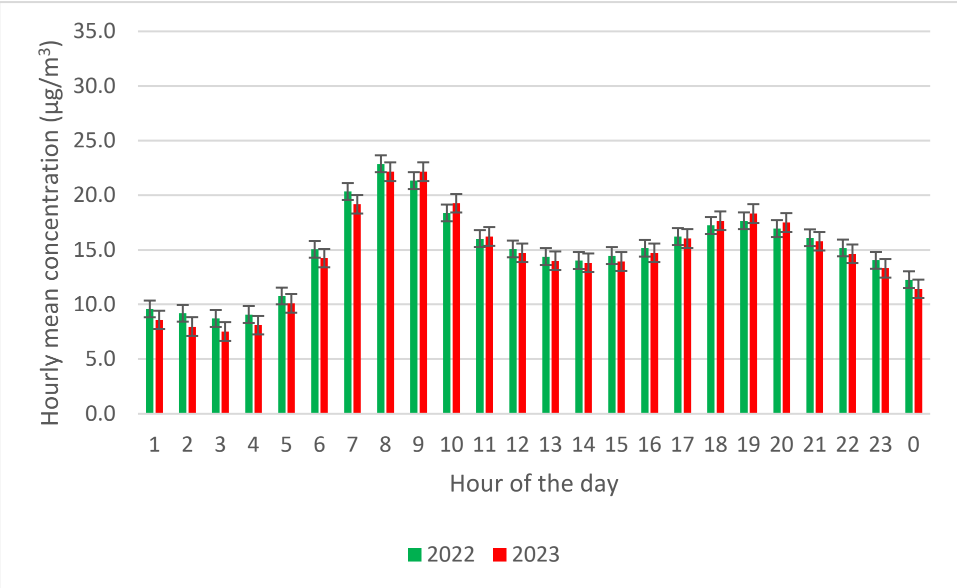

Figure 24. Time variations in Auckland NO_2 hourly mean concentrations. Error bars represent the standard errors of the mean.

The Auckland Council/NZTA air quality monitoring network, which uses passive diffusion tubes, recorded a 3.3% decrease in annual NO_2 concentration for 2023 compared to 2022, from 18.4 ± 6.1 µg/m3 to 17.8 ± 6.0 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 G provide further data from this network.

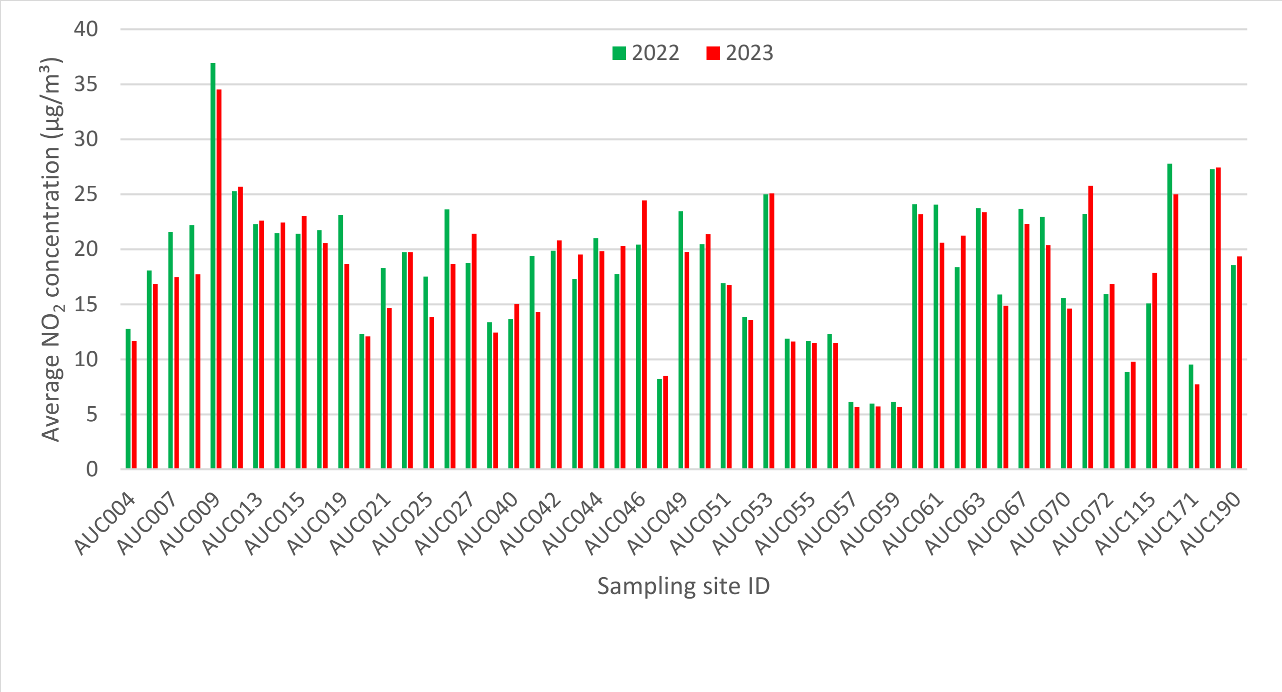

Figure 25. Annual NO_2 average levels at NZTA air quality monitoring sites across Auckland. See Appendix H for description of each site. The monitoring site on Canada Street, Newton, recorded the highest annual NO2 levels, whereas the sites in Glen Eden registered the lowest concentrations. See Appendix G for detailed description of the sites and their average annual NO_2 levels.

The combustion of fuel generates a range of nitrogen oxides (NO_X), as nitrogen in the air is oxidised in the combustion process. For industrial combustion processes, the majority of NO_X 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 NO_X 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 NO_X in 2016.

In 2016, an estimate of 20,520 t/yr of NO_X 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 NO_X 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 example, 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 2022 and 2023 were mostly similar, except for Queen Street.

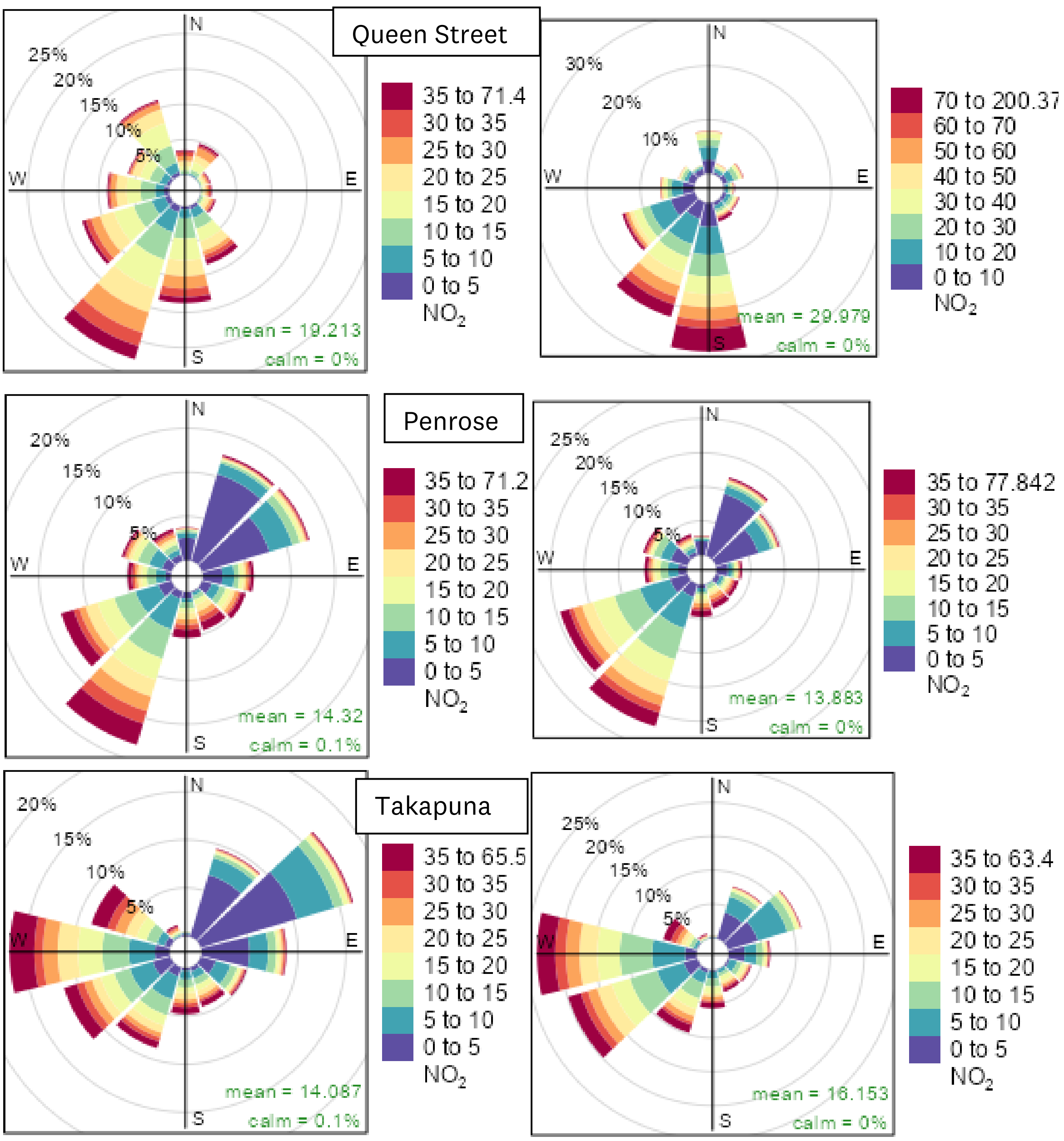

Figure 26. NO_2 pollution roses for Queen Street, Penrose, and Takapuna sites.

Higher NO_2 concentrations are associated with predominant prevailing wind direction as follows: Queen Street: south, Penrose: south-west, and Takapuna: west. The plots on the left are for 2022 data while the right plots are for 2023 data. Frequency of counts by wind direction (%).

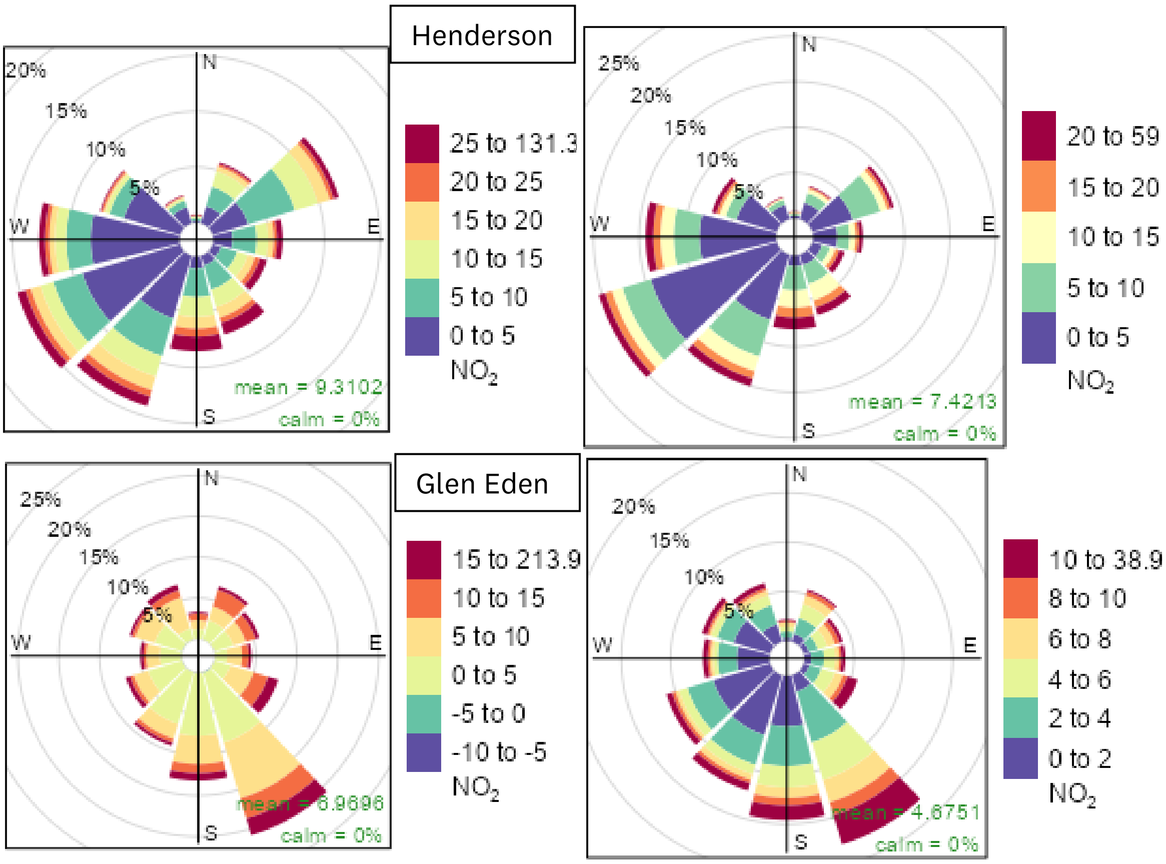

Figure 27. NO_2 pollution roses for Henderson and Glen Eden sites.

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 2022 data while the right plots are for 2023 data. Frequency of counts by wind direction (%).

3.2.4 Sulphur dioxide (SO_2)

The average SO_2 concentration of Auckland in 2023 marginally decreased by 0.7% compared to 2022 (from 2.14 ± 3.57 µg/m^3 to 2.13 ± 1.68 µg/m^3) ($p>0.05$). As found in 2022, the annual SO_2 mean concentration at Customs Street was higher than at the Penrose site. This could be attributed to the higher traffic volume on Customs Street and its proximity to the Port of Auckland, where shipping emissions are likely to be a contributing factor. Figure 28 presents the variation of SO_2 annual concentrations for the two sites.

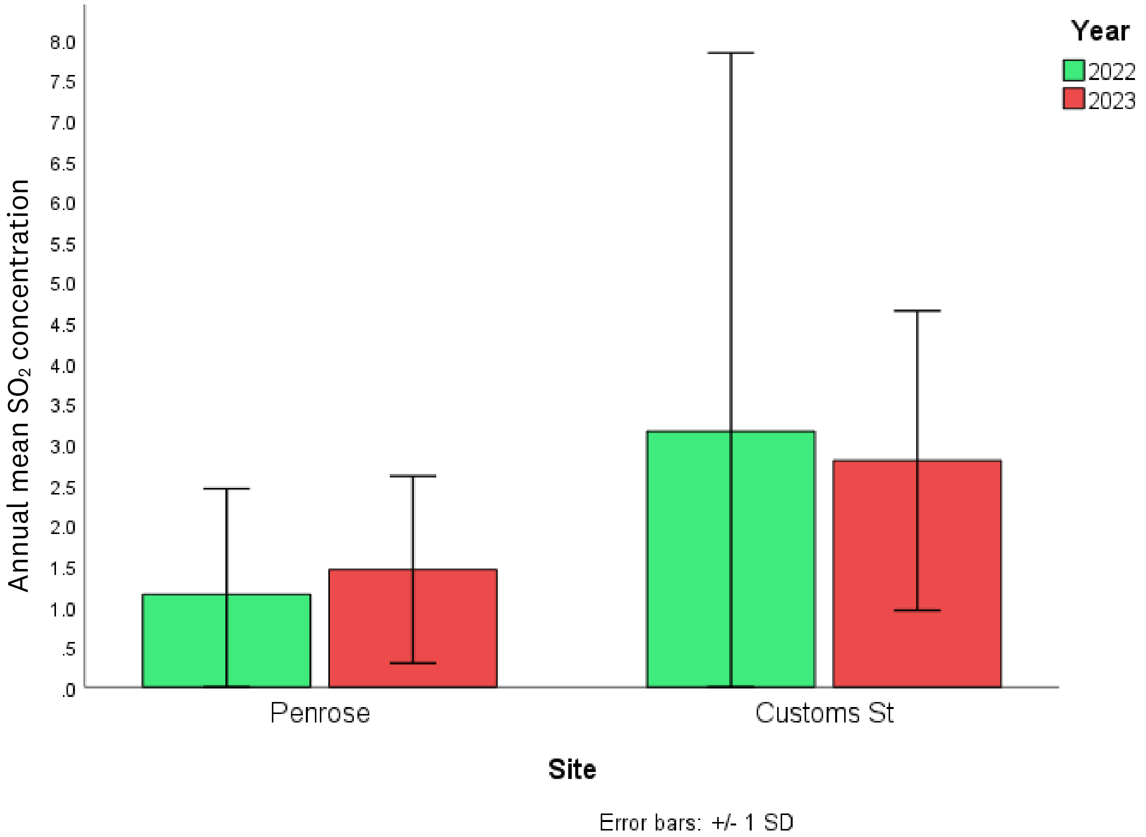

Figure 28. SO_2 annual mean concentrations at Customs Street and Penrose sites. Error bars represent the standard errors of the mean.

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 air quality standard or WHO guidelines during 2023 (See Appendix H). A box and whisker diagram showing the distribution of hourly mean concentrations across the sites is presented in Figure 29.

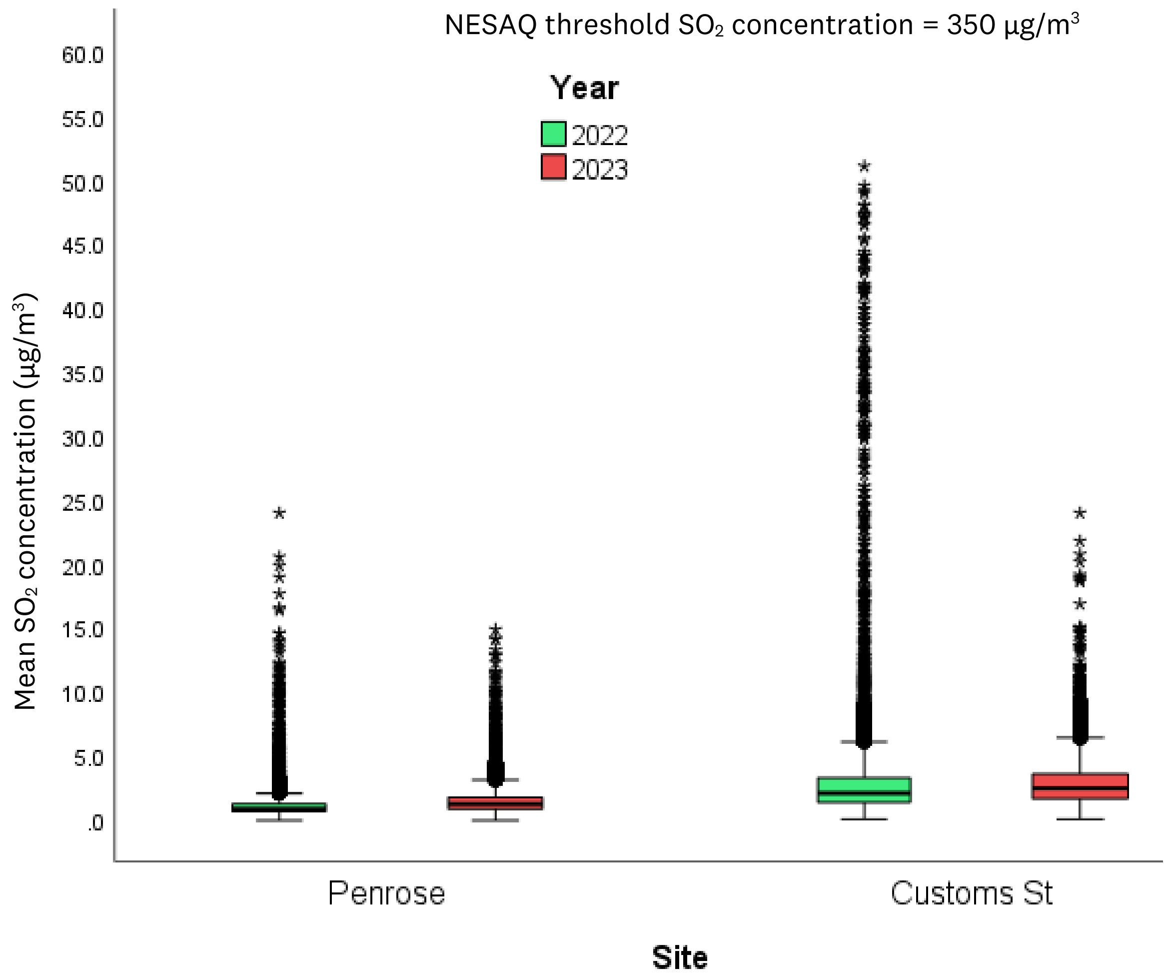

Figure 29. Boxplot of SO_2 hourly mean concentration measured at Customs Street and Penrose.

As in 2022, 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.

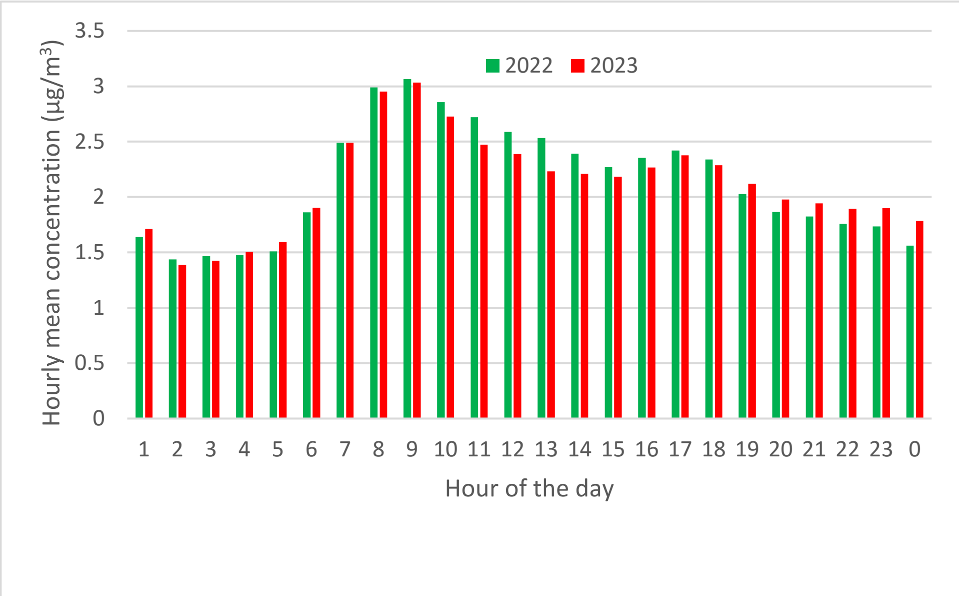

Figure 30. Time variations in SO_2 hourly mean concentrations. Error bars represent the standard errors of the mean.

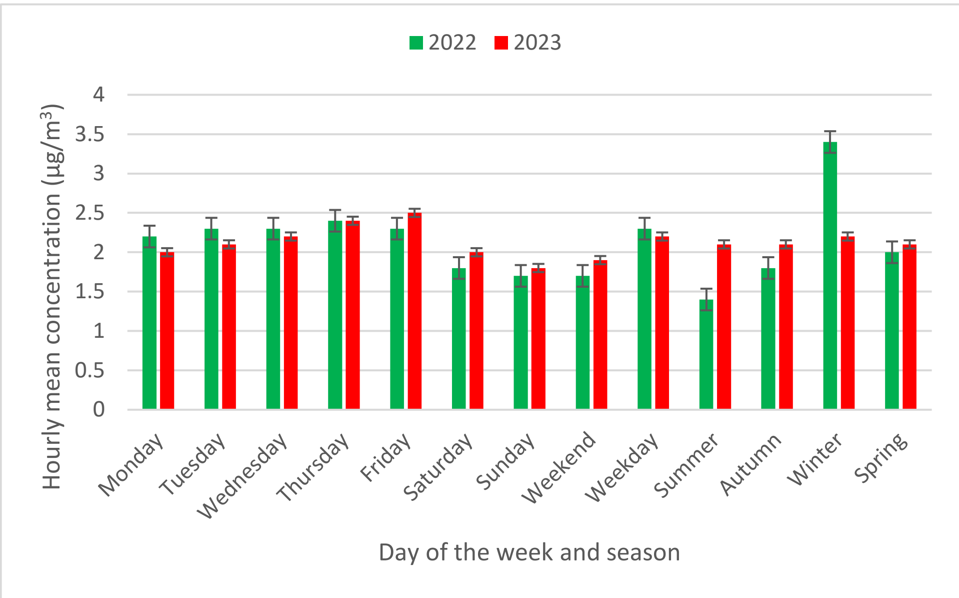

Figure 31. Temporal variations in Auckland SO_2 annual mean concentrations. Error bars represent the standard errors of the mean.

In the same manner as particulates and NO_2, SO_2 concentrations can 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 worth noting that the pattern of SO_2 pollution roses at the Penrose site in 2022 and 2023 was similar.

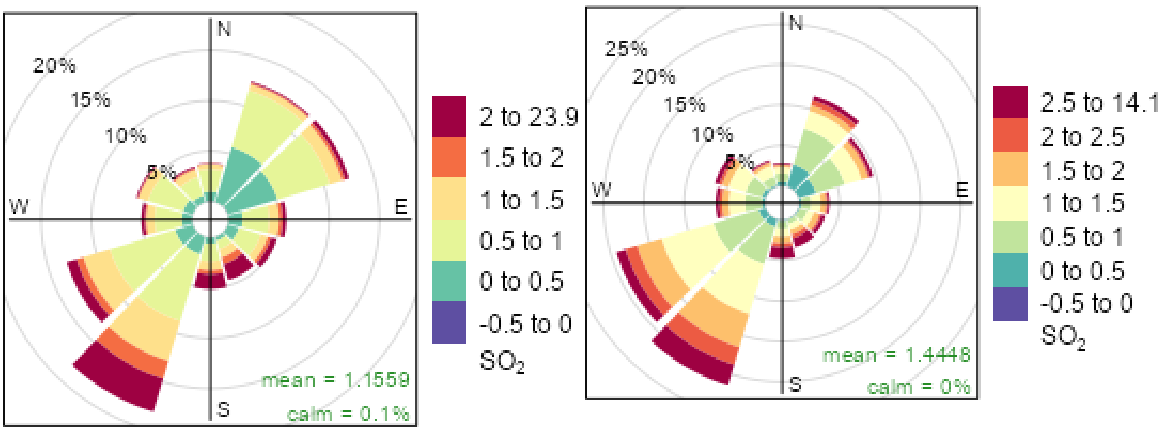

Figure 32. SO_2 pollution roses for Penrose site.

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)

In 2023, the average carbon monoxide (CO) concentration at the Khyber Pass Road site increased by 3.5% compared to 2022, rising from 0.188 ± 0.17 mg/m³ to 0.195 ± 0.17 mg/m³ ($p<0.05$). This statistically significant increase is attributed to a higher traffic volume. According to Auckland Transport's 7-day traffic count data, the traffic volume in 2023 rose from 125,249 to 127,710 vehicles compared to the previous year. For further details about the traffic volume count data, see Appendix N. Even though there were occasional hourly and 8-hour running means spikes in CO concentrations, there was no exceedance of national standard or 2021 WHO air quality guideline in 2023 (Appendix I). A box and whisker diagram showing the hourly mean concentrations is presented in Figure 33.

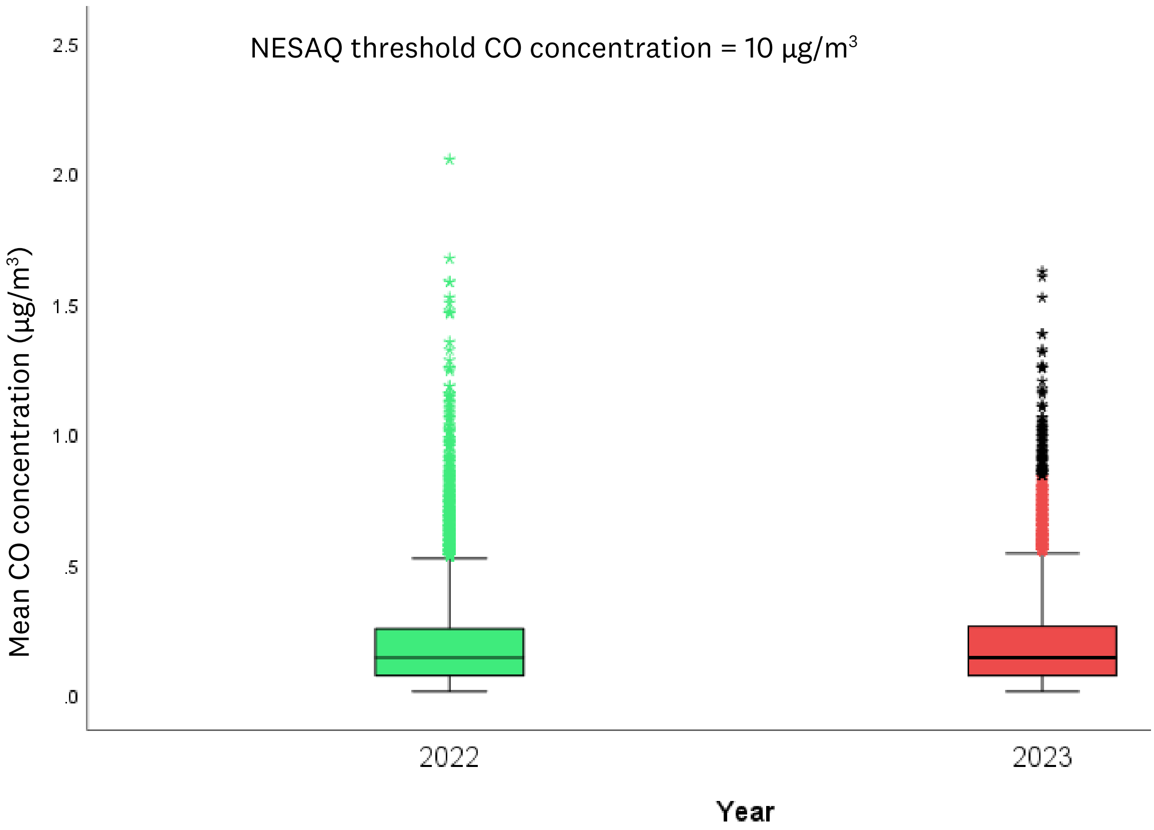

Figure 33. Boxplot of CO hourly mean concentration.

The highest CO concentrations were measured in winter (Figure 34). Similar to the previous year, CO concentrations were highest in the morning and late afternoon likely due to peak traffic, as presented in Figure 35 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.

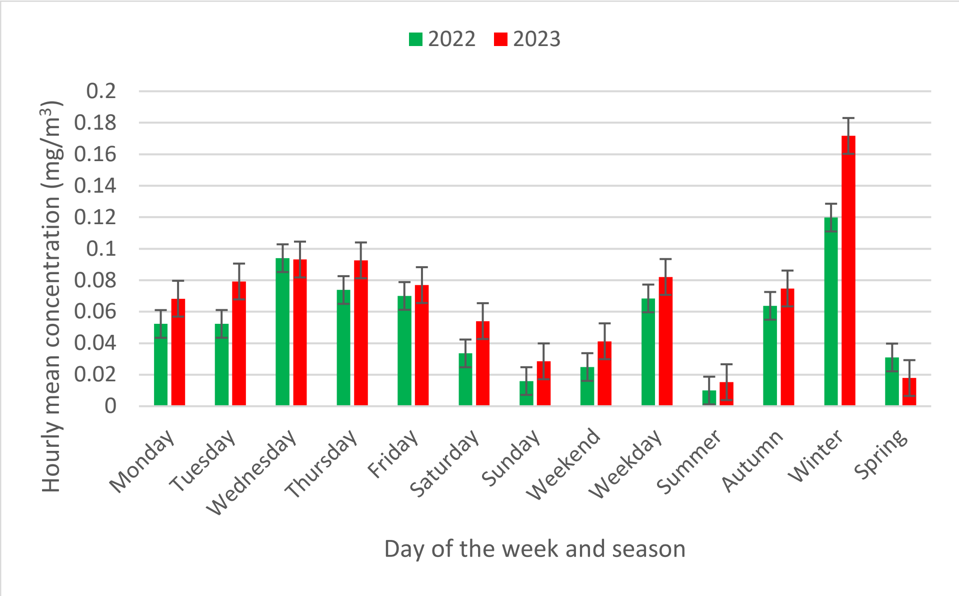

Figure 34. Temporal variations in CO annual mean concentrations. Error bars represent the standard errors of the mean.

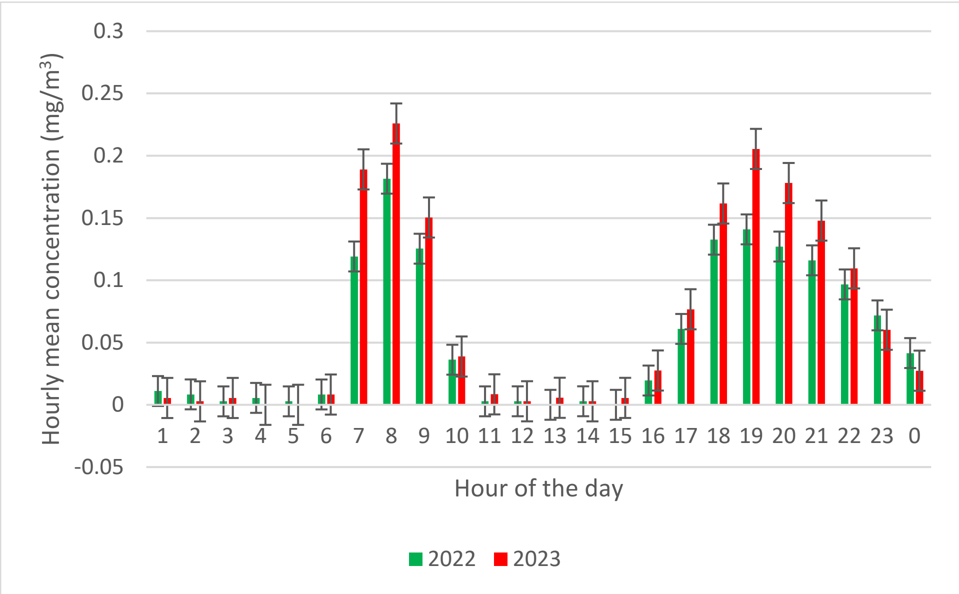

Figure 35. Time variations in CO hourly mean concentrations. Error bars represent the standard errors of the mean.

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 2023 decreased by 1.7% compared to 2022, dropping from 40.1 ± 15.1 µg/m³ to 39.4 ± 16.0 µg/m³ ($p<0.05$). As shown by Figure 36 (and Appendix J), there were occasional hourly mean spikes in O_3 concentrations, however, they did not cause any exceedance of the national standard and 2021 WHO air quality guidelines. A box and whisker diagram showing the hourly mean concentrations is given in Figure 37.

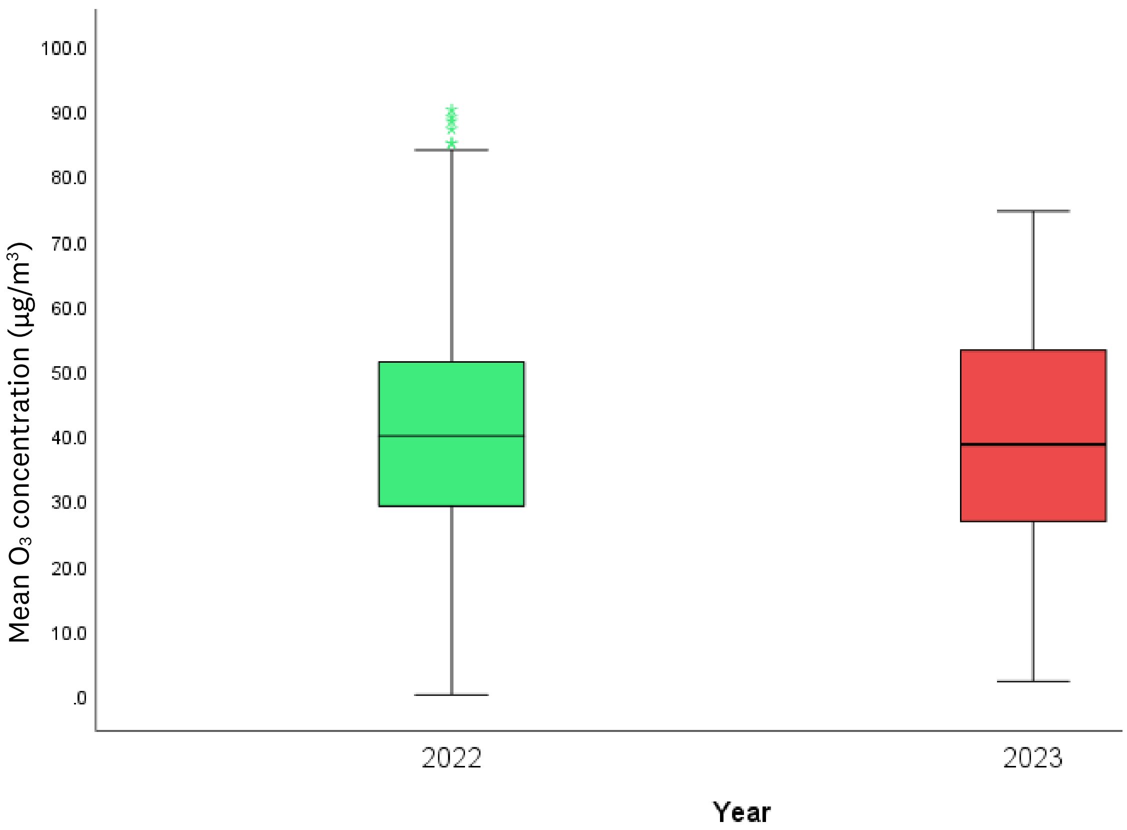

Figure 36. Boxplot of ozone hourly mean concentration.

Like in 2022, the highest O_3 concentrations were measured in spring and winter (Figure 37). In general, O_3 concentrations were highest in the afternoon as shown in Figure 38, 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 increasing sunlight (Xie et al., 2014; Talbot and Crimmins, 2020), explaining the pattern observed in Figure.

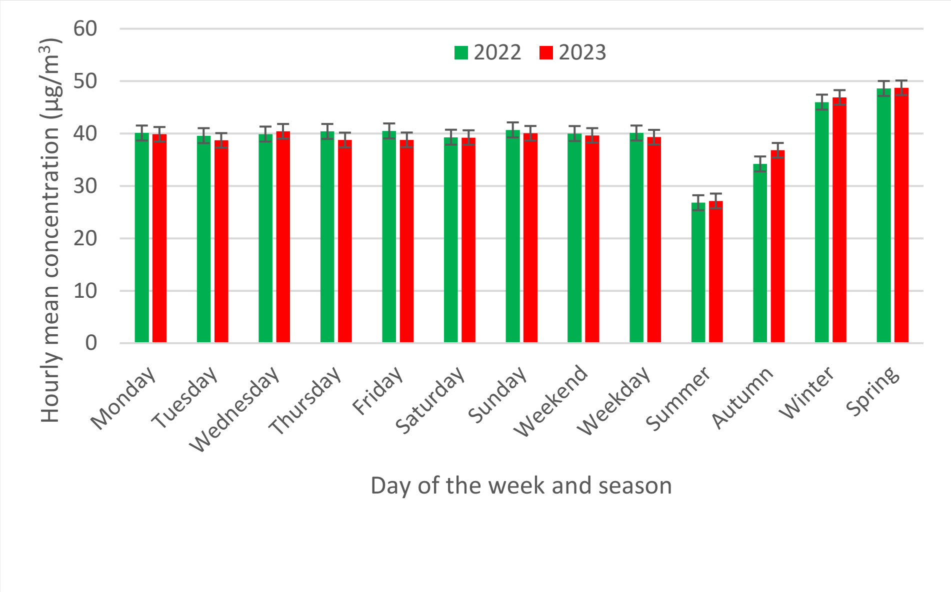

Figure 37. Temporal variations in ozone annual mean concentrations. Error bars represent the standard errors of the mean.

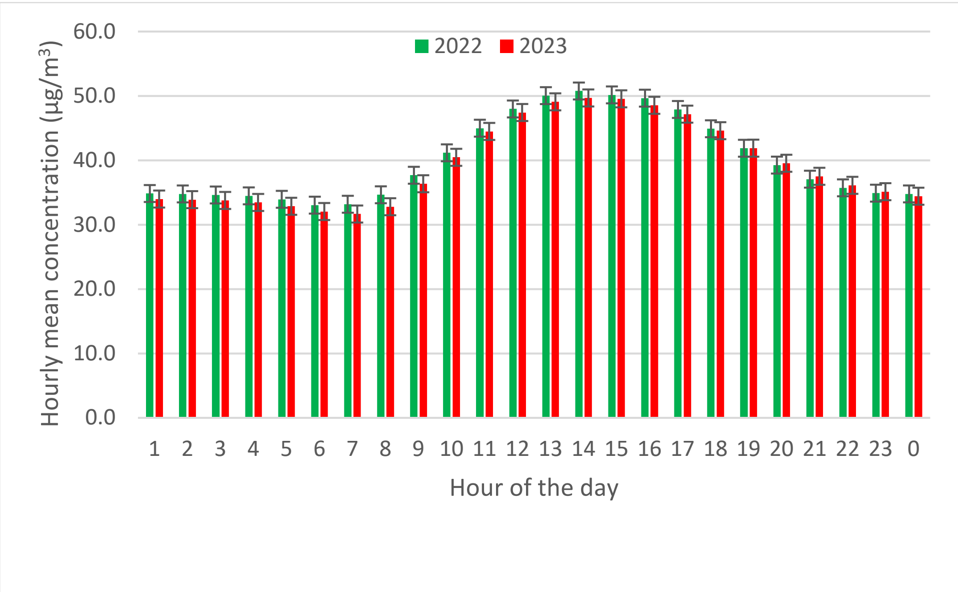

Figure 38. Time variations in ozone hourly mean concentrations. Error bars represent the standard errors of the mean.

3.2.7 Black carbon

The annual black carbon concentration measured at Customs Street in 2023 significantly decreased compared to the previous year, dropping from 1,755 ± 3,559 to 1,423 ± 1,363 ng/m^3 ($p < 0.05$). Similarly, the annual black carbon concentration recorded at Henderson also saw a significant decrease from 584 ± 737 to 437 ± 626 ng/m^3 compared to the previous year ($p < 0.05$). This decrease could be as a result of decrease in traffic volume on Lincoln road and

Customs Street. The reason for the decrease in traffic volume is unclear. Figures 39 and 40 present the variation and distribution of black carbon concentrations at the two sites.

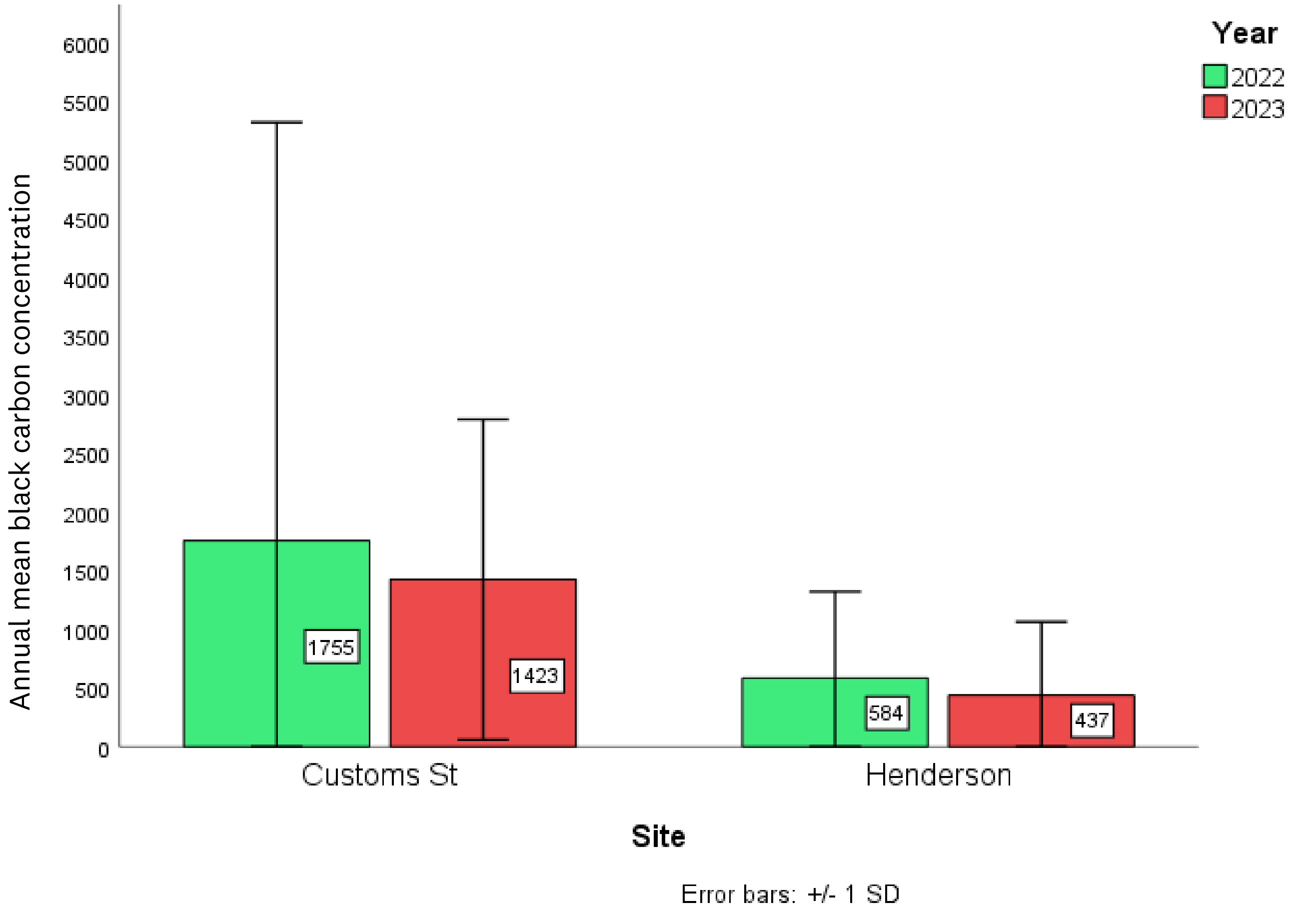

Figure 39. Black carbon annual mean concentrations for Henderson and Customs Street sites. Error bars represent the standard errors of the mean.

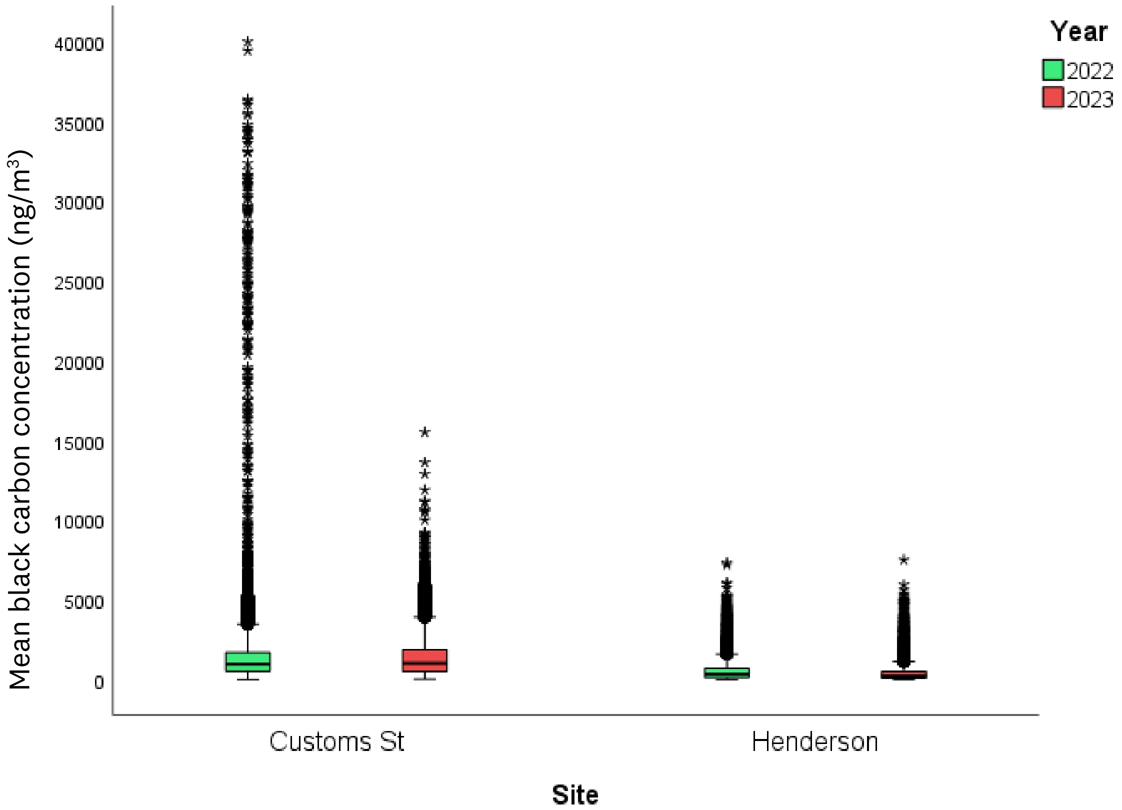

Figure 40. Boxplot of black carbon hourly mean concentration measured at two sites.

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 41). Black carbon concentrations on weekdays are slightly higher than on weekends. The highest black carbon concentrations were recorded in winter (See Appendix K). Concentrations of black carbon tend to increase later in the week with the highest concentrations seen between Wednesday and Friday (Figure 41). Higher traffic volume is a likely contributing factor.

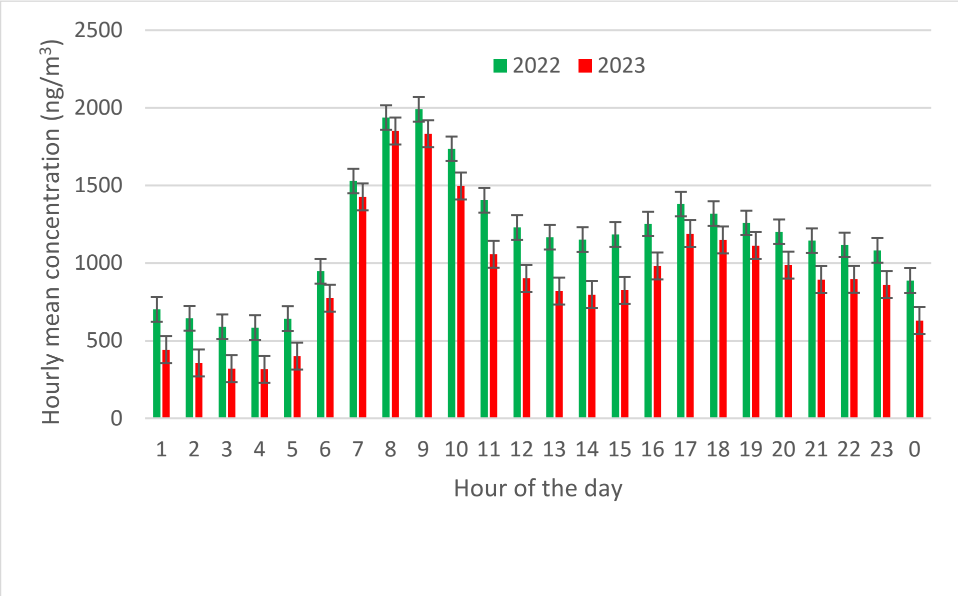

Figure 41. Time variations in black carbon hourly mean concentrations. Error bars represent the standard errors of the mean.

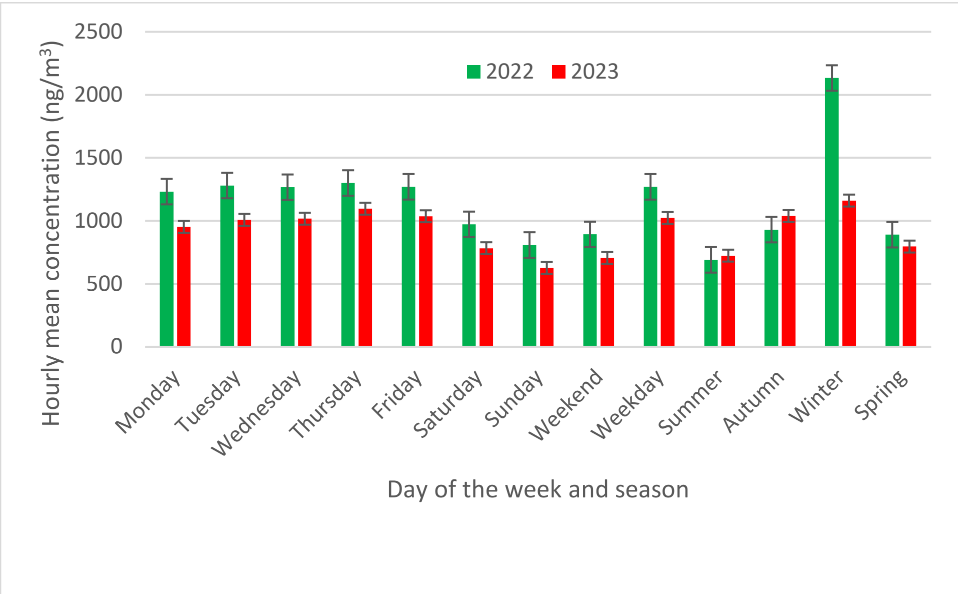

Figure 42. Temporal variations in black carbon annual mean concentrations. Error bars represent the standard errors of the mean.

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

Penrose's TSP mean in 2023 decreased by 24.2% compared to 2022 (from 12.4 ± 5.2 to 9.4 ± 5.5 μg/m^3) ($p<0.05$). As expected, the corresponding mean lead (Pb) levels in the TSP also decreased (from 0.0008 ± 0.0008 μg/m^3 to 0.0006 ± 0.0005 μg/m^3) but not statistically significantly.

At the Khyber Pass Rd and Penrose sites, benzene levels consistently remained below the detection limit, indicating minimal to negligible presence. In contrast, at the Crowhurst St (Newmarket) site, the annual average benzene concentration was 1.6 μg/m^3, below the targeted threshold of 3.6 μg/m^3 established by the Auckland Unitary Plan. Additionally, traces of other volatile organic compounds (VOCs) including toluene, ethylbenzene, hexane, trichloromethane, 1,1,1-trichloroethane, and butyl acetate were detected at some sites. For detailed results of VOC and BTEX measurements at the Newmarket and Penrose sites, see Appendix O. It is important to note that the level of benzene monitored at these sites in 2022 were all below the limit of detection.

4 Conclusions

Key findings:

- The annual average PM_{10} concentration of Auckland in 2023 was 13.3 μg/m^3, which is still below the 2021 WHO air quality guideline of 15 μg/m^3. It is worth noting that the Queen Street site was the only one to report an annual concentration higher than the WHO guideline. On 27th July 2023, the Queen Street site recorded one exceedance of NESAQ for PM_{10} (24-hour average). Our investigation indicated that this exceedance was likely due to the construction activities in the city centre.
- Even though the Auckland Unitary Plan targets for 24-hour and annual average $PM_{2.5}$ were not exceeded, the annual average $PM_{2.5}$ concentration of Auckland in 2023 was 6.3 μg/m^3 which is 26% higher than the 2021 WHO air quality guideline of 5 μg/m^3. In fact, all sites reported annual mean $PM_{2.5}$ concentrations equal or higher than the 2021 WHO guideline and breached, at least once, the more stringent 24-hour WHO air quality guideline of 15 μg/m^3.
- In general, Auckland's annual mean concentration of NO_2 in 2023 decreased by 8.4% compared to 2022. As expected, the highest NO_2 concentrations were measured at the city centre sites. There were no NO_2 national standard exceedance in Auckland. However, on 27 occasions (7%), the 24-hour average NO_2 concentrations exceeded the 2021 WHO air quality guideline of 25 μg/m^3.
- The average SO_2 concentration of Auckland in 2023 marginally increased by 0.7% compared to 2022. As found in 2022, the annual SO_2 mean concentration at Customs Street was higher than at the Penrose site. This could be attributed to the higher traffic volume on Customs Street and its proximity to the Port of Auckland, where shipping emissions are likely to be a contributing factor. There was no exceedance of NESAQ and the 2021 WHO air quality guideline for SO_2.
- The average CO concentration at the Khyber Pass Road site increased by 3.5% compared to 2022. This increase is likely due to the 2% increase in traffic volume on Khyber Pass Road. There was no exceedance of NESAQ and the 2021 WHO air quality guideline for CO.
- The average ground level O_3 concentration at Patumahoe in 2023 decreased by 1.7% compared to 2022. 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.
- In 2023, Penrose's Total Suspended Particulate (TSP) mean decreased by 24.2% compared to 2022, accompanied by a slight reduction in Pb levels, while benzene levels at Khyber Pass Rd and Penrose remained undetectable, and the Crowhurst St site recorded an annual average benzene concentration below the Auckland Unitary Plan threshold, with traces of various VOCs detected at some sites.
- 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.
- Overall, weekday air pollutants concentrations were slightly higher than weekends due to increased traffic and activities.

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 2023 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: Sources of air contaminants in Auckland.

Pollutant	Source	Site(s) impacted	References
PM, black carbon, CO, SO_2, NO_X, 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); Boamponsem et al. (2024)
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, NO_X, 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, NO_X, 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 B: Meteorological parameters descriptive statistics.

Ambient temperature					
Site	Year	Annual mean (ºC)	Std. Deviation	Significant?*	Change**
Glen Eden	2022	16.0	3.2	Yes	↓
	2023	15.3	4.1		
Penrose	2022	16.9	4.1	Yes	↓
	2023	15.7	3.8		
Pakuranga	2022	15.6	3.4	No	↗
	2023	16.0	4.4		
Papatoetoe	2022	16.6	4.4	Yes	↓
	2023	15.8	4.2		
Henderson	2022	16.5	3.3	Yes	↓
	2023	16.0	4.3		
Auckland	2022	16.3	3.9	Yes	↓
	2023	15.8	4.2		
Ambient relative humidity					
Site	Year	Annual mean(%)	Std. Deviation	Significant? *	Change**
Glen Eden	2022	72.9	13.2	Yes	↑
	2023	74.1	12.0		
Penrose	2022	70.5	12.8	Yes	↑
	2023	77.6	13.0		
Pakuranga	2022	72.3	23.9	Yes	↑
	2023	73.4	12.6		
Papatoetoe	2022	73.7	14.3	Yes	↑
	2023	79.6	13.4		
Henderson	2022	71.7	13.6	Yes	↑
	2023	73.3	12.6		
Auckland	2022	72.3	15.9	Yes	↑
	2023	75.6	13.0		

↑ Increased

* Mean difference

Appendix C: Mean difference comparison between 2022 and 2023: t-test results.

Site	Pollutant	p-value (2-tailed)	t	Degrees of freedom	Significant?	Change*
Penrose	SO_2	<0.001	16.168	16699	Yes	↑
Customs Street		0.035	-6.580	16699	Yes	↓
Auckland		0.610	0.511	33400	No	↘
Customs Street	Black carbon	<0.001	-8.033	16875	Yes	↓
Henderson		<0.001	-13.989	16573	Yes	↓
Auckland		<0.001	-10.258	23310	Yes	↓
Khyber Pass Road	CO	0.015	2.422	16946	Yes	↑
Patumahoe	O_3	0.007	-2.687	15592	Yes	↓
Patumahoe	NO_2	<0.001	-27.344	15382	Yes	↓
Penrose		<0.001	-3.669	16514	Yes	↓
Queen Street		<0.001	29.233	10965	Yes	↑
Customs Street		<0.001	-21.770	16700	Yes	↓
Glen Eden		<0.001	-25.688	16918	Yes	↓
Khyber Pass Road		<0.001	-5.614	16997	Yes	↓
Henderson		<0.001	-14.187	16894	Yes	↓
Takapuna		<0.001	6.353	15416	Yes	↑
Auckland		<0.001	-13.897	125801	Yes	↓
Patumahoe	PM_{10}	<0.001	-4.646	16326	Yes	↓
Penrose		<0.001	3.682	17255	Yes	↑
Queen Street		<0.001	4.420	11089	Yes	↑
Glen Eden		<0.001	3.155	17101	Yes	↑
Pakuranga		0.016	2.135	17273	Yes	↑
Papatoetoe		<0.001	3.440	17264	Yes	↑
Khyber Pass Road		<0.001	10.917	17000	Yes	↑
Henderson		<0.001	5.368	16853	Yes	↑
Takapuna		0.012	2.256	16532	Yes	↑
Auckland		<0.001	9.432	146639	Yes	↑
Queen Street	$PM_{2.5}$	<0.001	4.750	11090	Yes	↑
Penrose		<0.001	-3.546	15716	Yes	↓
Patumahoe		0.242	1.171	15288	No	↗
Takapuna		<0.001	12.768	15905	Yes	↑
Auckland		<0.001	6.141	58005	Yes	↑
Penrose	TSP	0.005	-2.904	97	Yes	↓
Penrose	Pb in TSP	0.278	-1.109	24	No	↘
*	↓		Decreased			
	↑		Increased			
	↗		Increased but not significant			
	↘		Decreased but not significant			

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

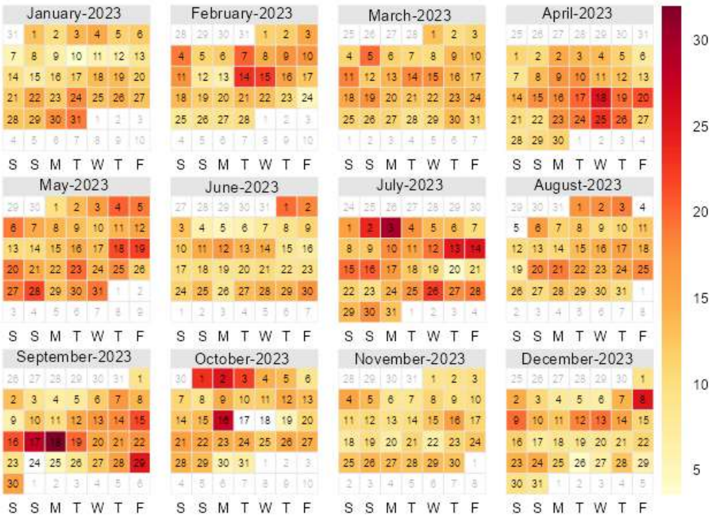

Figure D1. Calendar plot for PM_{10} concentrations in 2022 – nine sites combined.

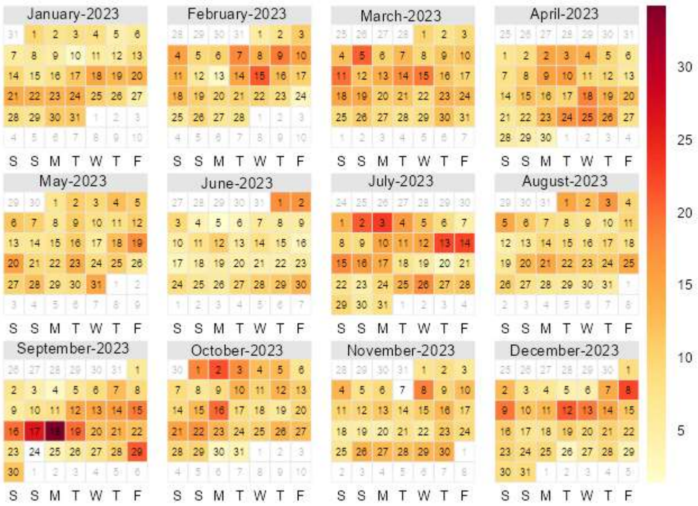

Figure D2. Calendar plot for PM_{10} concentrations in Patumahoe.

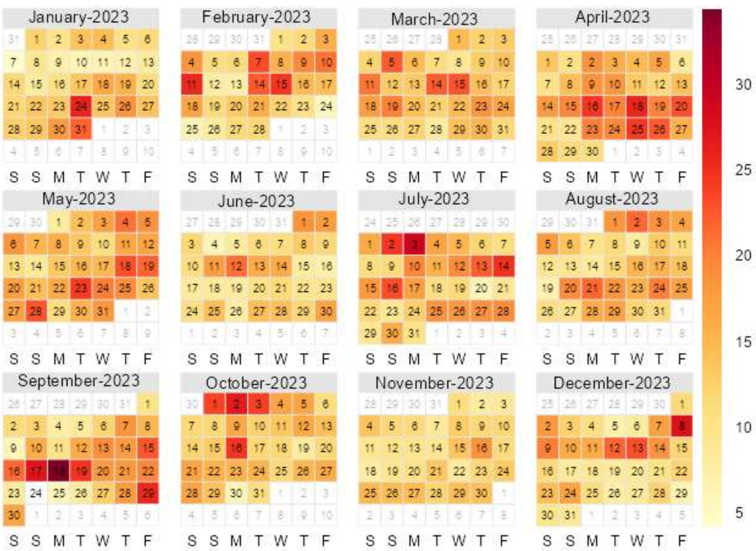

Figure D3. Calendar plot for PM_{10} concentrations in Penrose.

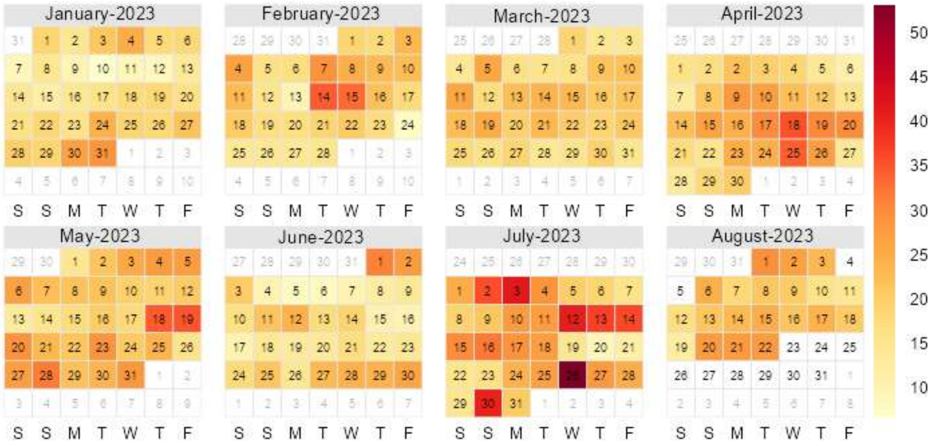

Figure D4. Calendar plot for PM_{10} concentrations in Queen.

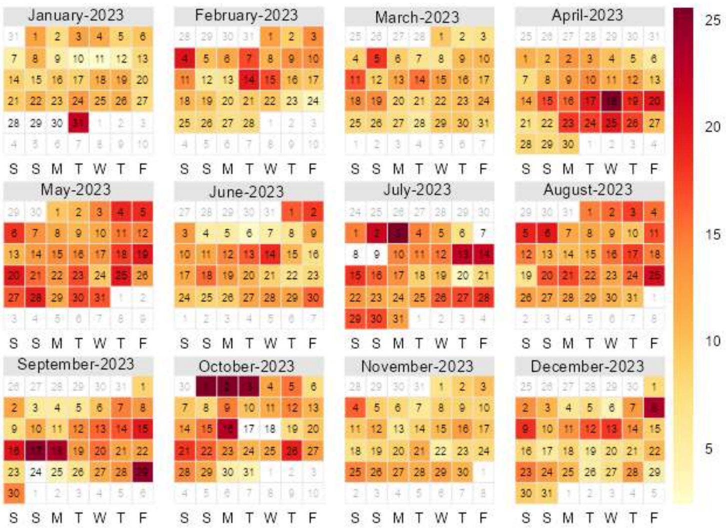

Figure D5. Calendar plot for PM_{10} concentrations in Glen Eden site.

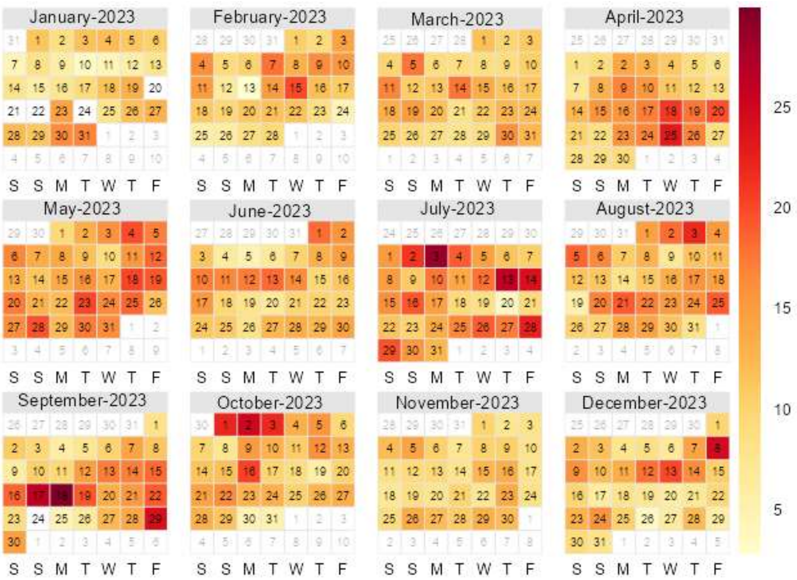

Figure D6. Calendar plot for PM_{10} concentrations in Pakuranga.

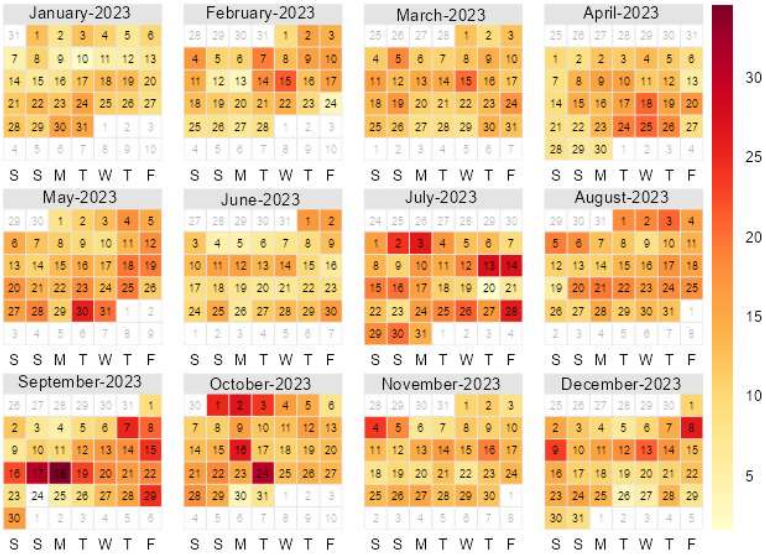

Figure D7. Calendar plot for PM_{10} concentrations in Papatoetoe

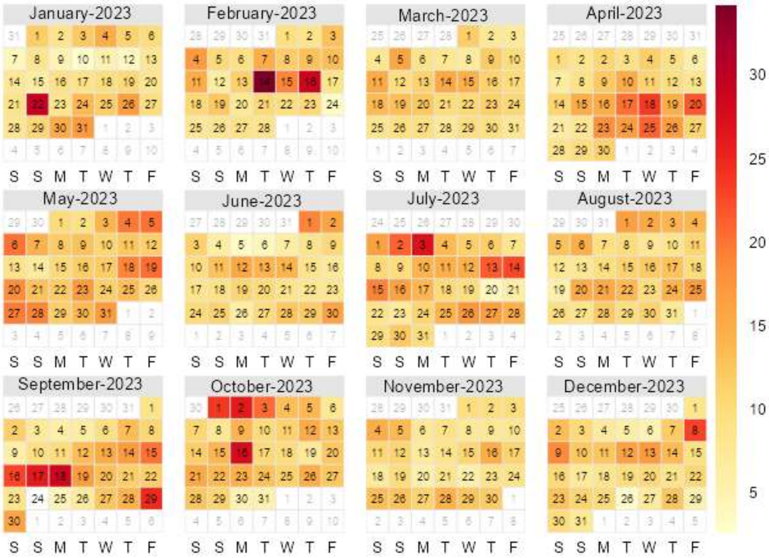

Figure D8. Calendar plot for PM_{10} concentrations in Henderson.

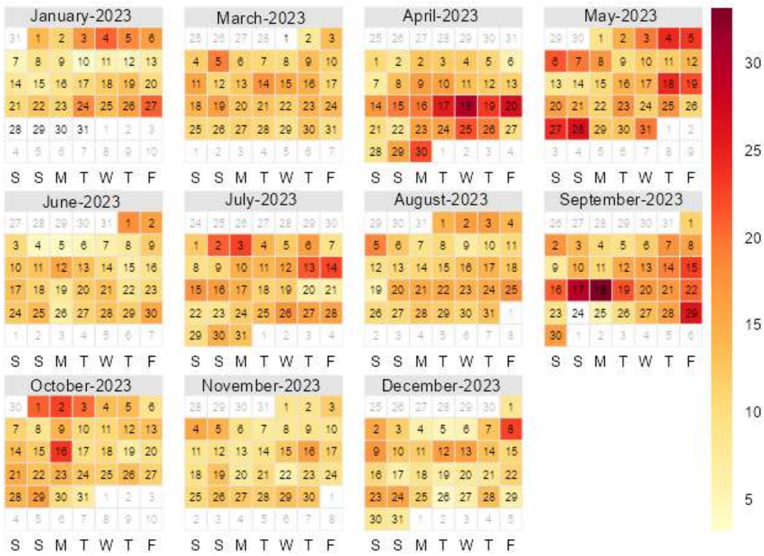

Figure D9. Calendar plot for PM_{10} concentrations in Takapuna.

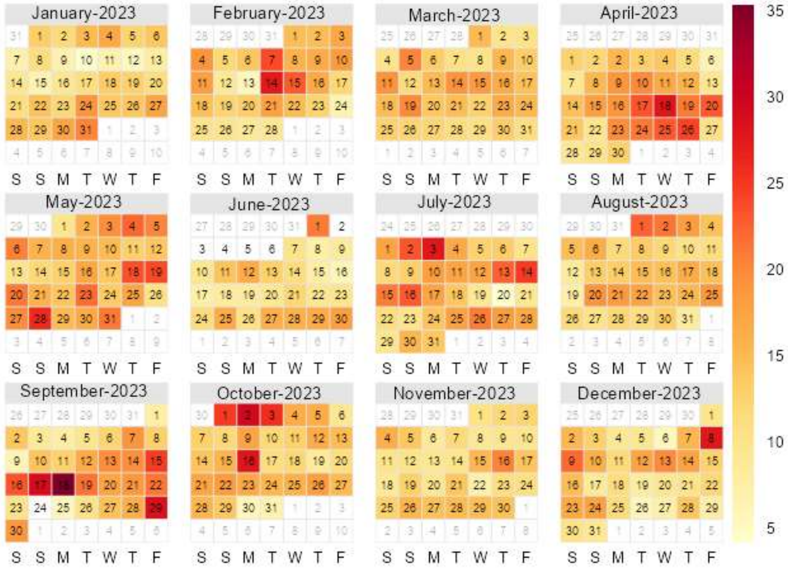

Figure D10. Calendar plot for PM_{10} concentrations in Khyber Pass Road.

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

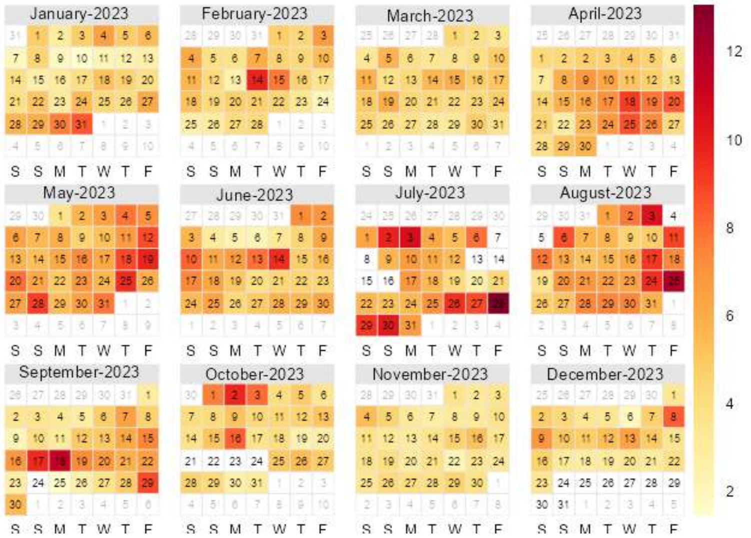

Figure E1. Calendar plot for Auckland $PM_{2.5}$ concentrations in 2023 (seven sites combined).

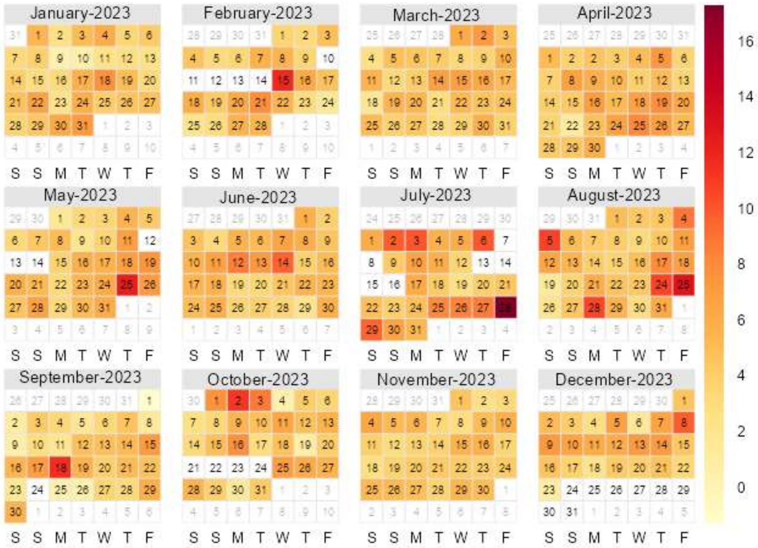

Figure E2. Calendar plot for $PM_{2.5}$ concentrations in Penrose.

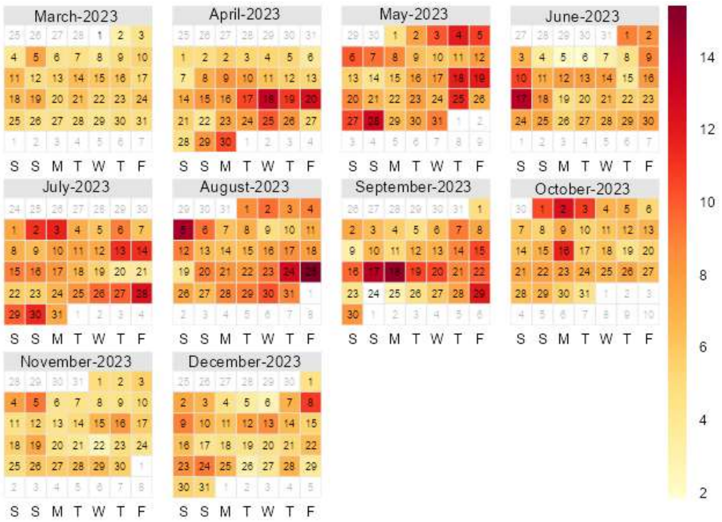

Figure E3. Calendar plot for $PM_{2.5}$ concentrations in Takapuna.

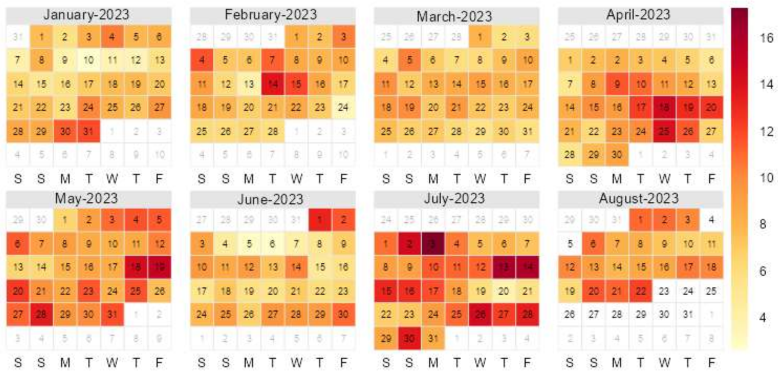

Figure E4. Calendar plot for $PM_{2.5}$ concentrations in Queen Street.

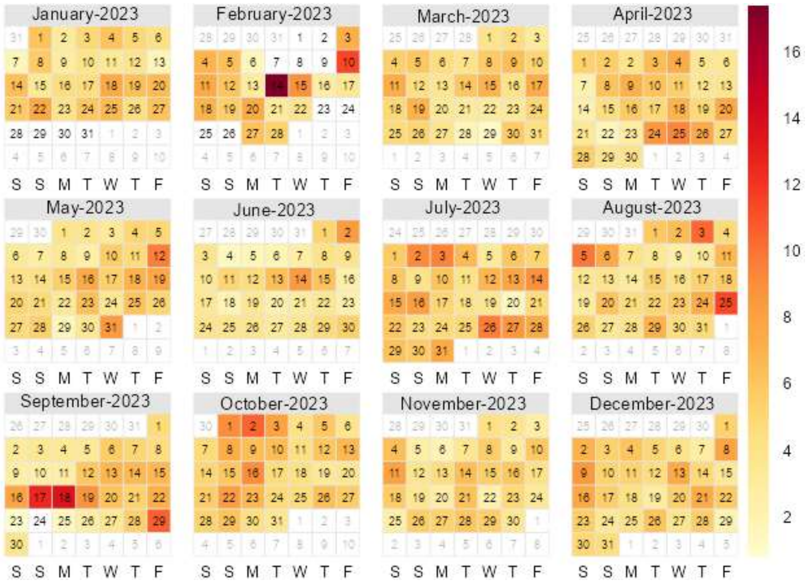

Figure E5. Calendar plot for $PM_{2.5}$ concentrations in Patumahoe.

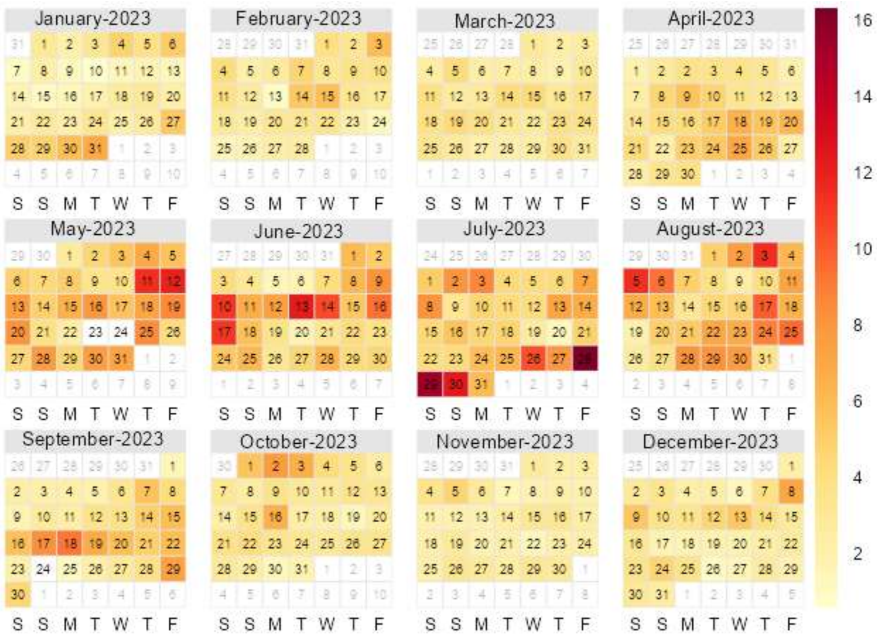

Figure E6. Calendar plot for $PM_{2.5}$ concentrations in Pakuranga.

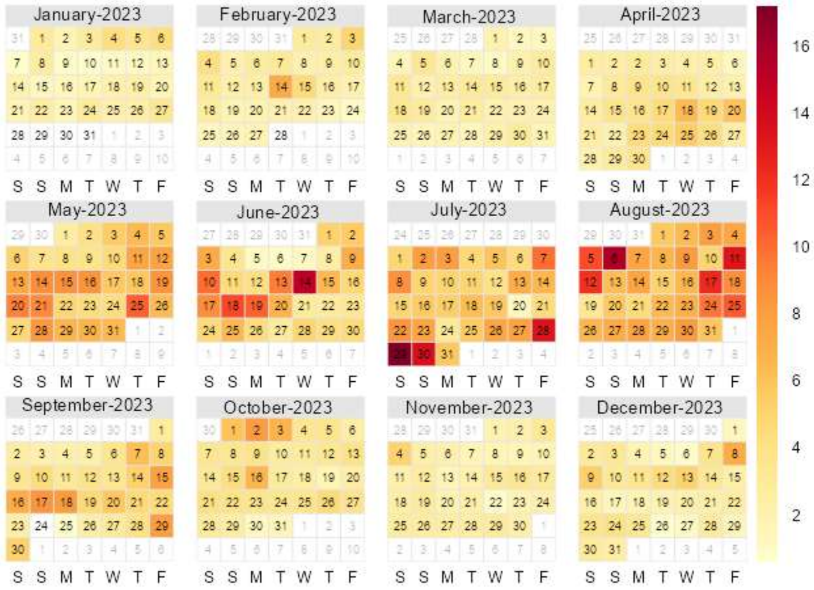

Figure E7. Calendar plot for $PM_{2.5}$ concentrations in Glen Eden.

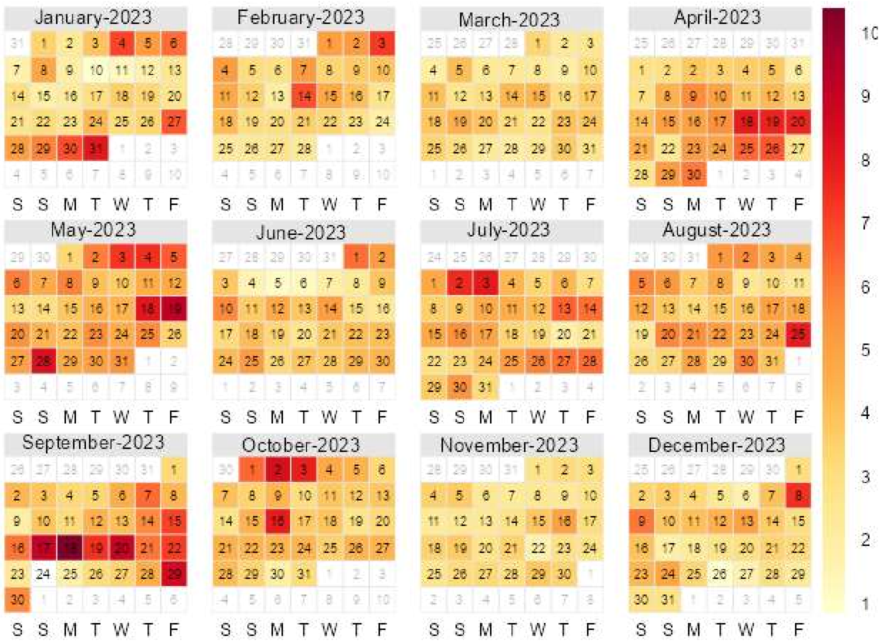

Figure E8. Calendar plot for $PM_{2.5}$ concentrations in Customs Street.

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

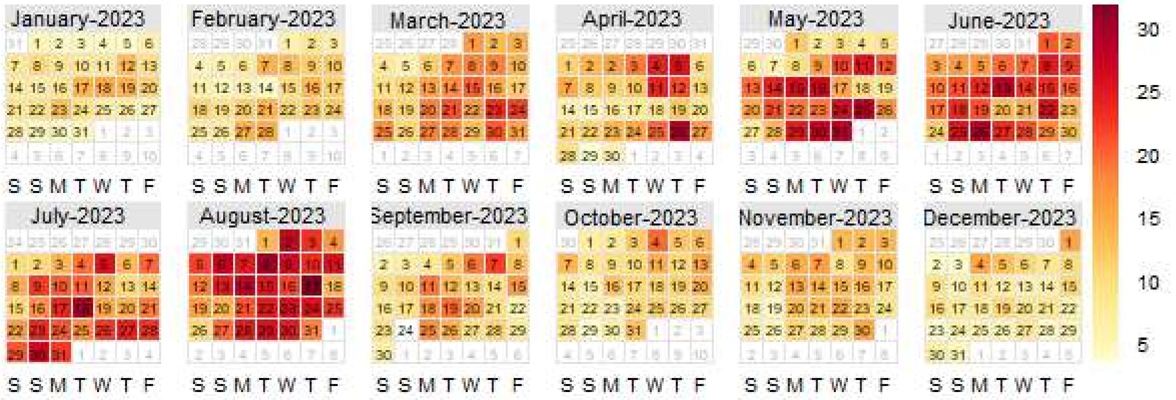

Figure F1. Calendar plot for NO_2 concentrations in 2022 – eight sites combined.

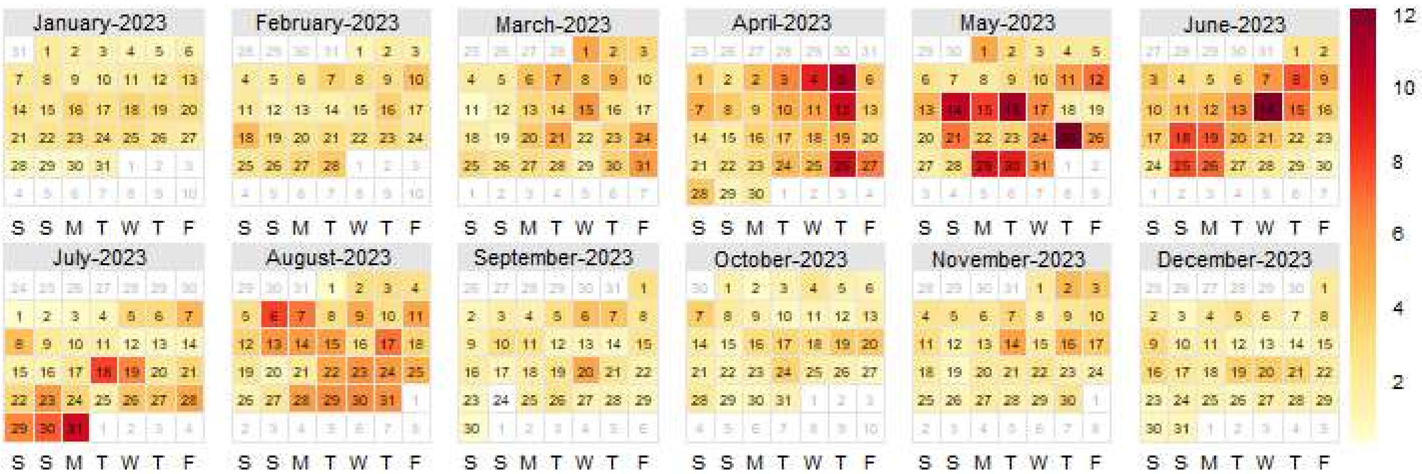

Figure F2. Calendar plot for NO_2 concentrations in Patumahoe.

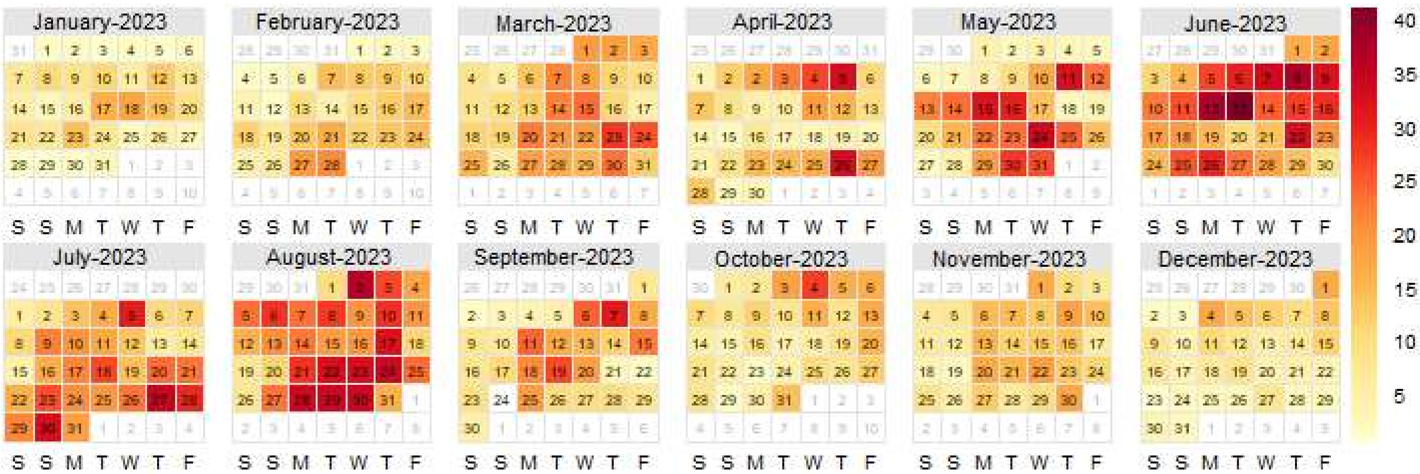

Figure F3. Calendar plot for NO_2 concentrations in Penrose.

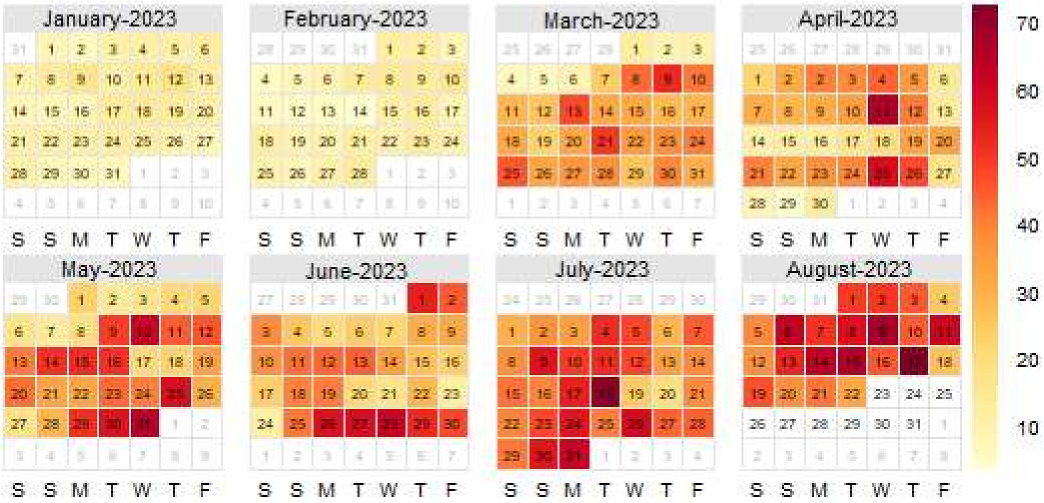

Figure F4. Calendar plot for NO_2 concentrations in Queen Street.

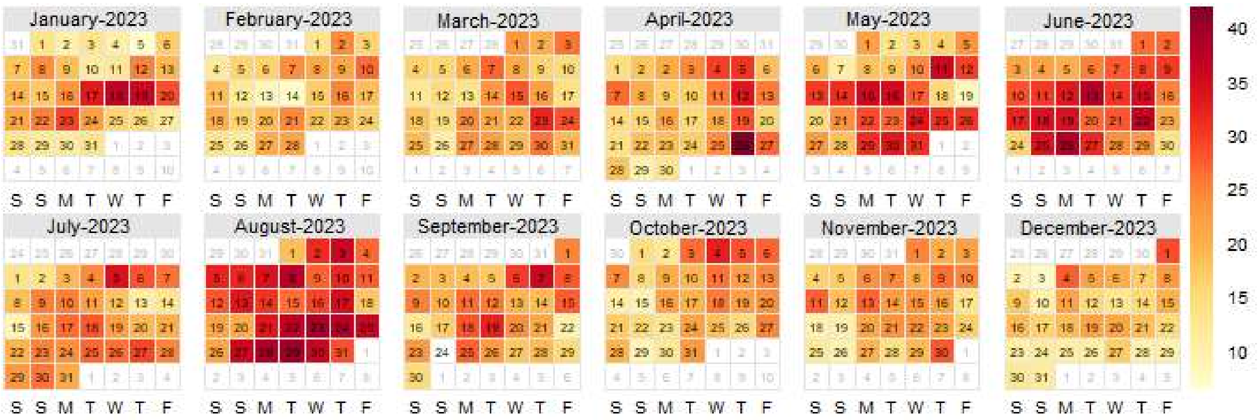

Figure F5. Calendar plot for NO_2 concentrations in Customs Street.

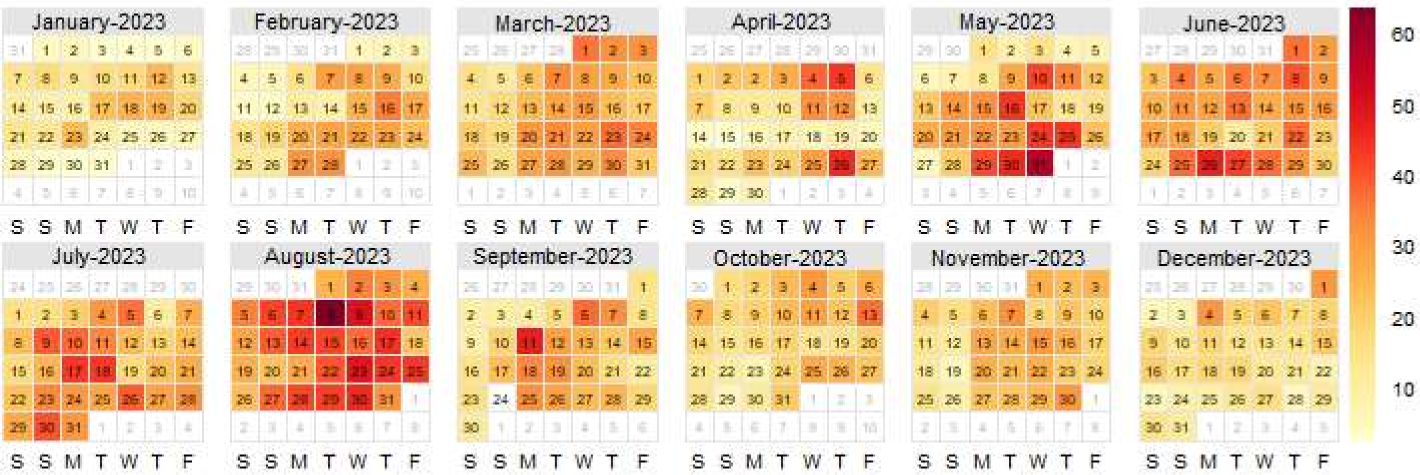

Figure F6. Calendar plot for NO_2 concentrations in Khyber Pass Road.

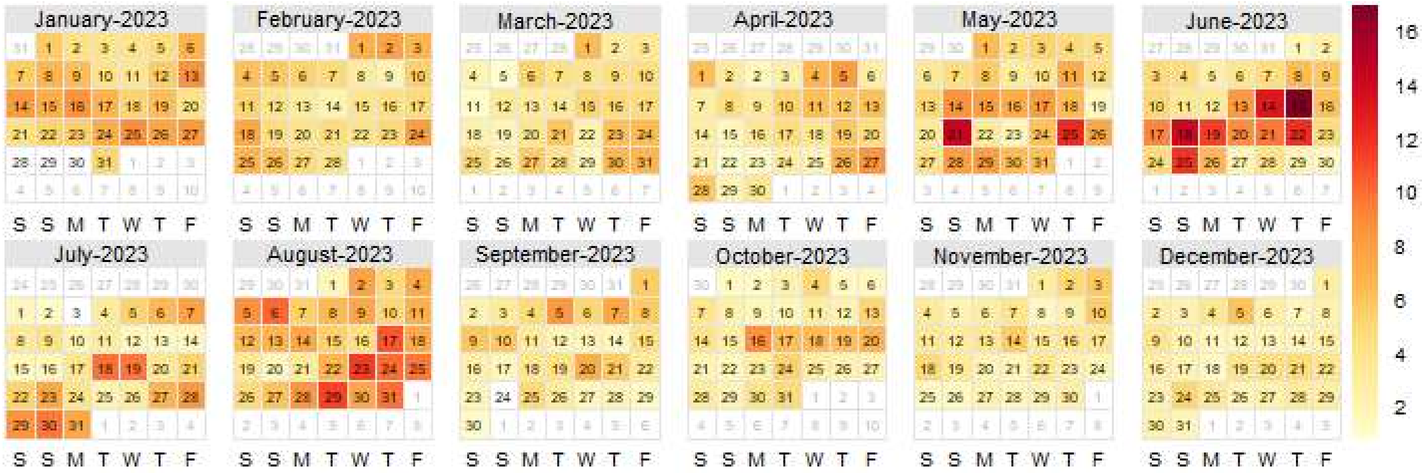

Figure F7. Calendar plot for NO_2 concentrations in Glen Eden.

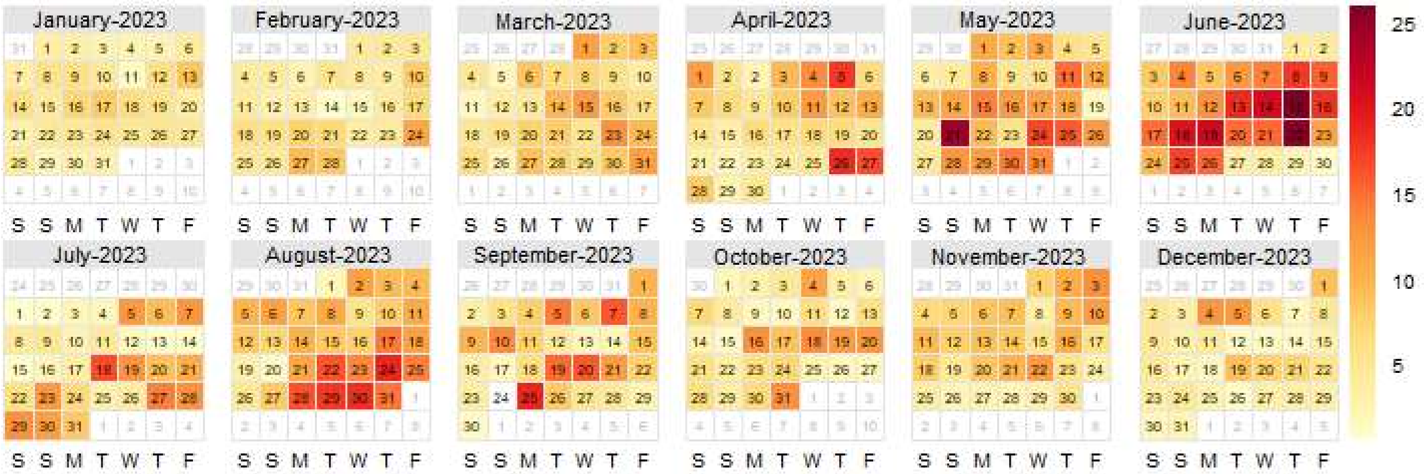

Figure F8. Calendar plot for NO_2 concentrations in Henderson.

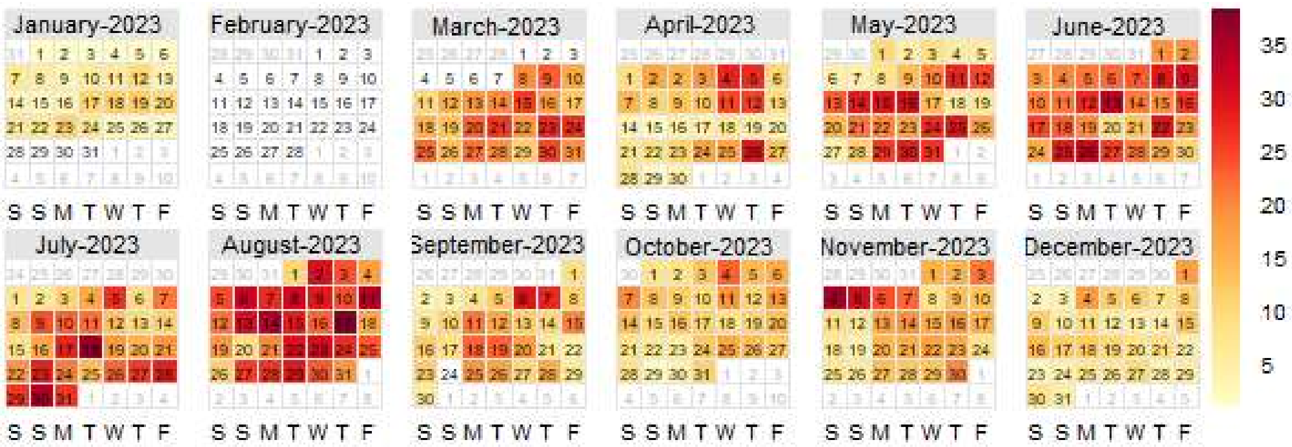

Figure F9. Calendar plot for NO_2 concentrations in Takapuna.

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

Table G1. Auckland sites description, annual averages(µg/m³) and percentage data coverage

Site ID	Coordinates (NZTM)		Area	Site name	Annual average		% valid data	
	Easting	Northing			2022	2023	2022	2023
AUC004	1750133	5949359	Orewa	Grand Dr / Tauranga Pl	12.8	11.7	75%	100%
AUC005	1753095	5935106	Albany	Oteha Valley Rd / Fairview Ave	18.1	16.9	92%	100%
AUC007	1756065	5923935	Northcote	Northern Motorway / Sulphur Beach Rd	21.6	17.5	92%	100%
AUC008	1755662	5921138	St Mary's Bay	Northern Motorway / St Mary's Bay Rd	22.2	17.7	67%	92%
AUC009	1756848	5919273	Newton	CMJ / Canada St	36.9	34.5	92%	100%
AUC011	1758969	5917106	Remuera	Southern Motorway / Mt Hobson Rd	25.3	25.7	83%	83%
AUC013	1761757	5914171	Penrose	Southern Motorway / Gavin St b	22.3	22.6	100%	100%
AUC014	1761757	5914171	Penrose	Southern Motorway / Gavin St c	21.5	22.4	100%	100%
AUC015	1761757	5914171	Penrose	Southern Motorway / Gavin St d	21.4	23.0	100%	100%
AUC018	1767509	5905866	Flat Bush	Southern Motorway / Waimate St	21.7	20.6	75%	75%
AUC019	1767713	5903803	Manukau	Southern Motorway / Liggett Dr	23.1	18.7	50%	100%
AUC020	1744702	5921634	Massey East	North Western Motorway / Redwood Dr	12.3	12.1	92%	83%
AUC021	1751667	5917766	Waterview	Waterbank Cres	18.3	14.7	83%	100%
AUC022	1755717	5918398	Arch Hill	North Western Motorway / Niger St	19.7	19.7	83%	83%
AUC025	1756246	5912958	Hillsborough	Hugh Watt Dr / Melrose Rd	17.5	13.9	75%	75%
AUC026	1759570	5909661	Mangere	South Western Motorway / Hastie Ave	23.6	18.7	92%	100%
AUC027	1760143	5908270	Mangere	South Western Motorway / Ashmore Pl	18.8	21.4	50%	75%
AUC039	1752074	5930540	Unsworth Heights	Albany Highway / Ashby Pl	13.4	12.4	83%	83%
AUC040	1749755	5928069	Greenhithe	Upper Harbour Dr / William Pitcher Pl	13.7	15.0	67%	58%
AUC041	1753390	5929775	Glenfield	Glenfield Rd / Sunset Rd	19.4	14.3	92%	100%
AUC042	1758078	5927136	Takapuna	Lake Rd / Service Ln	19.9	20.8	100%	100%
AUC043	1756069	5928070	Takapuna	Northern Motorway / Wairau Rd	17.3	19.5	100%	100%
AUC044	1756069	5928070	Takapuna	Northern Motorway / Wairau Rd	21.0	19.8	67%	100%
AUC045	1756069	5928070	Takapuna	Northern Motorway / Wairau Rd	17.7	20.3	100%	100%
AUC046	1758428	5926591	Takapuna	Lake Rd / Esmonde Rd	20.4	24.5	67%	83%
AUC047	1753696	5927375	Marlborough	Woodcote Dr	8.2	8.5	92%	92%
AUC049	1747171	5926306	Hobsonville	Hobsonville Rd / Carnegie Cres	23.5	19.8	83%	100%
AUC050	1742288	5926712	Whenuapai	SH16 / Kennedys Rd	20.5	21.4	100%	92%
AUC051	1744980	5921293	Massey East	North Western Motorway / Taitapu St	16.9	16.8	92%	92%
AUC052	1745187	5916791	Henderson	Henderson Valley Rd / Hickory Ave	13.9	13.6	100%	100%
AUC053	1746833	5918830	Te Atatu Sth	Te Atatu Rd / Edmonton Rd	25.0	25.1	75%	100%
AUC054	1745135	5918515	Henderson	Lincoln Rd / Henderson Intermediate	11.9	11.6	100%	100%
AUC055	1745135	5918515	Henderson	Lincoln Rd / Henderson Intermediate	11.7	11.5	100%	100%
AUC056	1745135	5918515	Henderson	Lincoln Rd / Henderson Intermediate	12.3	11.5	100%	100%
AUC057	1747149	5912480	Glen Eden	AC Glen Eden	6.1	5.7	92%	100%
AUC058	1747149	5912480	Glen Eden	AC Glen Eden	6.0	5.7	92%	92%
AUC059	1747149	5912480	Glen Eden	AC Glen Eden	6.1	5.7	92%	100%
AUC060	1752890	5916596	Mt Albert	New North Rd / Mount Albert Rd	24.1	23.2	83%	100%
AUC061	1759938	5915778	Greenlane	Great South Rd / Green Ln East	24.1	20.6	75%	100%
AUC062	1764307	5914946	Mt Wellington	Ellerslie Panmure Highway / Mountain Rd	18.4	21.2	100%	92%
AUC063	1749443	5913945	New Lynn	Great North Rd / Rata St	23.7	23.4	100%	75%
AUC064	1755692	5917809	Kingsland	Sandringham Rd / Kowhai Intermediate	15.9	14.9	100%	92%
AUC067	1761844	5906521	Mangere East	Southwestern Motorway / Ensor Pl	23.7	22.3	83%	100%
AUC069	1766535	5908095	Otara	Bairds Rd / Otara Rd	23.0	20.4	83%	100%
AUC070	1774740	5896065	Papakura	Dominion Rd / Settlement Rd	15.6	14.6	50%	67%
AUC071	1763755	5908915	Otahuhu	Mangere Rd / Walmsley Rd	23.2	25.8	67%	75%
AUC072	1768412	5913942	Pakuranga	Pakuranga Rd / Bell Reserve	15.9	16.8	83%	92%
AUC073	1771370	5912359	Botany	AC Botany	8.9	9.8	67%	92%
AUC115	1747004	5919893	Te Atatu	Northwestern Motorway / Titoki St 1	15.1	17.9	75%	92%
AUC170	1755482	5928973	Westlake	Northern Motorway / Tristram Ave	27.8	25.0	75%	92%
AUC171	1720175	6049513	Tikipunga	Korau Rd	9.5	7.7	50%	83%
AUC187	1718687	6045757	Avenues	Western Hills Dr / Central Ave	27.3	27.4	50%	83%
AUC190	1759358	5906628	Mangere	George Bolt Memorial Dr / Desford Pl	18.6	19.3	75%	100%

Site ID	Coordinates (NZTM)		Area	Site name	Annual average		% valid data	
	Easting	Northing			2022	2023	2022	2023
Auckland					18.4	17.8	83%	92%

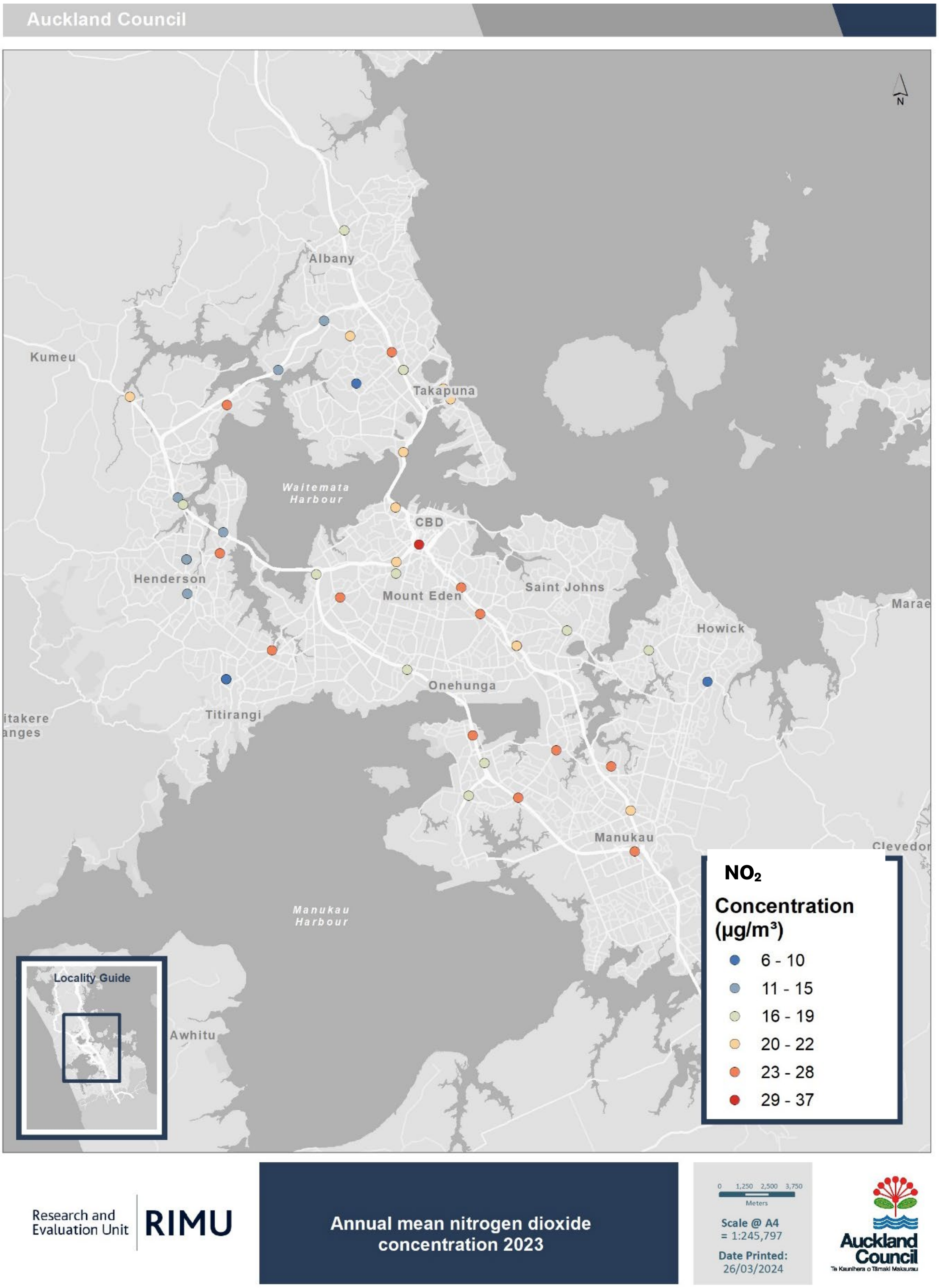

Figure G1. NZTA – Air quality monitoring network measurement of NO_2 by passive diffusion tubes: annual mean concentration across Auckland sites.

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

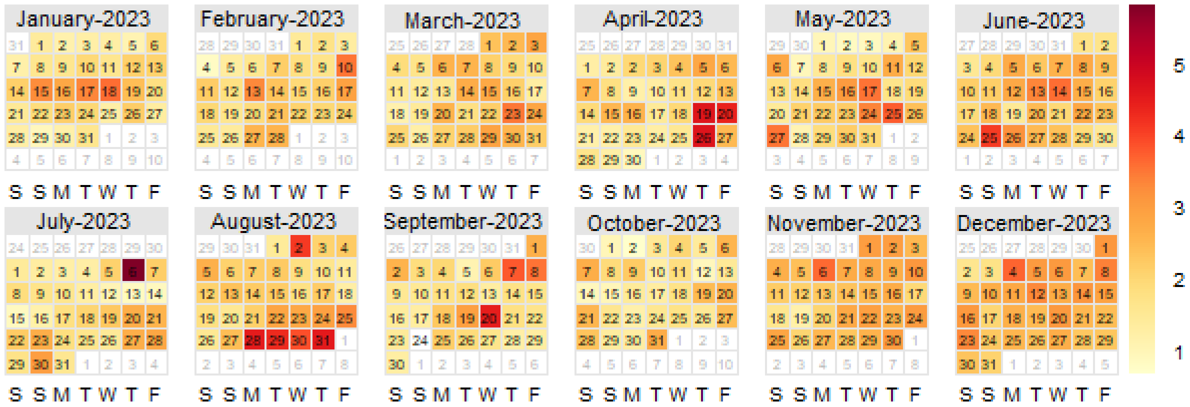

Figure H1. Calendar plot for SO_2 concentrations in 2022 – two sites combined.

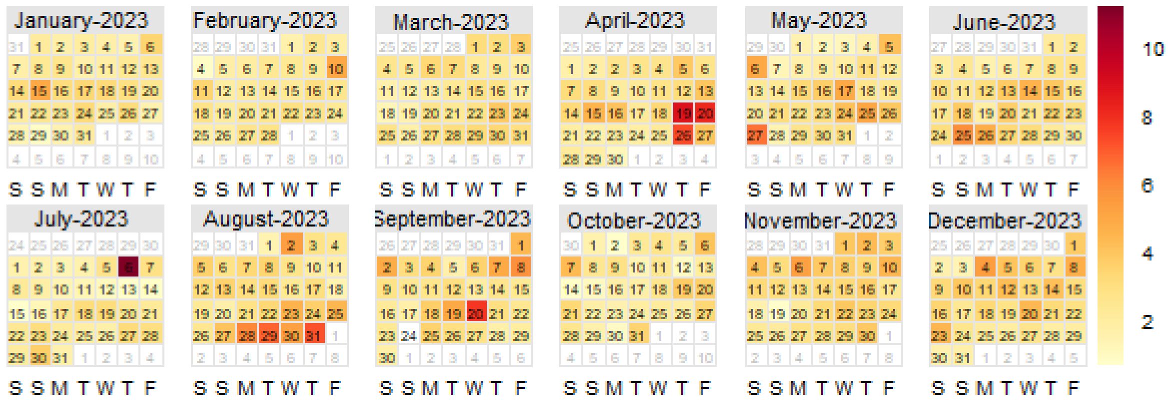

Figure H2. Calendar plot for SO_2 concentrations in Customs

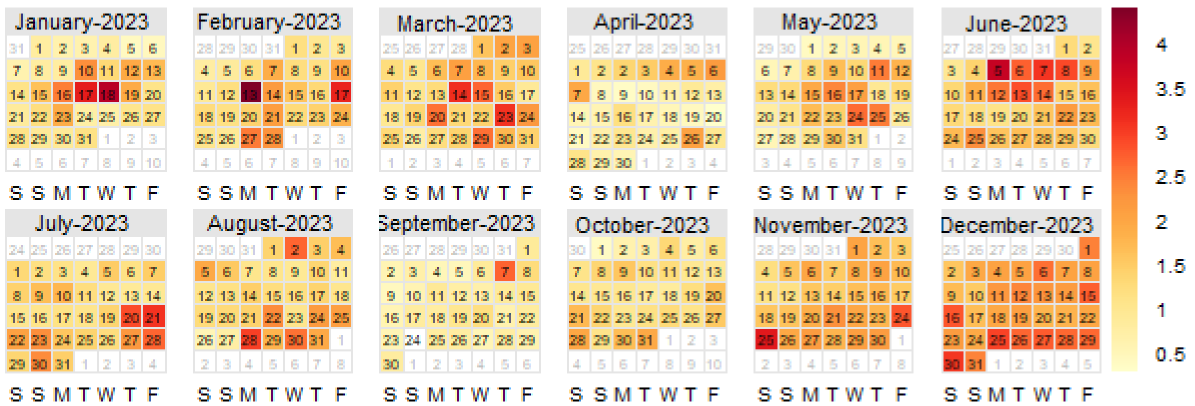

Figure H3. Calendar plot for SO_2 concentrations in Penrose.

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

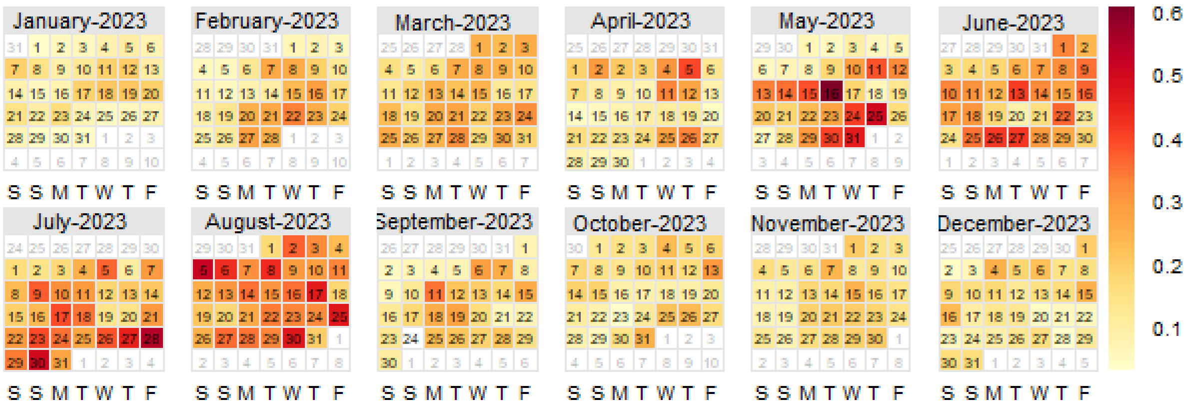

Figure I1. Calendar plot for CO concentrations in Khyber Pass Road.

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

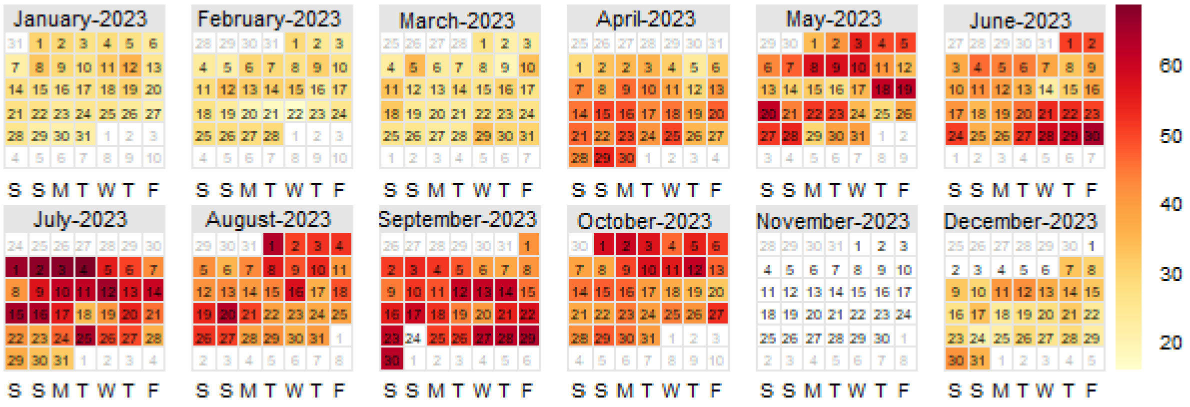

Figure J1. Calendar plot for ozone concentrations in Patumahoe.

Appendix K: Calendar plots for black carbon hourly mean concentration.

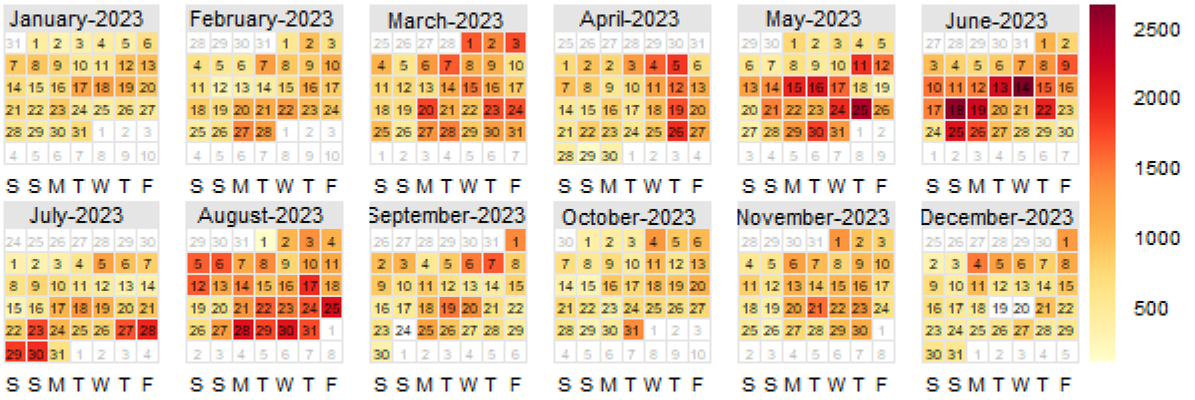

Figure K1. Calendar plot for black carbon concentrations in 2022 – two sites combined. ng/m³

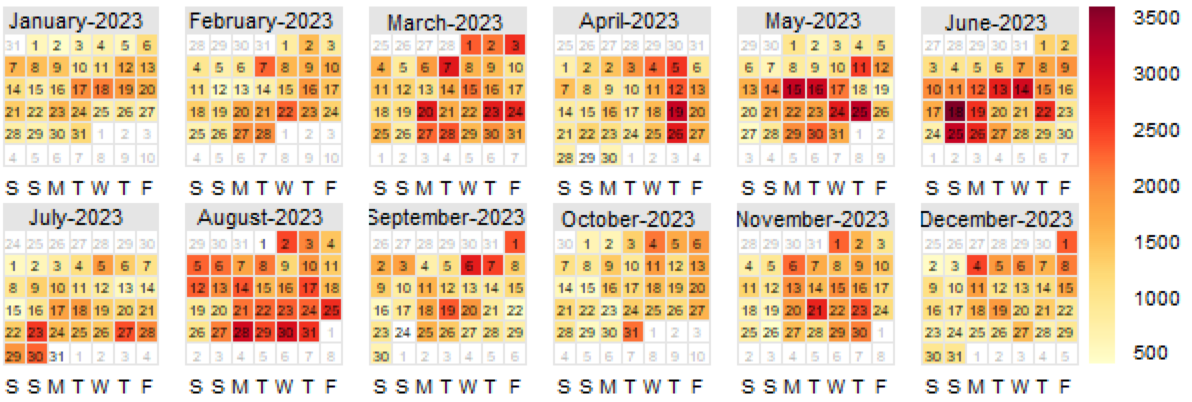

Figure K2. Calendar plot for black carbon concentrations in Customs Street. ng/m³

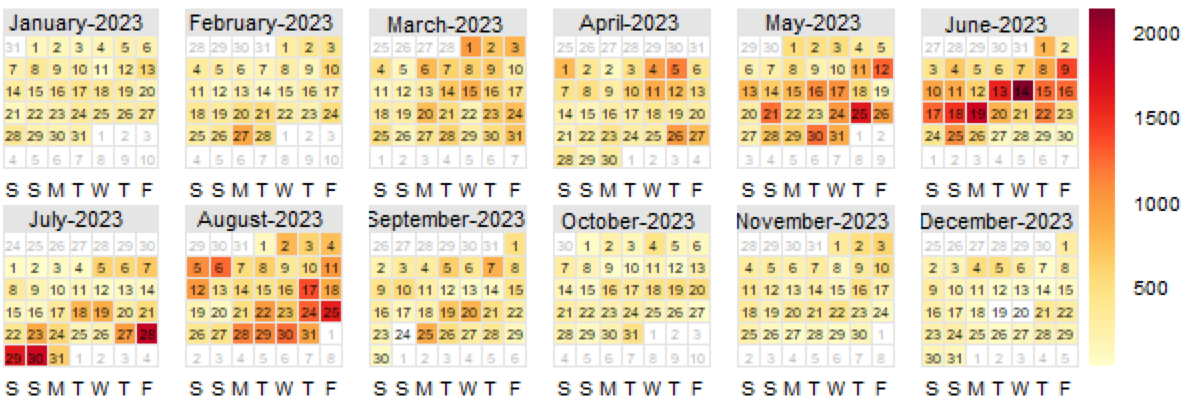

Figure K3. Calendar plot for black carbon concentrations in Henderson. ng/m³

Appendix L: Data coverage across the sites – 2022 and 2023.

Pollutant	Site	Year	Data coverage (%)
PM_{10}	Glen Eden	2022	99.4
		2023	95.8
	Henderson	2022	94.5
		2023	97.9
	Khyber Pass Road	2022	97.0
		2023	97.1
	Pakuranga	2022	82.3
		2023	98.0
	Papatoetoe	2022	98.8
		2023	98.3
	Patumahoe	2022	88.7
		2023	97.7
	Penrose	2022	98.8
		2023	98.2
	Queen Street*	2022	95.2
		2023	94.9
	Takapuna	2022	98.9
		2023	89.9
$PM_{2.5}$	Customs Street	2022	89.5
		2023	99.7
	Glen Eden	2022	82.8
		2023	98.2
	Pakuranga	2022	86.2
		2023	98.8
	Patumahoe	2022	84.7
		2023	89.8
	Penrose	2022	94.8
		2023	84.6
	Queen Street	2022	95.2
		2023	94.9
	Takapuna	2022	90.7
		2023	90.9
NO_2	Customs Street	2022	95.5
		2023	95.2
	Glen Eden	2022	97.3
		2023	95.9
	Henderson	2022	96.1
		2023	96.8
	Khyber Pass Road	2022	97.1
		2023	96.9
	Patumahoe	2022	78.9
		2023	96.7
	Penrose	2022	91.6
		2023	97.0

Pollutant	Site	Year	Data coverage (%)
	Queen Street	**2022**	94.3
		2023	93.8
	Takapuna	**2022**	89.4
		2023	86.6
SO_2	**Customs Street**	**2022**	93.8
		2023	96.8
	Penrose	**2022**	95.0
		2023	95.7
O_3	**Patumahoe**	**2022**	89.0
		2023	89.0
CO	**Khyber Pass Road**	**2022**	96.4
		2023	97.1
Black carbon	**Customs Street**	**2022**	95.0
		2023	97.7
	Henderson	**2022**	97.4
		2023	95.7

* Data up to 22 August 2023

Appendix M: Monthly averages: 2023 and past 3-5 years.

Pollutant	Site	Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PM_{10} ($\mu g/m^3$)	Glen Eden	2023	8.9	10.9	10.0	13.0	14.5	11.1	14.9	13.9	12.7	13.4	9.6	10.5
		Past 5 years	11.6	11.1	9.6	11.1	12.9	15.4	15.6	13.8	11.5	10.2	11.9	12.9
	Henderson	2023	10.1	12.2	10.6	12.5	13.8	10.4	13.5	11.4	13.1	13.2	10.0	10.6
		Past 5 years	12.0	11.5	11.0	11.7	12.5	12.9	13.1	12.1	11.1	10.5	12.5	12.8
	Khyber Pass Road	2023	12.2	14.6	14.0	16.0	16.6	11.8	16.0	14.3	16.2	15.5	12.2	13.0
		Past 4 years	11.8	11.4	10.8	11.4	10.9	11.1	11.9	11.3	11.2	11.0	12.9	13.8
	Pakuranga	2023	9.6	11.1	11.4	13.0	14.9	12.1	15.7	13.7	13.6	12.8	10.0	11.0
		Past 5 years	12.1	11.5	10.0	10.7	12.4	13.3	14.2	13.0	11.4	10.9	12.6	12.7
	Papatoetoe	2023	9.8	12.0	12.8	12.6	14.1	10.9	16.4	14.5	15.6	15.3	12.4	12.7
		Past 5 years	14.2	13.6	12.4	13.1	14.0	14.0	15.6	14.3	13.5	13.0	14.5	14.7
	Patumahoe	2023	8.9	10.7	12.0	11.0	9.7	7.1	12.3	9.8	11.8	11.5	9.9	10.4
		Past 5 years	14.9	14.3	12.5	12.2	11.8	9.9	10.5	10.8	11.4	11.1	13.3	14.9
	Penrose	2023	12.4	14.2	14.6	16.5	16.0	12.2	16.0	14.2	15.8	14.9	11.7	13.4
		Past 5 years	15.6	14.9	14.1	14.3	15.5	14.2	14.9	13.9	13.5	12.9	15.0	15.9
	Queen Street	2023	16.8	19.5	19.2	21.7	22.7	16.8	26.3	21.6	ND	ND	ND	ND
		Past 5 years	17.5	16.7	16.0	16.5	16.9	16.7	18.4	18.2	17.8	17.9	19.1	19.4
	Takapuna	2023	11.5	ND	12.6	15.0	15.9	10.9	14.0	12.4	16.1	13.0	10.4	10.8
		Past 5 years	13.1	12.3	11.0	12.4	12.8	13.3	14.1	12.9	11.7	11.3	13.0	13.4
$PM_{2.5}$ ($\mu g/m^3$)	Customs Street	2023	3.7	3.8	3.1	4.5	5.2	3.7	4.6	4.4	5.1	4.3	3.0	3.4
		Past 3 years	4.4	3.7	3.3	3.9	4.0	4.7	4.8	5.6	5.5	3.8	3.8	3.7
	Glen Eden	2023	2.1	2.7	2.2	3.3	6.2	5.6	6.8	7.8	4.4	3.6	2.4	2.8
		Past 4 years	2.7	2.5	2.0	3.1	5.7	9.8	9.7	7.7	5.0	3.2	3.5	3.2
	Pakuranga	2023	2.9	3.2	3.1	4.0	6.0	5.8	6.4	6.3	4.1	3.5	2.5	3.1
		Past 4 years	3.0	2.9	2.5	3.5	5.3	6.3	9.3	5.7	4.4	3.2	3.9	3.5
	Patumahoe	2023	4.9	6.4	4.8	5.2	4.8	4.0	6.0	5.5	5.5	5.8	4.5	5.2
		Past 5 years	5.4	4.5	4.3	5.0	5.4	5.1	4.7	4.8	4.7	4.4	5.2	5.3
	Penrose	2023	4.2	4.7	4.6	5.1	5.1	5.2	6.7	5.7	4.1	4.9	4.3	5.1
		Past 5 years	6.8	5.3	5.0	5.6	6.5	7.3	7.3	6.3	5.8	5.8	6.5	5.9
	Queen Street	2023	7.2	8.0	7.5	9.0	9.8	7.4	10.6	9.1	ND	ND	ND	ND
		Past 5 years	7.1	6.5	6.0	6.7	7.2	7.4	8.0	7.7	7.3	7.3	7.7	7.9
	Takapuna	2023	ND	ND	5.3	7.1	8.3	6.7	8.1	8.3	7.7	7.0	5.5	6.0
		Past 5 years	5.9	5.4	4.9	5.7	6.8	8.2	8.8	7.7	6.6	6.1	6.7	6.3
NO_2 ($\mu g/m^3$)	Customs Street	2023	18.7	17.8	20.1	21.3	23.8	28.5	21.8	30.6	22.2	19.8	19.9	16.1
		Past 3 years	34.8	36.9	39.1	30.8	37.1	52.4	37.4	35.6	30.8	29.1	24.1	23.9
	Glen Eden	2023	6.0	5.0	4.0	4.1	5.8	6.6	4.6	6.8	4.0	3.4	3.1	2.8
		Past 5 years	2.0	3.0	4.0	4.6	7.4	8.2	7.9	6.1	4.7	4.6	3.8	2.9
	Henderson	2023	4.5	5.1	7.0	7.6	9.8	13.2	6.6	10.3	8.1	5.7	7.2	4.4
		Past 5 years	3.9	7.3	8.4	8.7	12.0	12.8	11.7	9.2	7.5	6.5	6.1	4.7
	Khyber Pass Road	2023	11.4	18.7	26.0	11.2	23.5	31.1	27.7	37.4	22.5	19.6	21.3	15.1
		Past 4 years	21.5	19.5	22.4	23.8	32.8	33.8	35.1	30.8	30.2	24.9	30.0	20.1
	Patumahoe	2023	2.1	2.5	3.2	4.6	4.8	4.6	3.0	4.3	2.1	1.8	2.4	1.7
		Past 5 years	1.4	2.0	2.9	2.8	3.8	4.2	4.3	3.4	2.5	2.4	2.4	2.1
	Penrose	2023	6.3	9.2	15.4	11.7	14.1	23.5	17.9	23.3	12.5	9.7	11.2	6.6
		Past 5 years	9.0	10.8	13.4	16.9	22.3	22.8	22.8	18.7	16.6	12.6	12.9	8.5
	Queen Street	2023	10.8	10.0	30.1	29.7	34.3	35.6	43.7	49.8	ND	ND	ND	ND
		Past 5 years	28.2	28.8	30.8	31.0	37.4	39.5	43.2	42.1	37.7	36.4	32.2	28.0
	Takapuna	2023	5.3	ND	19.0	12.6		22.3	19.0	25.0	13.4	11.7	15.1	8.7
		Past 5 years	6.5	8.4	10.7	14.6	20.2	21.1	22.1	18.5	15.2	12.7	11.8	7.9
SO_2 ($\mu g/m^3$)	Customs Street	2023	2.3	2.4	2.5	3.2	2.5	2.9	2.3	3.2	3.3	2.2	3.2	3.1
		Past 3 years	1.6	1.6	2.3	1.5	1.7	4.4	2.6	2.8	2.2	2.2	1.6	1.5
	Penrose	2023	1.2	1.6	1.7	0.9	1.7	1.8	1.5	1.5	0.9	1.2	1.8	2.2
		Past 5 years	0.5	0.8	1.1	0.8	1.2	1.2	1.0	0.8	1.0	0.8	1.0	0.5
O_3 ($\mu g/m^3$)	Patumahoe	2023	26.1	25.8	26.3	40.1	26.3	42.3	52.6	45.6	51.7	45.9	ND	30.0
		Past 5 years	26.6	29.3	33.4	38.9	41.2	43.1	46.8	52.6	51.4	46.9	41.0	31.4
CO (mg/m^3)	Khyber Pass Road	2023	0.105	0.159	0.220	0.160	0.053	0.143	0.162	0.209	0.037	0.010	0.007	0.004
		Past 4 years	0.206	0.180	0.192	0.216	0.268	0.258	0.297	0.220	0.204	0.178	0.183	0.164
Black carbon (ng/m^3)	Customs Street	2023	1095	1286	1735	1429	1735	1767	1245	1953	1309	1180	1435	1211
		Past 3 years	1447	1535	1316	1094	1356	3363	1350	1326	1034	1016	1127	1047
	Henderson	2023	247	316	510	455	510	824	473	725	382	221	257	190
		Past 5 years	265	458	566	540	995	1204	1113	879	542	412	381	301
ND = No data measured due to Auckland flood, Queen St August data is up to 22 August (due to power outage at the site)														

Appendix N: Traffic volume – Khyber Pass Road (2022 and 2023).

According to Auckland Transport's 7-day traffic count data, the traffic volume in 2023 increased compared to 2022, from 125,249 to 127,710 vehicles. The count was conducted at Khyber Pass Road, between Mountain Rd and Maungawhau Rd (both directions). The 2022 count took place between June 13th and 19th, while the 2023 count occurred between March 14th and 20th.

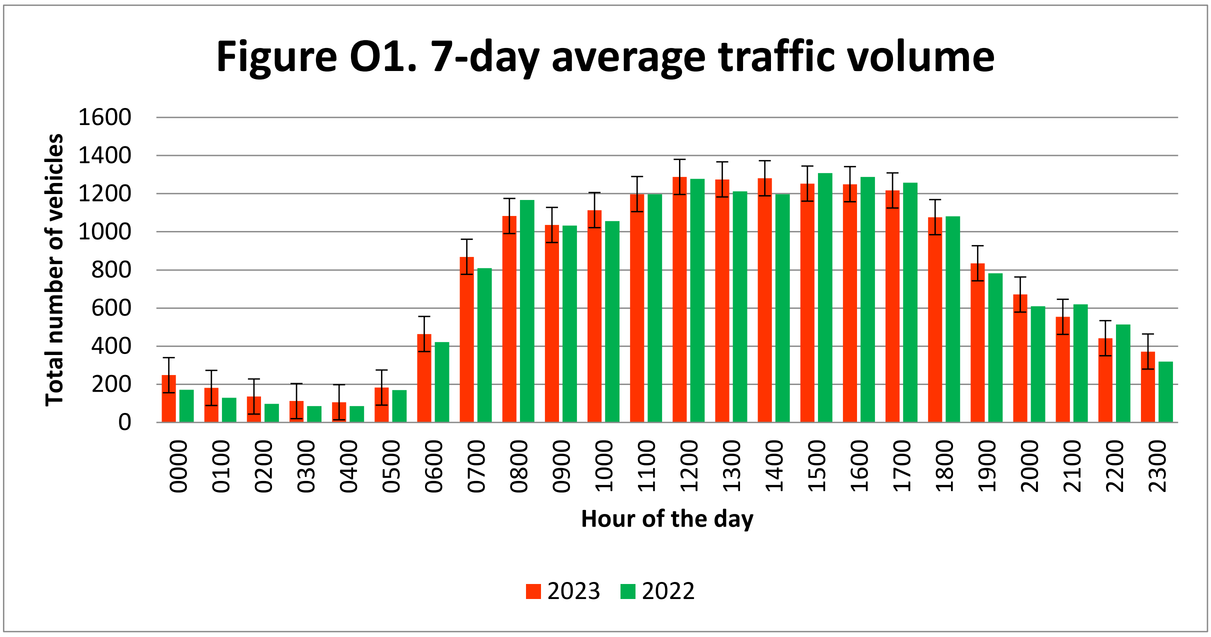

Table N1. 7-day peak traffic volume: Direction 1: towards Maungawhau Rd and Direction 2: towards Mountain Rd

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

2023

Peaks Summary	Direction 1							Direction 2						
	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon
AM PEAK														
60 Minutes beginning	0745	0830	0745	**0800**	0900	0900	0745	0815	0815	**0800**	0745	0900	0900	0745
Volume	612	651	583	**658**	424	305	612	752	715	**759**	708	477	337	694
MID PEAK														
60 Minutes beginning	1400	1215	1300	1230	**1230**	1330	1400	0915	0915	1130	1200	**1130**	1115	1145
Volume	692	742	758	752	**803**	698	612	609	631	653	662	**750**	640	540
PM PEAK														
60 Minutes beginning	1515	1415	1530	1415	**1415**	1415	1745	1615	1600	1600	1630	**1415**	1430	1700
Volume	670	729	705	694	**794**	687	714	639	683	663	723	**732**	593	611

Appendix O: Volatile organic compounds levels (2023)

Monthly sampling at Newmarket – Results							
		Concentration (µg/m³)				Average (µg/m³)	
Sampling date	Analyte	Crowhurst Street A	Crowhurst Street B	Khyber Pass Road A	Khyber Pass Road B	Crowhurst Street	Khyber Pass Road
Mar-23	Toluene	8.8	8.5	2.0	2.2	8.6	2.1
Apr-23	Ethylbenzene	7.3	7.0	2.1	2.0	7.2	2.1
May-23	Benzene	1.8	2.1	<1.1	<1.1	2.0	<1.1
May-23	Toluene	8.2	2.2	1.9	2.0	5.2	2.0
Jun-23	Benzene	1.6	1.8	<1.1	<1.1	1.7	<1.1
Jun-23	toluene	6.9	7.1	2.2	2.1	7.0	2.2
Jul-23	Toluene	1.5	1.3	<1.1	<1.1	1.4	<1.1
Jul-23	Toluene	5.7	4.9	1.5	1.6	5.3	1.6
Aug-23	Benzene	1.7	1.8	<1.1	<1.1	1.7	<1.1
Aug-23	Toluene	4.9	5.2	2.3	2.3	5.1	2.3
Sep-23	Toluene	3.6	3.3	1.3	<1.2	3.4	<1.2
Oct-23	Toluene	6.3	6.8	1.4	1.8	6.6	1.6
Nov-23	Toluene	<2.2	<2.2	5.0	4.7	<2.2	4.9
Dec-23	Benzene	1.3	1.3	<1.2	<1.2	1.3	<1.2
Dec-23	Toluene	5.7	6.0	2.3	<1.2	5.9	<1.2

3 – monthly sampling at Penrose (Results) – Concentration (µg/m³)				
Sampling date	Analyte	Penrose A	Penrose B	Average
Jan - Mar 2023	Toluene	2.7	2.6	2.7
April - June 2023	Hexane	0.1	0.2	0.1
April - June 2023	Toluene	3.0	2.8	2.9
April - June 2023	Trichloromethane	0.1	<0.1	0.1
April - June 2023	1,1,1-trichloroethane	0.3	<0.3	0.3
Jul - Sep 2023	Hexane	0.1	0.1	0.1
Jul - Sep 2023	Toluene	2.5	2.6	2.5
Oct - Dec 2023	Toluene	1.7	1.5	1.6
Oct - Dec 2023	Butyl acetate	0.1	0.1	0.1

*Benzene annual average Ambient Air Quality Guideline (AAQG) and Auckland Unitary Plan target is 3.6µg/m³

*For other target VOCs measured concentrations were all below detection limits

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