Auckland Air Quality – 2021 Annual Data Report

Louis Boamponsem

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Research and Evaluation Unit RIMU

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Executive summary

Air pollution is the leading environmental risk factor worldwide. World Health Organization (WHO) estimates show that around seven million deaths are attributable to air pollution. People with pre-existing respiratory and heart conditions, diabetes, the young, and elderly people are particularly vulnerable to air pollution effects. Each year, air pollution causes more than 300 premature deaths in Auckland and results in increased numbers of reduced activity days and hospital visits, and higher usage of medications. It is estimated that the social cost of air pollution in Auckland is $1.07 billion per year. Air pollution can affect the atmosphere and climate directly through the warming and cooling properties of some pollutants.

Auckland sits on an isthmus between the Tasman Sea and the South Pacific Ocean. With no landmass close to the east or west of the city, there is a relatively clean and reliable airflow in Auckland, helping remove air pollutants emitted across the region. Despite this, some anthropogenic activities in Auckland create pollution levels that can exceed national and international standards and impact people's health.

Transport, home heating, and industrial emissions are the main anthropogenic sources of air contaminants in Auckland. Auckland Council is responsible for the management of air quality in the region. The council is required to monitor air quality under the Resource Management Act 1991 and the National Environmental Standards for Air Quality (NESAQ). To achieve this, the council continuously collects air quality data to assess compliance and provide information to aid policy development and evaluation. The data the council collects enables us to quantify ambient air quality in the region and note spatial and temporal variations. 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.

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

Key findings:

- No breach of national air quality standards occurred in 2021.
- Auckland's air quality in 2021 slightly improved by 0.34% compared to the previous year. This improvement could be due to the COVID-19 restrictions.
- The average PM_{10} concentration of Auckland in 2021 increased by 1.3% compared to 2020 but did not exceed the new 2021 WHO air quality guideline of 15 $\mu g/m^3$. Queen Street monitoring site exceeded the WHO annual guideline by 24%.
- The average $PM_{2.5}$ concentration of Auckland in 2021 increased by 6.7% compared to 2020. This increase was over the 2021 WHO air quality guideline of 5 $\mu g/m^3$. Auckland's target for 24-hour average $PM_{2.5}$ concentration was exceeded on one occasion during winter at Pakuranga
- Overall, concentrations of particulate matter peak in the afternoon and night hours and mostly increase later in the week with the highest concentrations typically occurring on Wednesday to Friday.
- The annual mean NO_2 concentration for Auckland in 2021 is the lowest recorded since 2006. The annual mean concentration significantly decreased by 16.7% compared to 2020. However, Auckland's overall annual average NO_2 concentration exceeded the 2021 WHO air quality guideline of 10 $\mu g/m^3$. The WHO 24-hour guideline for NO_2 was exceeded on many occasions at Queen Street, Customs Street, Khyber Pass Road, Takapuna and Penrose.

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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
Air quality index (AQI)	Score out of 100, based on dividing a pollutant concentration by a relevant standard. It can be used to approximate relative impact of different pollutants
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.
MfE	Ministry for the Environment
MoH	Ministry of Health
Monitoring site	A facility for measuring the concentration of one or more pollutants in the ambient air; also referred to as 'monitoring station'.
NESAQ	National Environmental Standard for Air Quality
NO_2	Nitrogen dioxide, a type of air pollutant.

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

$\mu g/m^3$	Microgram of pollutant (1 millionth of a gram) per cubic metre of air, referenced to temperature of 0°C (273.15 K) and absolute pressure of 101.325 kilopascals (kPa).

1 Introduction

Air pollution is the leading environmental risk factor worldwide. World Health Organization (WHO) estimates show that around seven million deaths are attributable to the joint effects of ambient and household air pollution (WHO, 2018, 2021). On average, a person inhales about 14,000 litres of air every day, and the presence of contaminants in this air can adversely affect people's health. People with pre-existing respiratory and heart conditions, diabetes, the young, and elderly people are particularly vulnerable to these effects (MfE and Stats NZ, 2014). Each year, air pollution causes more than 300 premature deaths in Auckland and results in increased numbers of reduced activity days and hospital visits, and higher usage of medications. It is estimated that the social cost from air pollution in Auckland is $1.07 billion per year (Kuschel et al., 2012). Air pollution can affect the atmosphere and climate directly through the warming and cooling properties of some pollutants. Indirectly, air pollution can change rainfall and the reflectivity and distribution of clouds. Particulate matter and ground-level ozone are two examples of air pollutants that affect our atmosphere and climate (MfE and Stats NZ, 2014).

Auckland sits on an isthmus between the Tasman Sea and the South Pacific Ocean. With no landmass close to the east or west of the city, there is a relatively clean and reliable airflow in Auckland, helping remove air pollutants emitted across the region. Despite this, some anthropogenic activities in Auckland create pollution levels that can exceed national and international standards and impacts people's health (Kuschel et al., 2012; Sridhar, 2013; Dirks et al., 2017; Talbot and Crimmins, 2020).

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

Auckland Council is responsible for the management of air quality in the region. The council is required to monitor air quality under the Resource Management Act 1991 and the National Environmental Standards for Air Quality (NESAQ). To achieve this, the council continuously collects air quality data to assess compliance and provide information to aid policy development and evaluation. Auckland Council is required to publicly report any breach of

NESAQ. The data the council collects enables us to quantify ambient air quality in the region and note spatial and temporal variations.

Data and information from the Auckland air quality monitoring network are reported in multiple ways. Monthly reports are regularly published on the Knowledge Auckland Website, data is available on the RIMU Environmental Data Portal, Land, Air, and Water Aotearoa (LAWA) website, and technical reports are produced in specific reporting years. This is the annual data report for 2021 data and its assessment against the NESAQ, Auckland Unitary Plan air quality target, National Ambient Air Quality Guidelines, and the revised 2021 WHO air quality guidelines.

This report provides a summary of the 2021 data and assesses it against the NESAQ standard, Auckland Unitary Plan air quality target, and the revised 2021 WHO air quality guidelines. A separate technical report on air quality trend analysis (2006 to 2021) is in preparation. Assessment of the impact of COVID-19 restrictions on Auckland's air quality was conducted by Xie (2021a, 2021b) and Boamponsem (2021).

1.1 Why do we monitor air pollutants?

Auckland Council continuously collects air quality data to assess compliance with national standards and provide information to aid policy development and evaluation. The data the council collects enables us to quantify ambient air quality in the region and note spatial and temporal variations. This supports the understanding of whether national or regional air quality standards, targets, objectives, and environmental outcomes are being met.

The national environmental standards for air quality (NESAQ) sets 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). Further ambient air quality targets are scheduled by the Auckland Unitary Plan (Table 1). Objectives and policies of the Auckland Unitary Plan require Auckland Council to have regard to these targets to minimise potential health risks (Talbot and Crimmins, 2020).

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

The specific objectives of the air monitoring programme are to:

- determine the level of contaminants in designated airsheds to compare with NESAQ and Auckland Unitary Plan – Air quality targets
- provide air quality information for policy and strategy development
- assess and evaluate the effectiveness of policies and plans based on air quality trends
- support state of the environment reporting

- generate data for air quality research and modelling
- infer typical air pollution exposure levels experienced by Auckland's population and assess potential health risks
- ensure that there is a good scientific understanding of pollutant levels, trends and sources
- better understand ambient meteorological conditions and provide input into air emissions modelling
- aid the application and processing of resource consents.
- provide information for local and national organisations such as Auckland Transport, and New Zealand Transport Agency (NZTA).

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

Pollutant	Time period	NESAQ	Auckland target[a]	2021 WHO AQ guideline[c]	NESAQ number of exceedances allowed per year	Units
$PM_{2.5}$	Annual	NA	10	5	-	µg/m^3
	24 - hour	NA	25	15	-	µg/m^3
PM_{10}	Annual	NA	20	15	-	µg/m^3
	24 - hour	50	NA	45	1	µg/m^3
O_3	8 - hour[b]	NA	100	100	-	µg/m^3
	1 - hour	150	NA	NA	0	µg/m^3
NO_2	Annual	NA	40	10	-	µg/m^3
	24 - hour	NA	100	25	-	µg/m^3
	1 - hour	200	NA	200	9	µg/m^3
SO_2	24 - hour	350	120	40	9	µg/m^3
CO	1 - hour	NA	30	35	-	mg/m^3
	8 - hour	10	NA	10	1	mg/m^3
	24 - hour	NA	NA	4	-	mg/m^3

[a] Auckland ambient air quality target

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

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

µg/m^3 : micrograms per cubic metre

mg/m^3 : milligrams per cubic metre

NA : Not available

1.2 Monitored air contaminants

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

Particulate matter is a term used for a mixture of solid particles and liquid droplets found in the air (US EPA, 2021; MfE & Stats NZ, 2021). We monitor two types of particulate matter – PM_{10}: larger particles (but still small enough that they can be inhaled), 10 micrometres (μm), or less in aerodynamic diameter. $PM_{2.5}$: finer particles, 2.5 micrometres or less in aerodynamic diameter.

The burning of wood for home heating is a major contributor to particulate matter concentrations in Auckland. These are identified in winter peaks in PM_{10} and $PM_{2.5}$ concentrations and bottom-up emission inventories (Metcalfe et al., 2018; Xie et al., 2019). Secondary sulphates are also a significant particulate source. For Auckland, these will generally originate from oceanic biogenic gas emissions such as dimethyl sulphate, which are then stabilise as fine particulates within the atmosphere (Davy et al., 2017; Talbot and Crimmins, 2020).

In Auckland, combustion-derived particulates make up 44% of total particulate concentrations ($PM_{2.5}$ and PM_{10}, combined) (Davy et al., 2017; Talbot and Crimmins, 2020). Transport emissions are the major source of $PM_{2.5}$ across the Auckland region, most notably within urban centres and alongside major arterial routes (Talbot & Lehn 2018). Non-exhaust transport sources of PM_{10}, brake and tyre wear, and unsealed road dust, are deposited rapidly due to gravitational force but are often resuspended into the atmosphere through vehicle induced air turbulence alongside roads (Xie et al., 2016; Talbot and Crimmins, 2020; MfE & Stats NZ, 2021).

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

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

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

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

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

b. Nitrogen oxides (NOx)

NOx is principally formed by the oxidation of nitrogen contained in the air at high combustion temperatures. Vehicle traffic is a major source of anthropogenic NOx emissions and nitrogen dioxide (NO_2) in particular has been identified as an indicator pollutant for motor vehicle pollutants. Most NOx (approximately 95%) is emitted as nitric oxide (NO) at the point of discharge. Nitric oxide (NO) is generally considered not harmful to human health. The remaining 5% of NOx is NO_2 and is known to negatively affect human respiratory function. Nitric oxide (NO) will normally convert to NO_2 depending on the presence of atmospheric oxidants, mainly ozone (O_3). Atmospheric oxidants increase the rate of conversion of NO to NO_2 (Crimmins, 2018; Moore 2019).

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

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

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

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

c. Carbon monoxide (CO)

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

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

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

d. Ground-level ozone (O_3)

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

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

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

e. Sulphur dioxide (SO_2)

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

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

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

f. Black carbon

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

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

g. Volatile organic compounds (VOCs)

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

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

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

2 Methods

2.1 Auckland air quality monitoring network

Continuous instrumental ambient air quality monitoring has been performed in the Auckland region for many decades and Auckland Council has data from 1964 to date. This dataset is the longest continuous air quality dataset in New Zealand. The current Auckland ambient air quality monitoring network comprises 10 fixed and permanent sites. Carbon monoxide (CO) is measured at one site, nitrogen dioxide (NO_2) at eight sites; particulates at nine sites; ozone (O_3) at one site; lead (in total suspended particles) at one site, sulphur dioxide (SO_2) at two sites, and black carbon at two sites. Passive monitoring of Benzene, toluene, ethylbenzene and xylene (BTEX) is also undertaken at Newmarket (Intersection of Crowhurst Street and Mountain Road West) and Penrose.

The sites range in their scope 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 appendix L. The sites are funded by the Auckland Council while data collection and equipment maintenance are performed by the Air Quality Department of Watercare Services Limited. Source apportionment modelling that quantifies the contribution of sources to particulate matter is conducted by GNS Science. Figure 1 presents a map of the current monitoring sites.

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

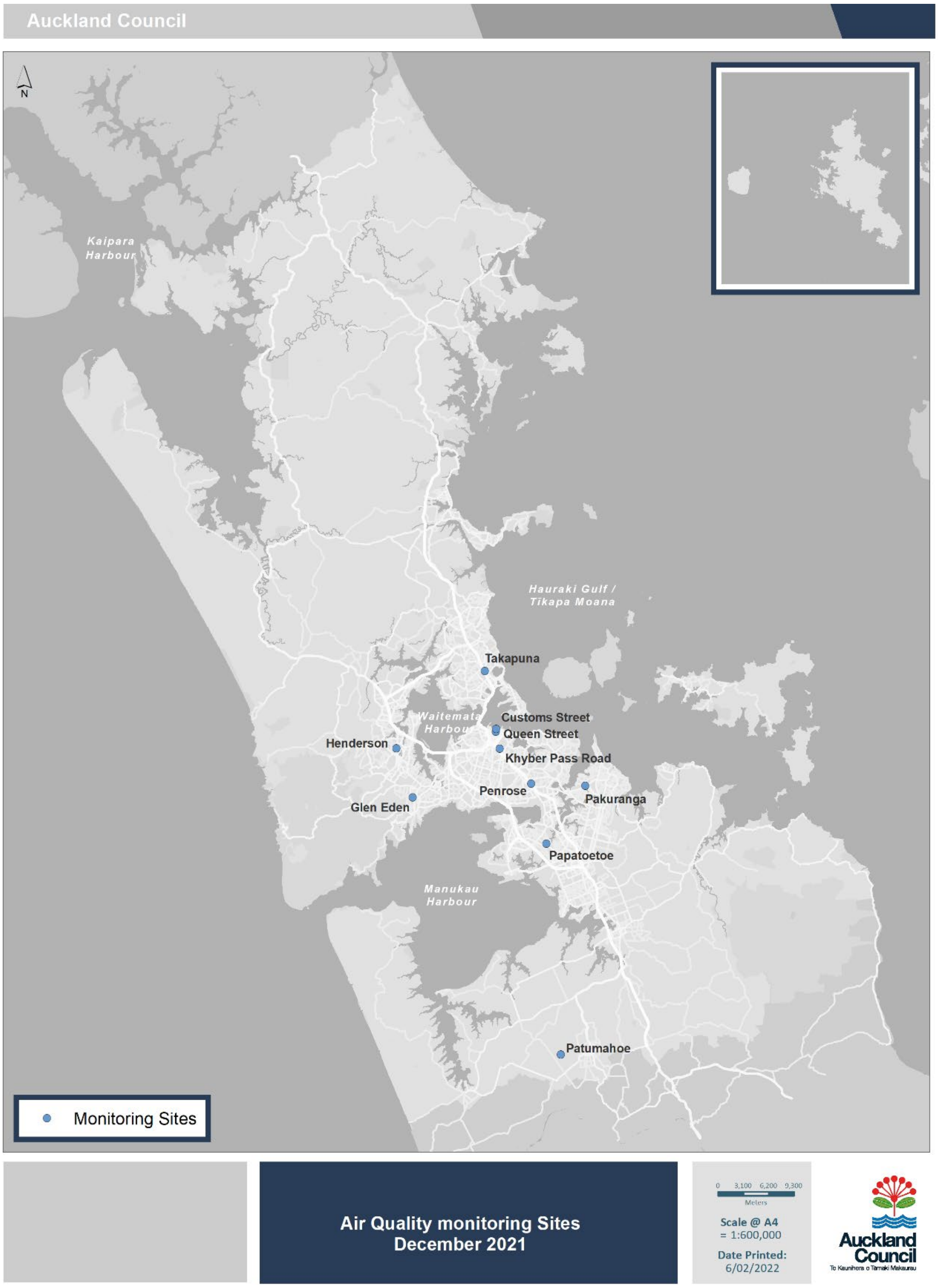

Figure 1. Auckland Council air quality monitoring sites.

Table 2. Monitoring sites pollutants, meteorological parameters measured.

Site	Established date	Pollutants monitored	Meteorological parameters measured on site[a]	Pollutant sensors used
Glen Eden[b]	2005	PM_{10}, $PM_{2.5}$ and NO_2,	WS, WD, AT, RH	NOx – API 200E Gas Analyser, PM_{10} – Thermo FH62C14 Beta Attenuation Monitor, $PM_{2.5}$ – MetOne ES642 Nephelometer (non-regulatory)
Pakuranga[b]	1998	PM_{10} and $PM_{2.5}$	WS, WD, AT, RH	PM_{10} – Thermo FH62C14 – Beta Attenuation Monitor $PM_{2.5}$ – MetOne ES642 Nephelometer (non-regulatory)
Patumahoe	1996	PM_{10}, $PM_{2.5}$, NO_2, and O_3	N/A	Ozone – Thermo 49i Gas Analyser NOx – API 200E Gas Analyser PM_{10} – Thermo FH62C14 Beta Attenuation Monitor $PM_{2.5}$ – Thermo 5014i Beta Attenuation Monitor
Khyber Pass Road	1995	PM_{10}, CO, NO_2, and VOCs	N/A	PM_{10} – Thermo FH62C14 Beta Attenuation Monitor CO - API 300E Gas Analyser NOx – API 200E Gas Analyser BTEX – Passive Samplers, Monthly sampling (Mountain Road West and Crowhurst St)
Papatoetoe[b]	2017	PM_{10}	WS, WD, AT, RH	PM_{10} – Thermo FH62C14 Beta Attenuation Monitor
Penrose[b]	2000	PM_{10}, $PM_{2.5}$, NO_2, SO_2, TSP/Lead, and VOCs	WS, WD, AT, RH	NOx – API 200E Gas Analyser, SO2 – API T100 Gas Analyser PM_{10} – Thermo FH62C14 Beta Attenuation Monitor $PM_{2.5}$ – Thermo 5014i Beta Attenuation Monitor TSP/Lead – Department of Health Medium Volume Sampler, VOC – Passive Sampler,
Takapuna[c]	1995	PM_{10}, $PM_{2.5}$, and NO_2	WS, WD, AT, RH	NOx – API T200 Gas Analyser PM_{10} – Thermo FH62C14 Beta Attenuation Monitor, $PM_{2.5}$ - Teledyne T640 PM Mass Monitor,
Queen Street[b]	1998	PM_{10}, $PM_{2.5}$, and NO_2	WS, WD, AT, RH	PM_{10} – T640 Teledyne PM Mass Monitor $PM_{2.5}$ - T640 Teledyne PM Mass Monitor NOx – API 200E Gas Analyser
Henderson[b]	1993	PM_{10}, black carbon, and NO_2	WS, WD, AT, RH	NOx - API 200E Gas Analyser, PM_{10} – Thermo FH62C14 Beta Attenuation Monitor, Black carbon – Magee AE33 Aethalometer
Customs Street	2020	$PM_{2.5}$, black carbon, NO_2, and SO_2	N/A	NOx – API T200 Gas Analyser SO_2 – API T100 Gas Analyser $PM_{2.5}$ – MetOne ES642 Nephelometer (non-regulatory) Black Carbon – MetOne 1060 Aethalometer
NB: N/A implies not applicable		WS : wind speed, WD : wind direction, AT : ambient temperature, RH : relative humidity		
[a]All meteorology parameters are measured in real time with Vaisala Weather Transmitter WXT520				
[b]Meteorological mast height = 6 m		[c]Meteorological mast height = 10 m		

2.2 Data collection and analysis

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

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

In this report, most graphs were plotted using MS Excel and the Openair R package (Carslaw & Ropkins 2012). Inferential statistical analysis was conducted using IBM SPSS version 20. Wind roses were generated using Kristers Aquisnet REP software. The parametric independent-samples t-test (or independent t-test) in SPSS was used to compare mean differences between sites and years (2020 and 2021). 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.

3 Results

3.1 Weather conditions/meteorological differences

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

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

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

a. Ambient temperature

The overall average temperature of Auckland in 2021 significantly increased by 1.3% compared to 2020 (from 16.02 ± 4.1 ^{O}C to 16.2 ± 4.1 ^{O}C) ($p<0.05$). As shown by Figure 2, the pattern of temperature variations in 2021 was similar to the previous year. All the average annual ambient temperatures across the sites significantly increased compared to 2020 ($p<0.05$). Appendix B presents the temperature descriptive statistics for each site.

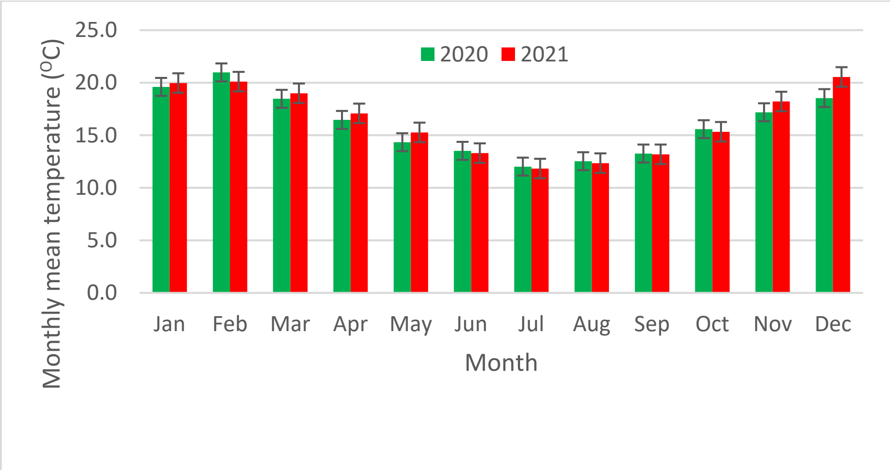

Figure 2. Monthly average ambient temperature measured at six monitoring sites – 2021 compared to 2020. Error bars represent the standard errors of the mean.

b. Relative humidity

The overall average relative humidity of Auckland in 2021 significantly increased by 2.1% compared to 2020 (from 68.0 ± 13.4% to 69.4 ± 13.0%) ($P<0.05$). The pattern of ambient relative humidity variations in 2021 was similar to the previous year (See Figure 3). Apart from Pakuranga, which significantly had an increased relative humidity, all the other sites had a marginal increase which was not statistically significant. Appendix B presents the relative humidity descriptive statistics for each site.

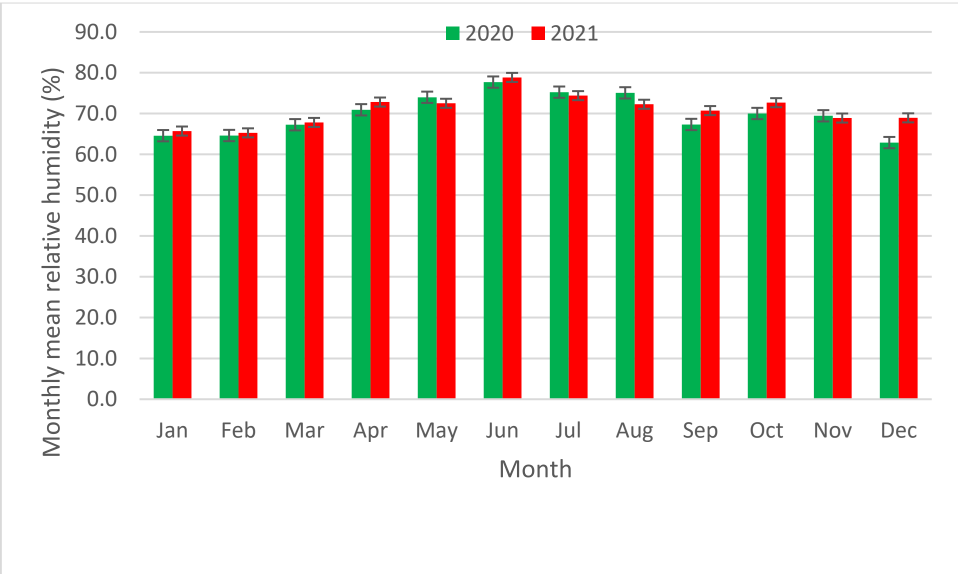

Figure 3. Monthly average relative humidity measured at six monitoring sites – 2021 compared to 2020. Error bars represent the standard errors of the mean.

3.1.1 Wind speed direction

Wind roses are graphical charts that characterise the speed and direction of winds at a monitoring site. They are presented in a circular format, where the length of each "spoke" around the circle indicates the amount of time that the wind blows from a given direction. The colours along the spokes show categories of wind speed (Figures 4 to 6). A wind rose is a very useful way of summarising meteorological data. It is particularly useful for showing how wind speed and wind direction conditions vary by year (Carslaw and Ropkins, 2012). By visually inspecting wind roses we can get an overview of the general prevailing wind direction and speed of a site in a specified duration.

The general patterns of wind speed and direction for all the monitoring sites in 2021 were quite comparable to the previous year. Wind rose diagrams showing the general frequency distribution of the wind speed and direction during 2020 and 2021 for six sites are provided in figures 4 to 6.

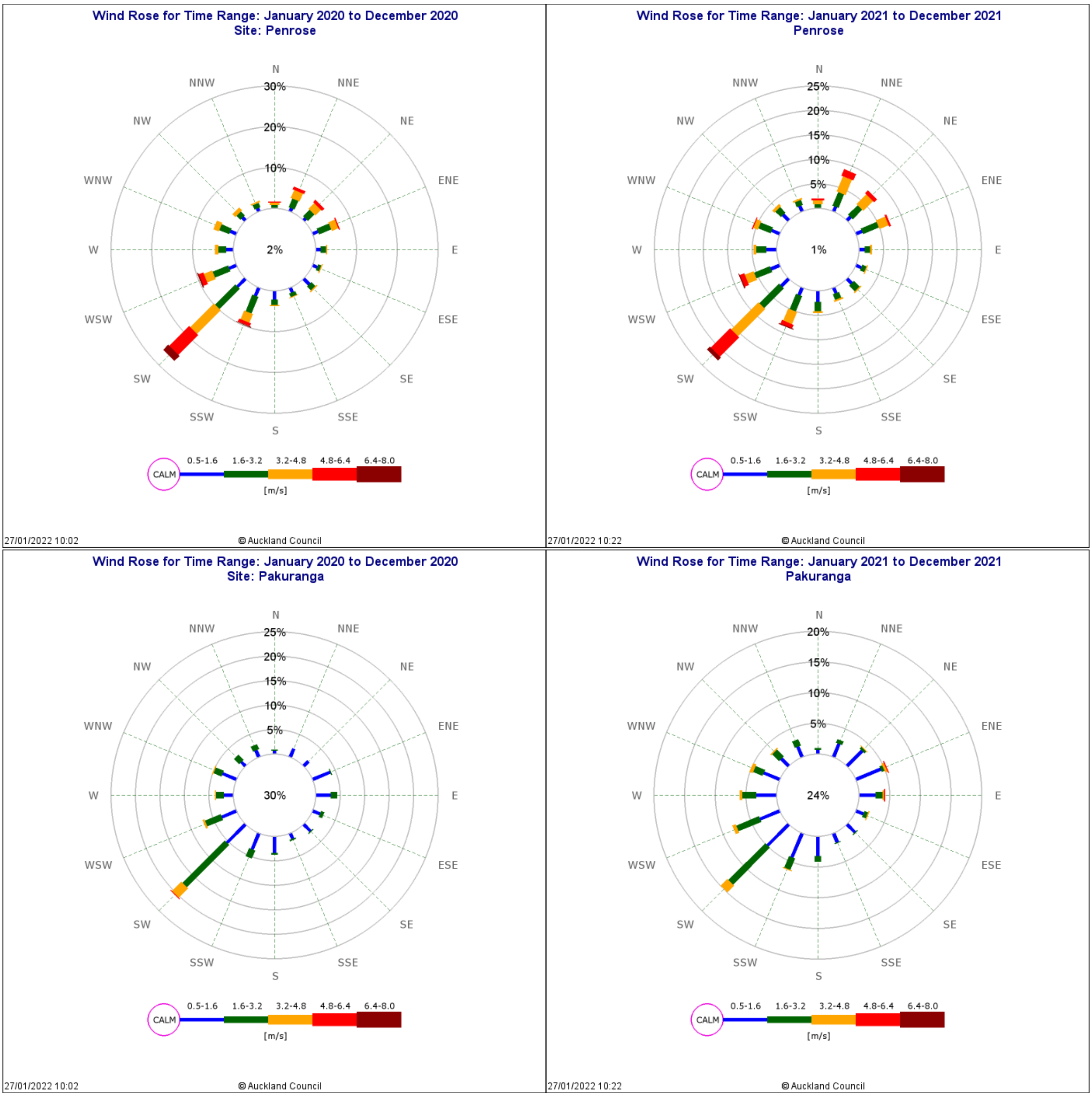

Figure 4. Wind roses for Penrose and Pakuranga.

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 2020 data while the right plots

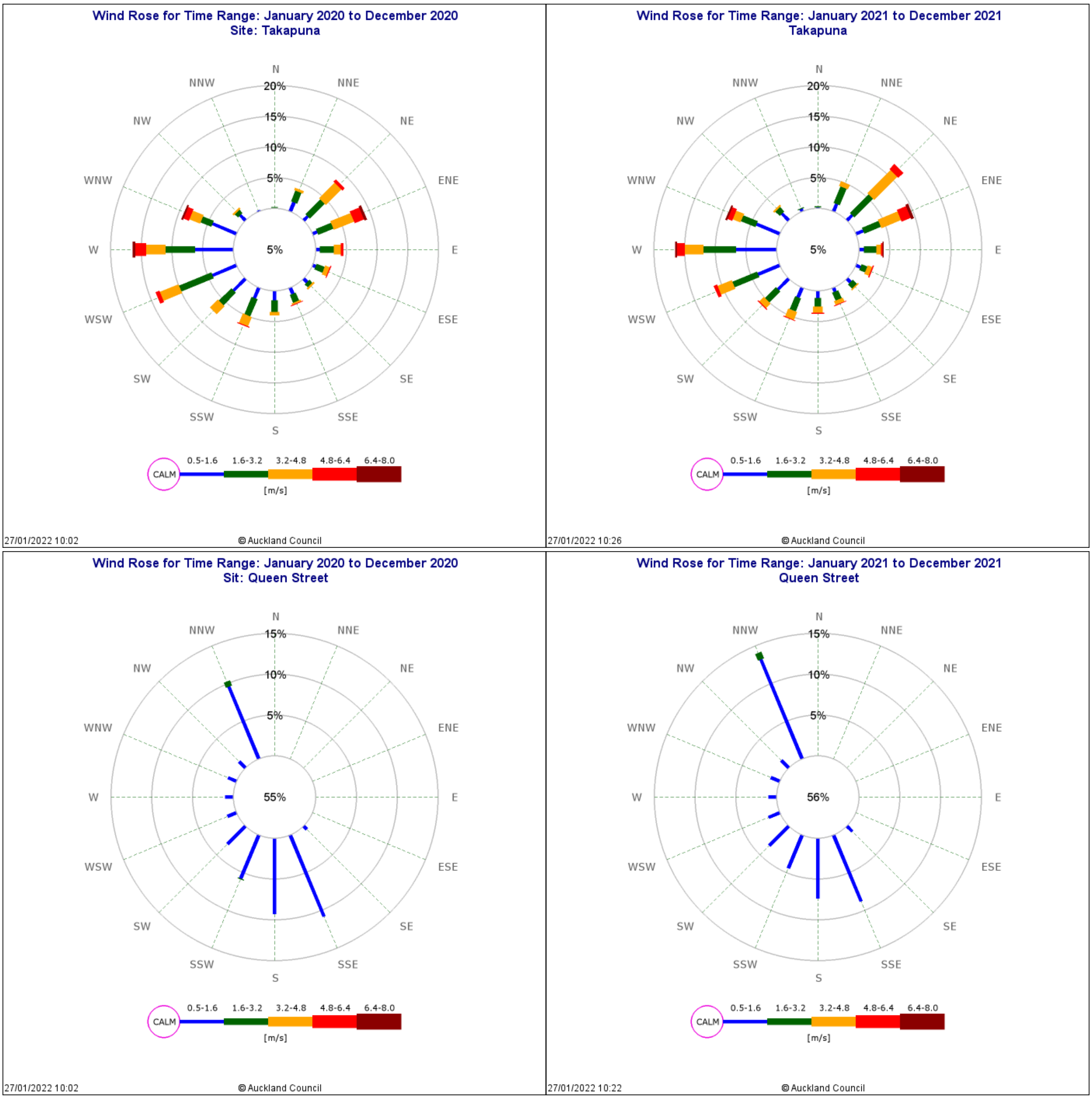

Figure 5. Wind roses for Takapuna and Queen Street.

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 2020 data while the right plots are for the 2021 data.

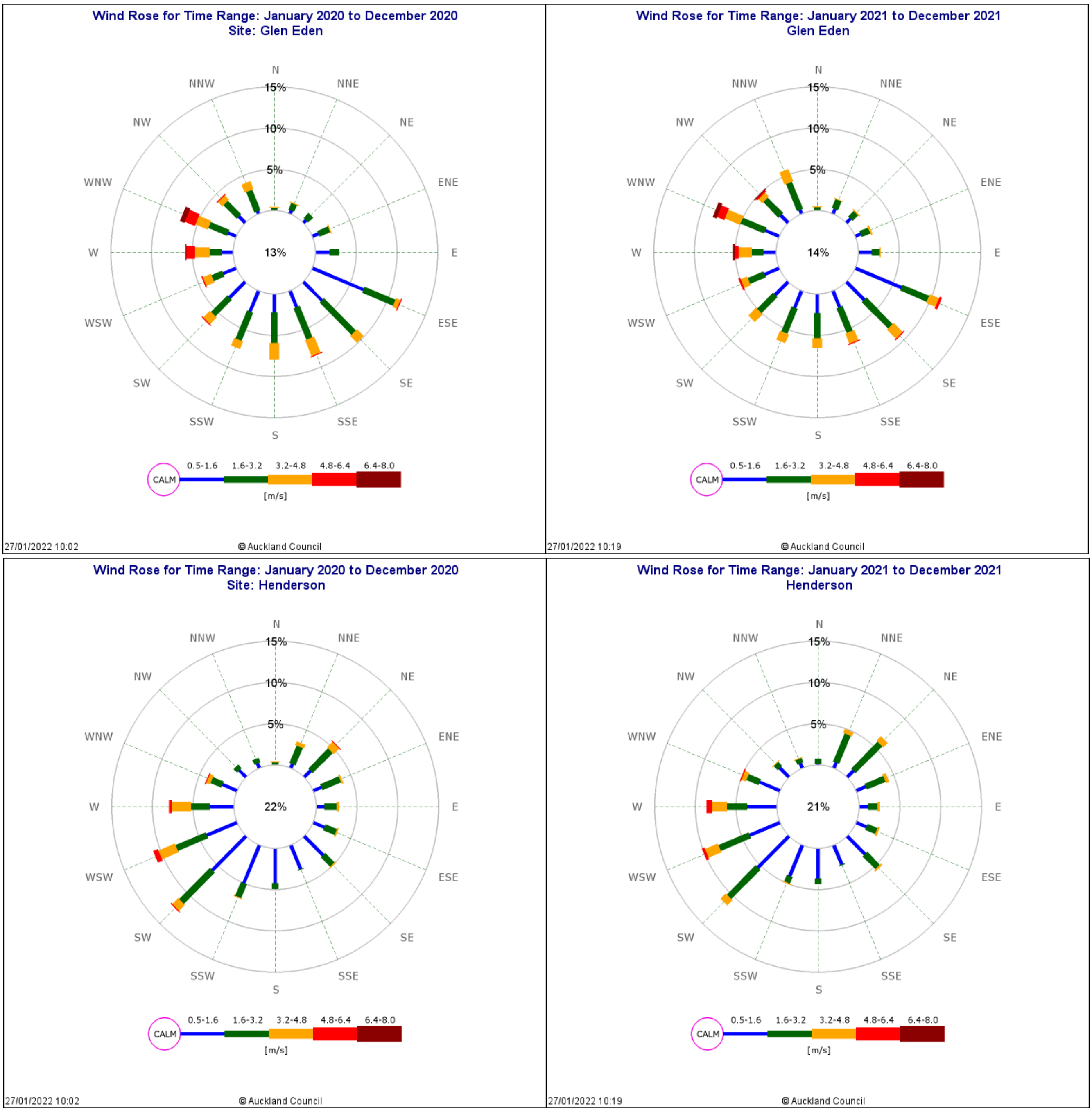

Figure 6. Wind roses for Glen Eden and Henderson.

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 2020 data while the right plots are for the 2021 data.

3.2 Auckland's air quality data – 2021

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

Occasionally, exceptional events result in air pollutant concentrations to exceed the national standard or target limits. For instance, in October 2019, the smoke from the New Zealand International Convention Centre building site fire led to the PM_{10} and $PM_{2.5}$ concentrations at the Queen Street monitoring site exceeding the NESAQ and the Auckland targets. In December 2019, the Australian dust storms and bushfires led to a PM_{10} exceedance detected at three sites (Papatoetoe, Penrose and Patumahoe). See Appendix A for a full list of Auckland specific air pollution sources.

3.2.1 Particulate matter (PM_{10})

The average PM_{10} concentration of Auckland in 2021 increased by 1.3% compared to 2020 (from 12.29 ± 8.69 $\mu g/m^3$ to 12.74 ± 8.69 $\mu g/m^3$) ($p<0.05$). However, this increase did not exceed the new 2021 WHO air quality guideline of 15 $\mu g/m^3$. It is important to note that on the individual sites level, Queen Street exceeded the WHO annual guideline by 24%. As in the previous year, the Khyber Pass Road monitoring site recorded the lowest annual PM_{10} mean concentration of 11 $\mu g/m^3$, while Queen Street recorded the highest level of 19 $\mu g/m^3$. Further investigation is needed to ascertain the reason Khyber Pass Road's PM_{10} annual average concentration was lower than the rural site (Patumahoe). Figure 7 presents the variation of PM_{10} concentration across the nine monitoring sites.

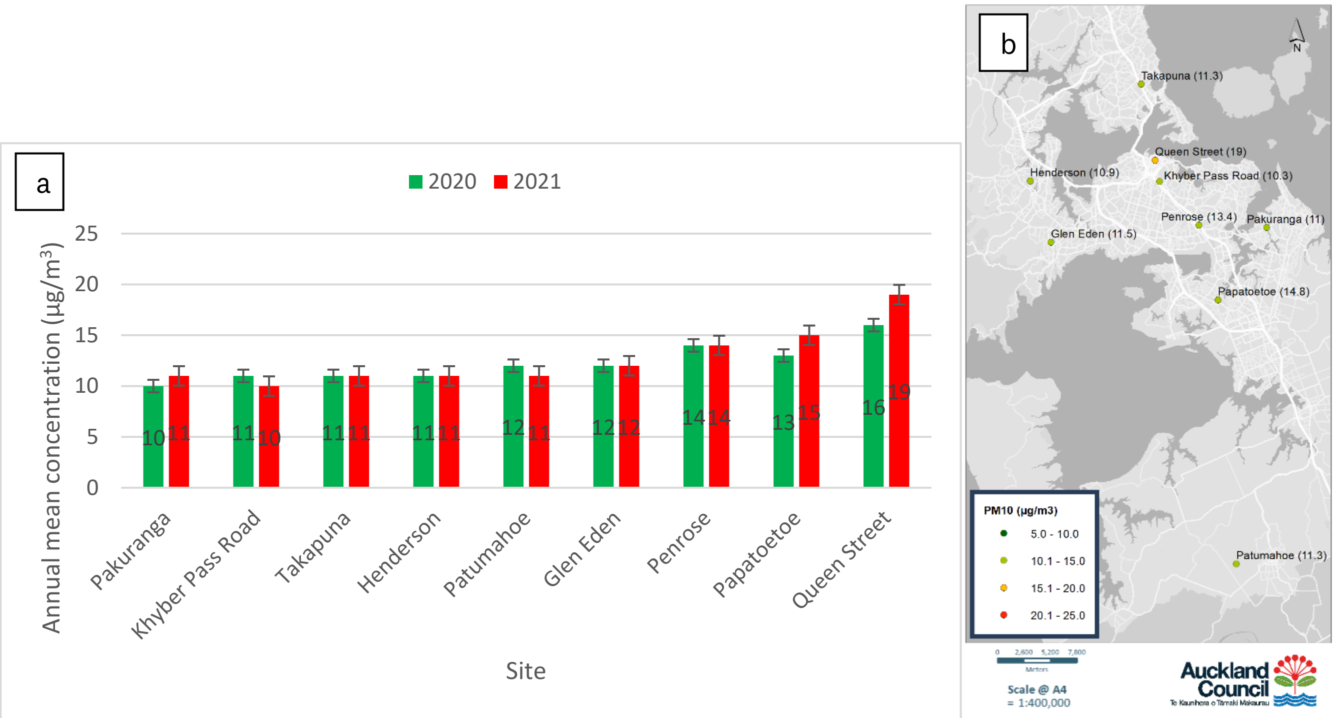

Figure 7. PM_{10} annual mean concentrations at nine sites – arranged in increasing order from left to right.

Error bars represent the standard errors of the mean. Map b (right) shows sites and their 2021 annual mean PM_{10} concentration in brackets.

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

It is important to note that even though at times there were hourly spikes in PM_{10} mean concentrations in most of the sites, there was no exceedance of national standard and the 2021 WHO air quality 24-hour guideline (See Appendix D). A box and whisker diagram depicting the hourly mean concentrations across the sites is given by Figure 8.

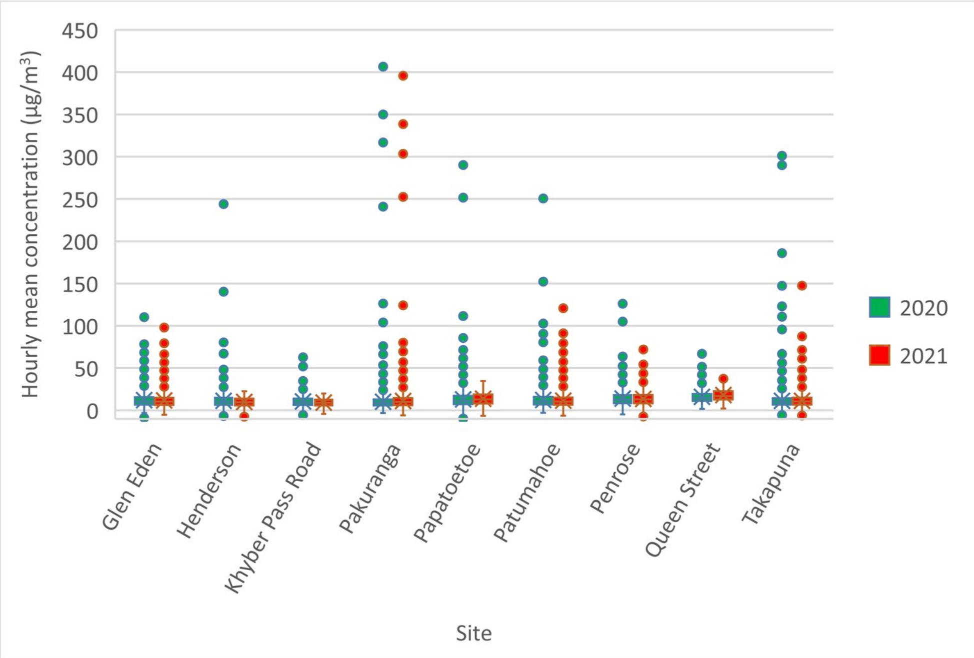

Figure 8. Boxplot of PM_{10} hourly mean concentration measured at nine sites.

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

Similar to findings by Talbot et al. (2017), daily PM_{10} emissions were higher in winter probably due to the use of solid fuels for home heating (See Figure 9). In summer, transport is the main anthropogenic source of daily PM_{10} emissions. Afternoon concentrations are generally lower than those of the evening due to increased mixing in the atmosphere (Figure 10). As the ground cools in the evening, so the atmosphere becomes more stable, and concentrations increase with less dispersion. Weekday concentrations are higher than weekends due to increased traffic (Talbot et al., 2017).

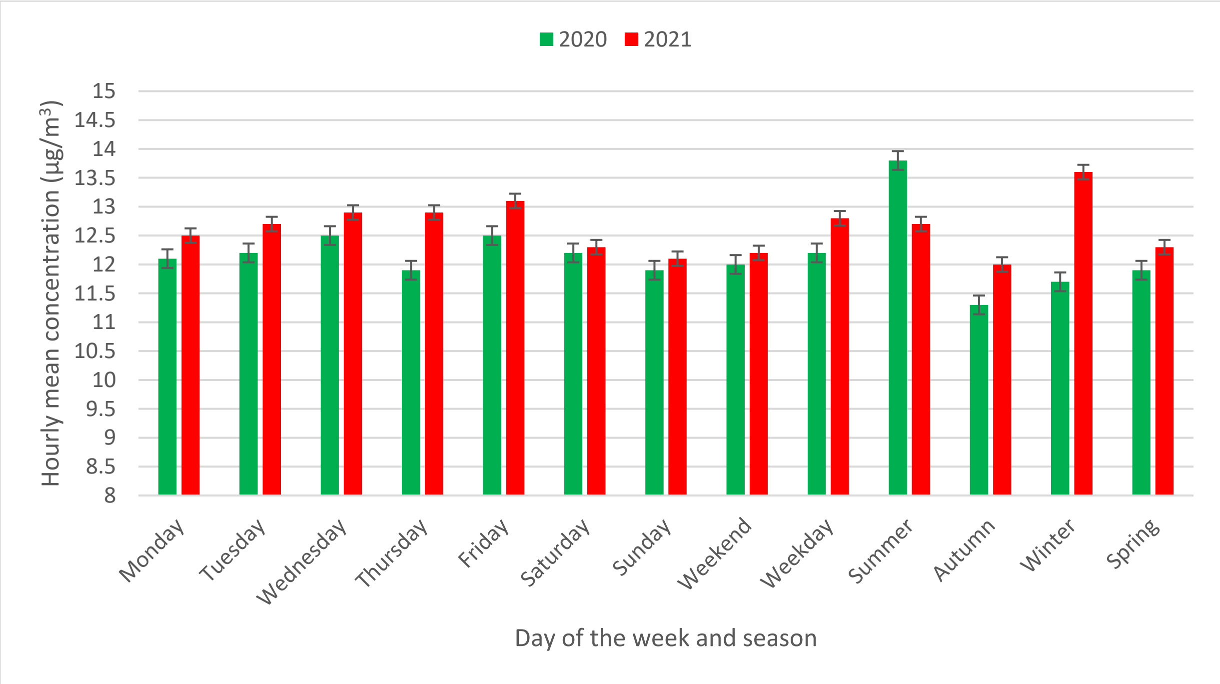

Figure 9. Temporal variations in Auckland PM_{10} annual mean concentrations. Error bars represent the standard errors of the mean.

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

As indicated in section 3.1, PM_{10} concentrations may vary from site to site depending on meteorological conditions and other factors. PM_{10} pollution rose charts are useful in showing which wind directions dominate the overall concentrations as well as providing information on the different concentration levels. Figures 11 and 12 indicate that different dominant wind speeds and directions occur at each monitoring site. For example, Figure 11 shows that the highest PM_{10} concentrations arrive at the Penrose site mostly from the southwest sector while that of Queen Street are from the southeast sector. It is interesting to note that the patterns of PM_{10} pollution roses at all the sites in 2020 and 2021 were identical.

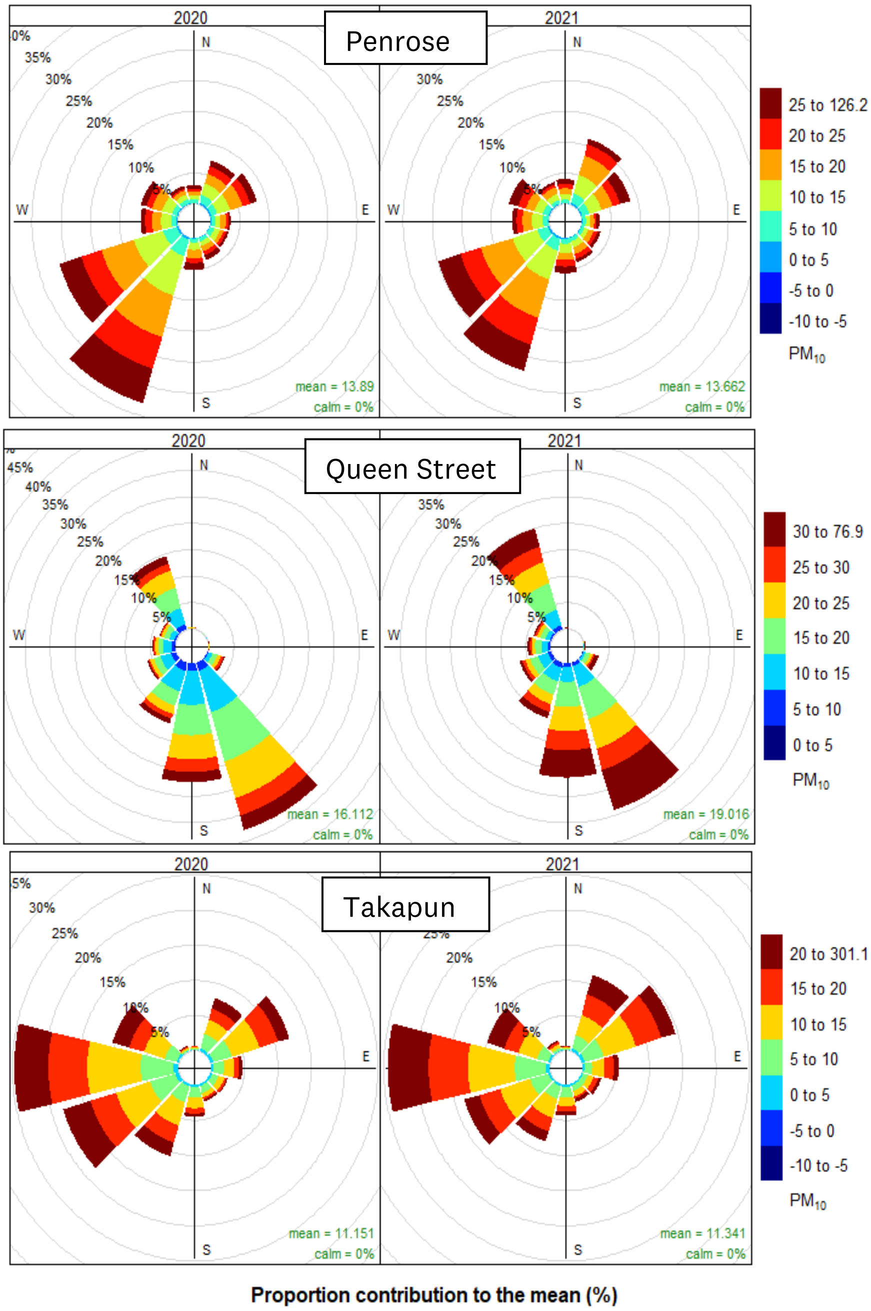

Figure 11. PM_{10} pollution roses for Penrose, Queen Street and Takapuna sites.

Higher PM_{10} concentrations are associated with predominant prevailing wind direction as follows: Penrose: southwest, Queen Street: southeast, and Takapuna: south westerly. The plots on the left are for 2020 data while the right plots are for 2021 data.

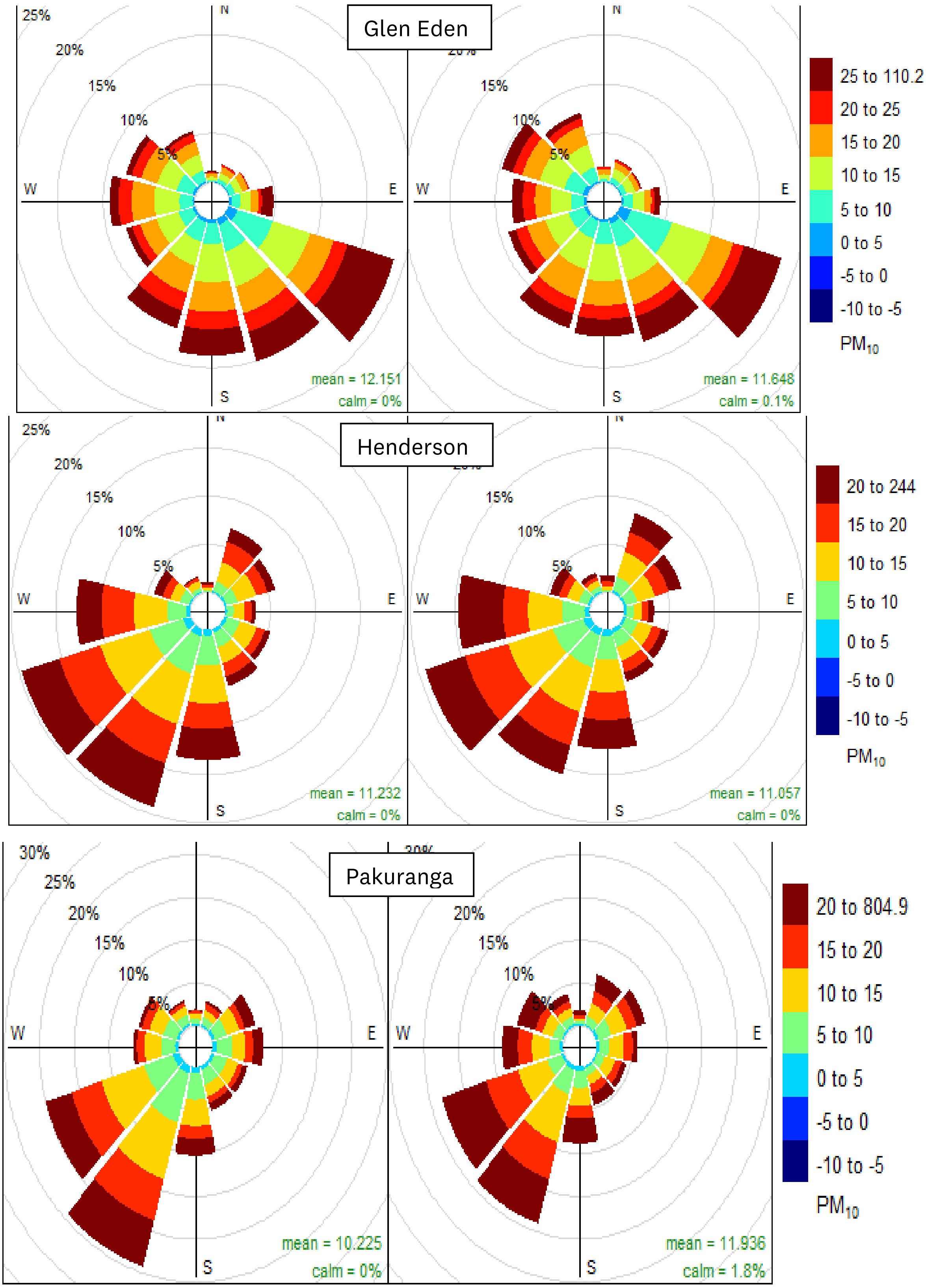

Figure 12. PM_{10} pollution roses for Glen Eden, Henderson, and Pakuranga sites.

Higher PM_{10} concentrations are associated with predominant prevailing wind direction as follows: Glen Eden: southeast, Henderson: southwest, and Pakuranga: southwest. The plots on the left are for 2020 data while the right plots are for 2021 data.

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

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

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

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

3.2.2 Particulate matter ($PM_{2.5}$)

The average $PM_{2.5}$ concentration of Auckland in 2021 increased by 6.7% compared to 2020 (from 5.66 ± 4.15 μg/m^3 to 6.04 ± 5.11 μg/m^3) ($p<0.05$). This increase was over the 2021 WHO air quality guideline of 5 μg/m^3. Patumahoe monitoring site had the lowest annual $PM_{2.5}$ mean concentration of 4.6 μg/m^3, while Queen Street recorded the highest mean of 7.6 μg/m^3. Apart from Penrose, all the monitored sites registered annual mean concentrations higher than the previous year. All the differences in annual mean concentrations were statistically significant ($p<0.05$) (See Appendix C). Figure 13 presents the variation of $PM_{2.5}$ annual concentration for four monitoring sites.

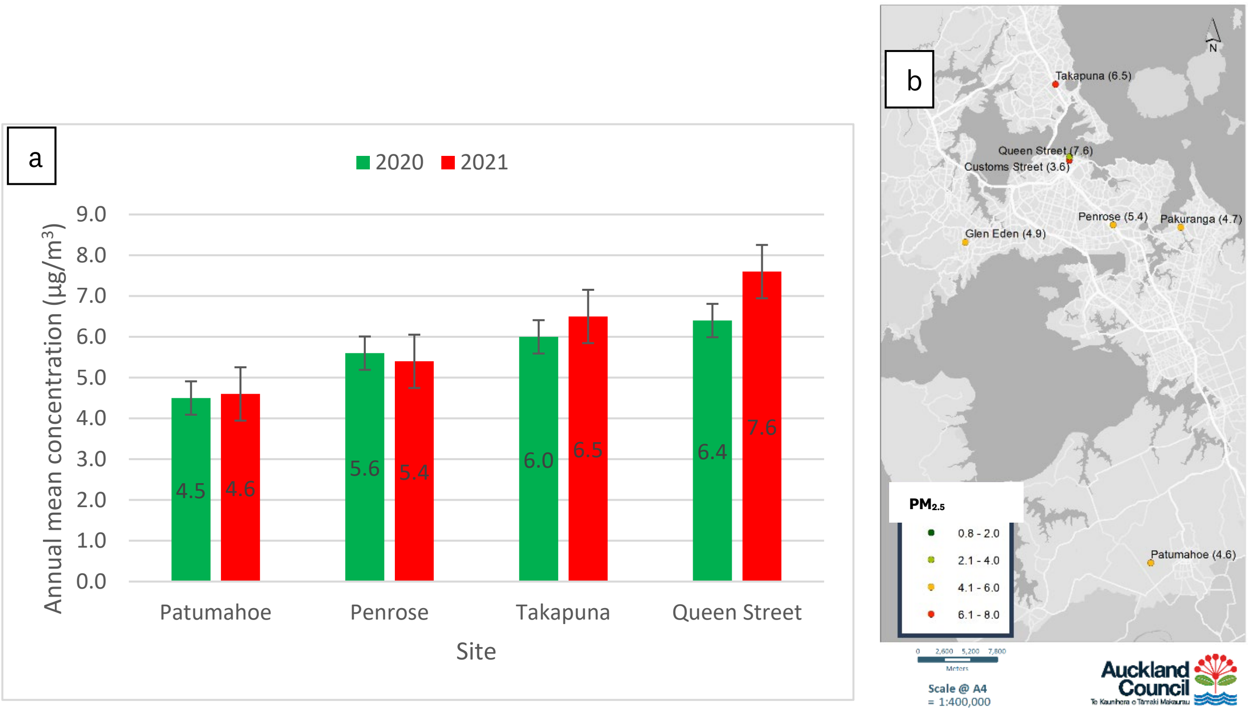

Figure 13. $PM_{2.5}$ annual mean concentrations at four sites – arranged in increasing order from left to right.

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

As with PM_{10}, there were occasional hourly spikes in $PM_{2.5}$ mean concentrations in all the sites (See Appendix E). On 24th June 2021, a 24-hour $PM_{2.5}$ mean concentration of 26.5 µg/m³ was recorded at Pakuranga. This slightly exceeded the Auckland Unitary Plan target of 25 µg/m³. This exceedance is likely due to home heating. The annual $PM_{2.5}$ averages for Penrose, Takapuna, and Queen Street sites were higher than the more stringent WHO air quality guideline of 5 µg/m³. A box and whisker diagram showing the distribution of hourly mean concentrations across the sites is presented in Figure 14.

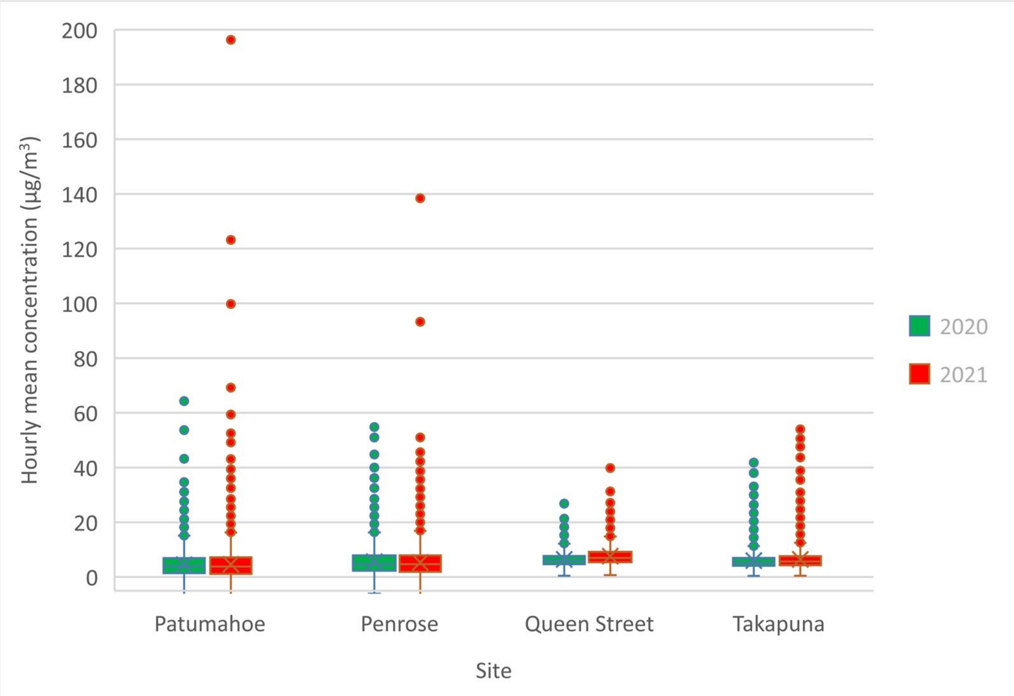

Figure 14. Boxplot of $PM_{2.5}$ hourly mean concentration measured at four sites.

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

In the same manner as PM_{10}, $PM_{2.5}$ concentrations were higher in winter most likely due to the increase in the use of home heating systems. Overall, concentrations peak in the afternoon and night hours (See Figure 16). Overall, between the hours 12 noon and 6 pm, higher average PM2.5 values were recorded in 2021 than in 2020. This is likely due to increased source contribution from motor vehicles. Concentrations of $PM_{2.5}$ tend to increase later in the week with the highest concentrations typically occurring on Wednesday to Friday (Figure 15). Weekday concentrations are slightly higher than weekends most probably due to increased human activities.

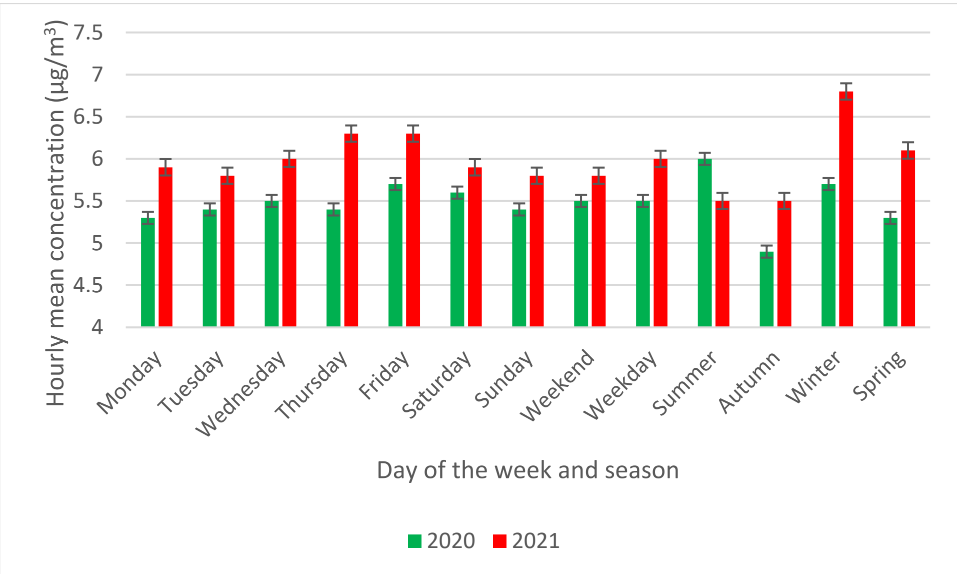

Figure 15. Temporal variations in Auckland $PM_{2.5}$ annual mean concentrations. Error bars represent the standard errors of the mean.

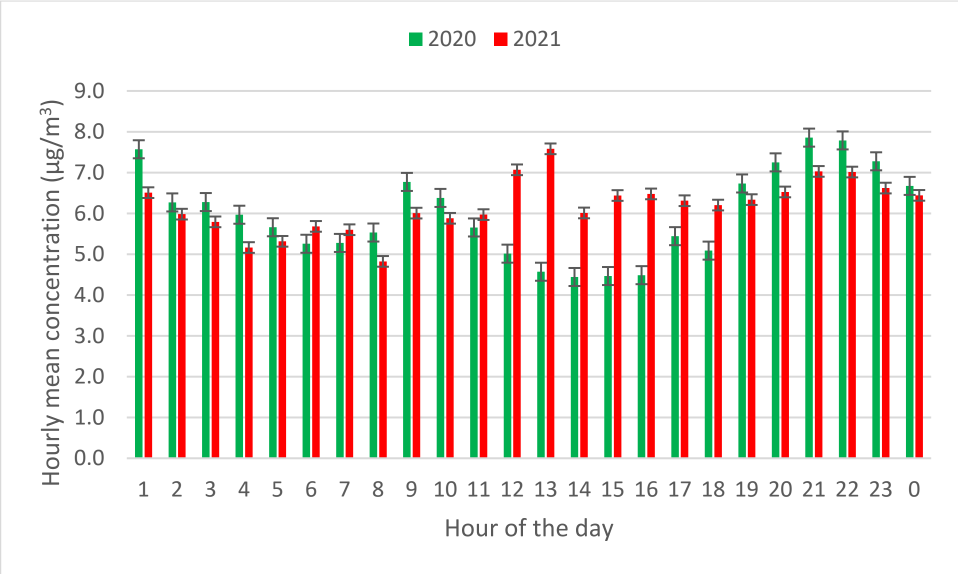

Figure 16. Time variations in Auckland $PM_{2.5}$ hourly mean concentrations. Error bars represent the standard errors of the mean.

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

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

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

$PM_{2.5}$ pollution rose plots show that the predominant wind direction where the $PM_{2.5}$ contaminants are originating from are similar to the previous year. Figure 17 shows the $PM_{2.5}$ pollution roses for three sites where wind speed and direction are monitored.

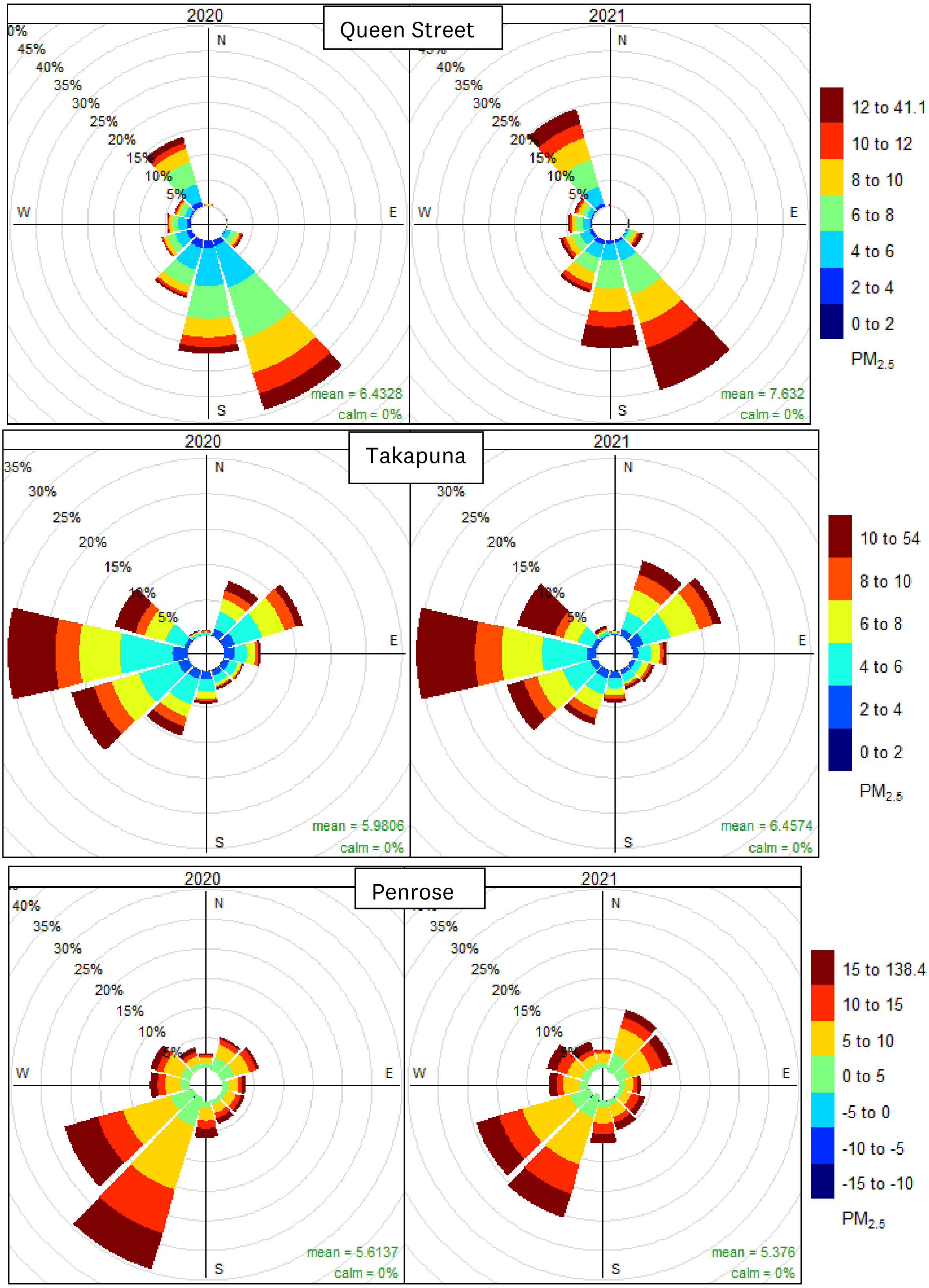

Figure 17. $PM_{2.5}$ pollution roses for Queen Street, Takapuna, and Penrose sites.

Higher $PM_{2.5}$ concentrations are associated with predominant prevailing wind direction as follows: Queen Street: southeast, Takapuna: southwest, and Penrose: southwest. The plots on the left are for 2020 data while the right plots are for the 2021 data.

3.2.3 Nitrogen dioxide (NO_2)

The annual mean NO_2 concentration for Auckland in 2021 is the lowest recorded since 2006. The mean annual NO_2 concentration for 2021 significantly decreased by 16.7% (from 18.58 ± 22.0 µg/m^3 to 15.47 ± 17.5 µg/m^3) compared to 2020 ($p<0.05$). However, Auckland's overall annual average NO_2 concentration exceeded the 2021 WHO air quality guideline of 10 µg/m^3. As in the previous year, the Patumahoe monitoring site recorded the lowest annual NO_2 mean concentration of 3.0 µg/m^3, while Customs Street registered the highest of 42.0 µg/m^3. Figure 18 presents the variation of NO_2 concentration across the monitoring sites.

The annual NO_2 mean concentrations recorded at Penrose, Queen Street, Customs Street, Khyber Pass Road, and Henderson sites were statistically significantly ($p<0.05$) lower than the previous year (See Appendix C). However, the marginal increase in the annual NO_2 mean concentration at Patumahoe, Glen Eden, and Takapuna was not statistically significant ($p>0.05$).

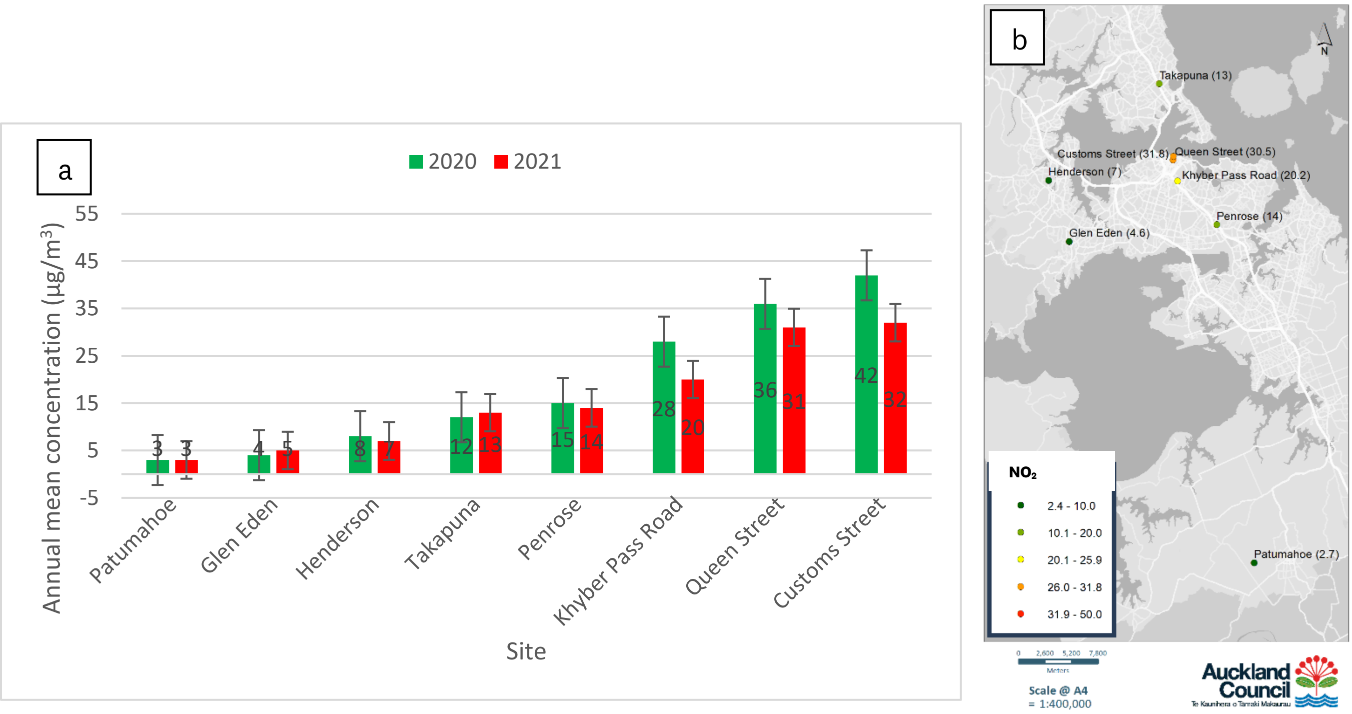

Figure 18. NO_2 annual mean concentrations at eight sites – arranged in increasing order from left to right.

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

A box and whisker diagram showing the distribution of the hourly mean concentrations across the sites is given in Figure 19. It is worth noting that even though there were occasional hourly spikes in NO_2 mean concentrations in all the sites, there was no breach of national standard. On the contrary, on 26 occasions, Auckland exceeded the new 2021 WHO air quality 24-hour guideline for NO_2 (See Appendix F). Figure 20 presents the annotated calendar plot of the daily NO_2 mean concentrations indicating the days where the measured values reached or exceeded the WHO guideline of 25 µg/m^3. In more than half of the days in 2021, the two Auckland city centre sites recorded 24-hour average NO_2 concentrations more than the 2021 WHO guideline (See Appendix F; Figures F7 and F9).

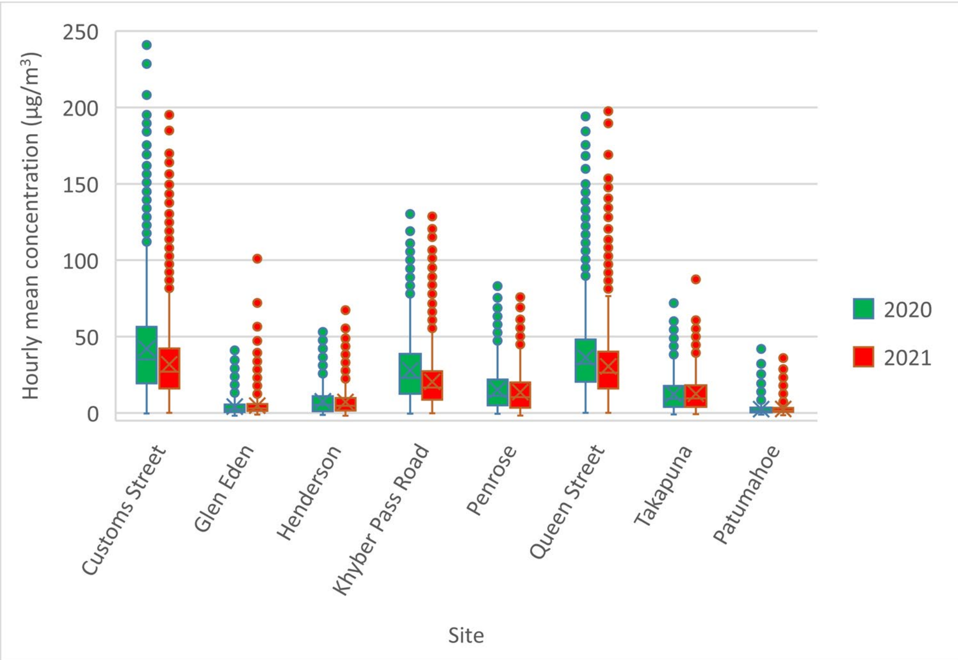

Figure 19. Boxplot of NO_2 hourly mean concentration measured at eight sites.

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

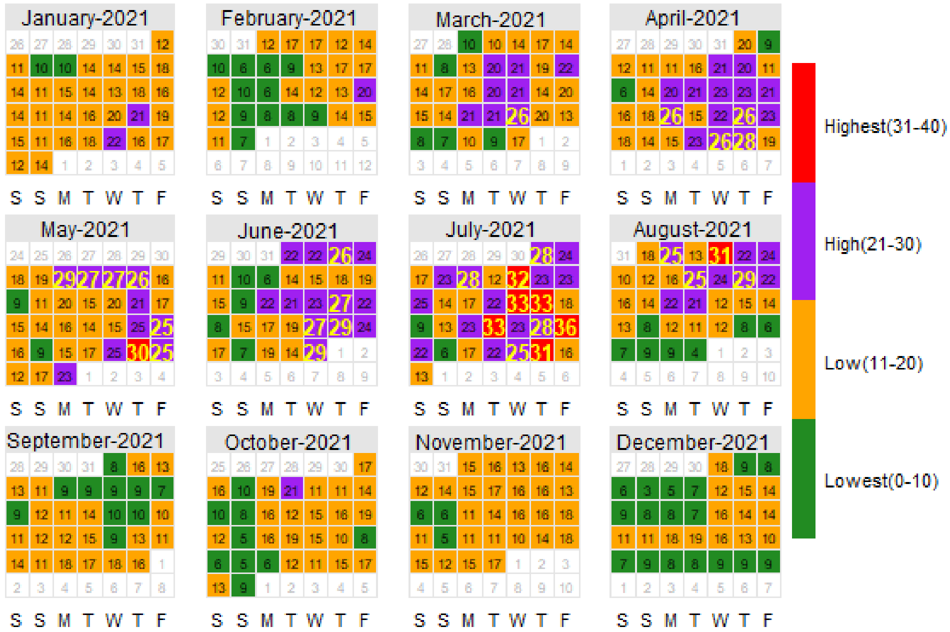

Figure 20. Calendar plot for NO_2 overall Auckland concentrations in 2021 with annotations highlighting those days where the concentration of NO_2 were equal or greater than the 2021 WHO guideline of 25 µg/m³. The numbers show the NO_2 24-hour mean concentration in µg/m³.

The highest NO_2 concentrations were recorded in winter (Figure 21). 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 22 with the increase between 7am and 9am, and 5pm and 9pm. Weekday concentrations are slightly higher than weekends most likely due to increased traffic volume.

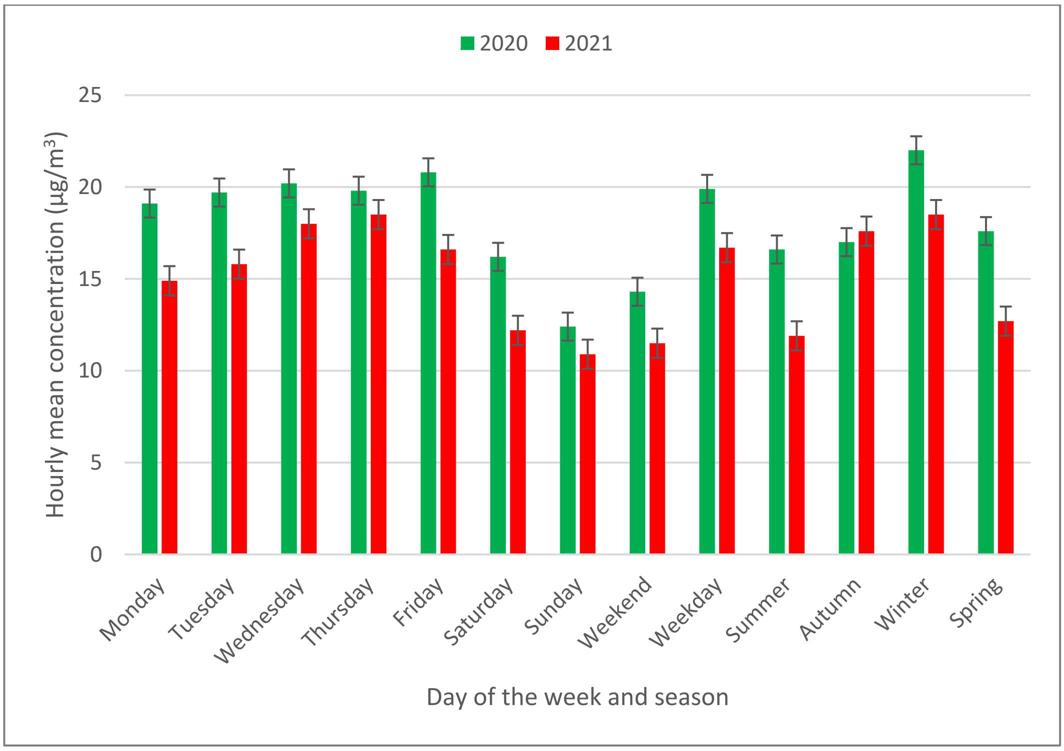

Figure 21. Temporal variations in Auckland NO_2 annual mean concentrations. Error bars represent the standard errors of the mean.

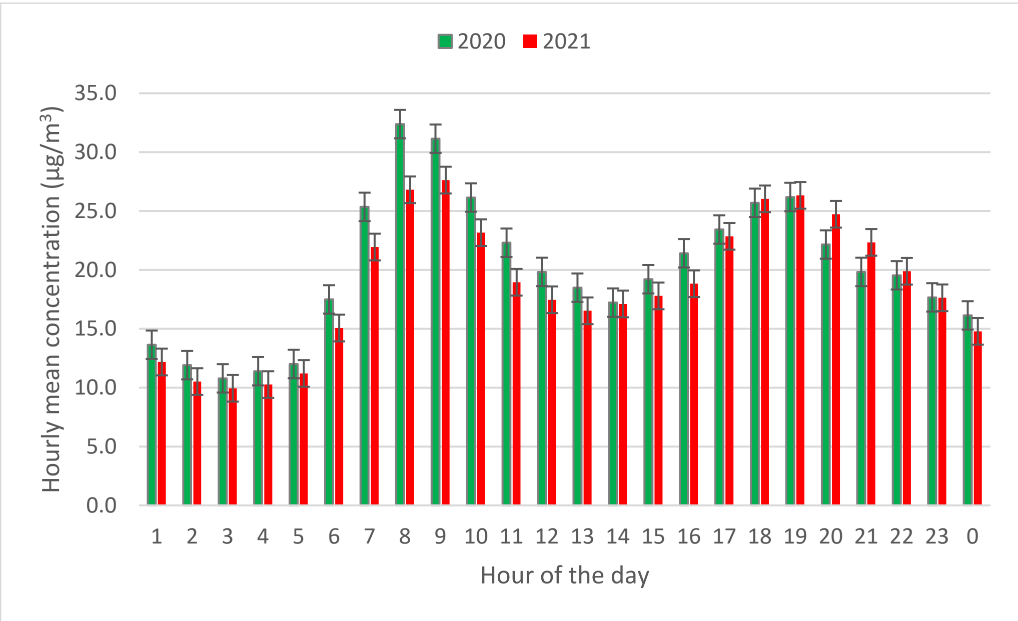

Figure 22. Time variations in Auckland NO_2 hourly mean concentrations. Error bars represent the standard errors of the mean.

Overall, it was estimated that 2606 tonnes of NOx were emitted from stacks and other industrial point sources in 2016. Within the Auckland urban boundary, industry is estimated to have emitted 775 tonnes of NOx in 2016. The combustion of any fuel generates a range of nitrogen oxides (NOx), as nitrogen in the air is oxidised in the combustion process. For industrial combustion processes, the majority of NOx is emitted as nitrogen oxide (NO), which is generally considered not to be harmful to human health or the environment at typical ambient concentrations. However, over time in the presence of sunlight, atmospheric ozone and/or organic compounds, NO is oxidised to the hazardous air pollutant NO_2 (Crimmins, 2018).

In 2016 estimate 15,473 tonnes per year of NOx were emitted from transport (67% motor vehicles, 17% aircraft, 15% off-road vehicles). It was estimated that on-road motor vehicles contribute 10,251 t/yr of NOx (Sridhar and Metcalfe, 2019).

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

As indicated in section 3.1, NO_2 concentrations may vary from site to site depending on meteorological conditions and other factors. NO_2 pollution rose charts are useful in showing which wind directions dominate the overall concentrations as well as providing information on the different concentration levels. Figures 23 and 24 indicate that different dominant wind speeds and directions occur at the monitoring sites. For instance, Figure 24 shows that the highest NO_2 concentrations arrived at the Penrose site mostly from the southwest sector while that of Queen Street are from the southeast sector. In the same manner as the other contaminants, patterns of NO_2 pollution roses at all the sites in 2020 and 2021 were very similar.

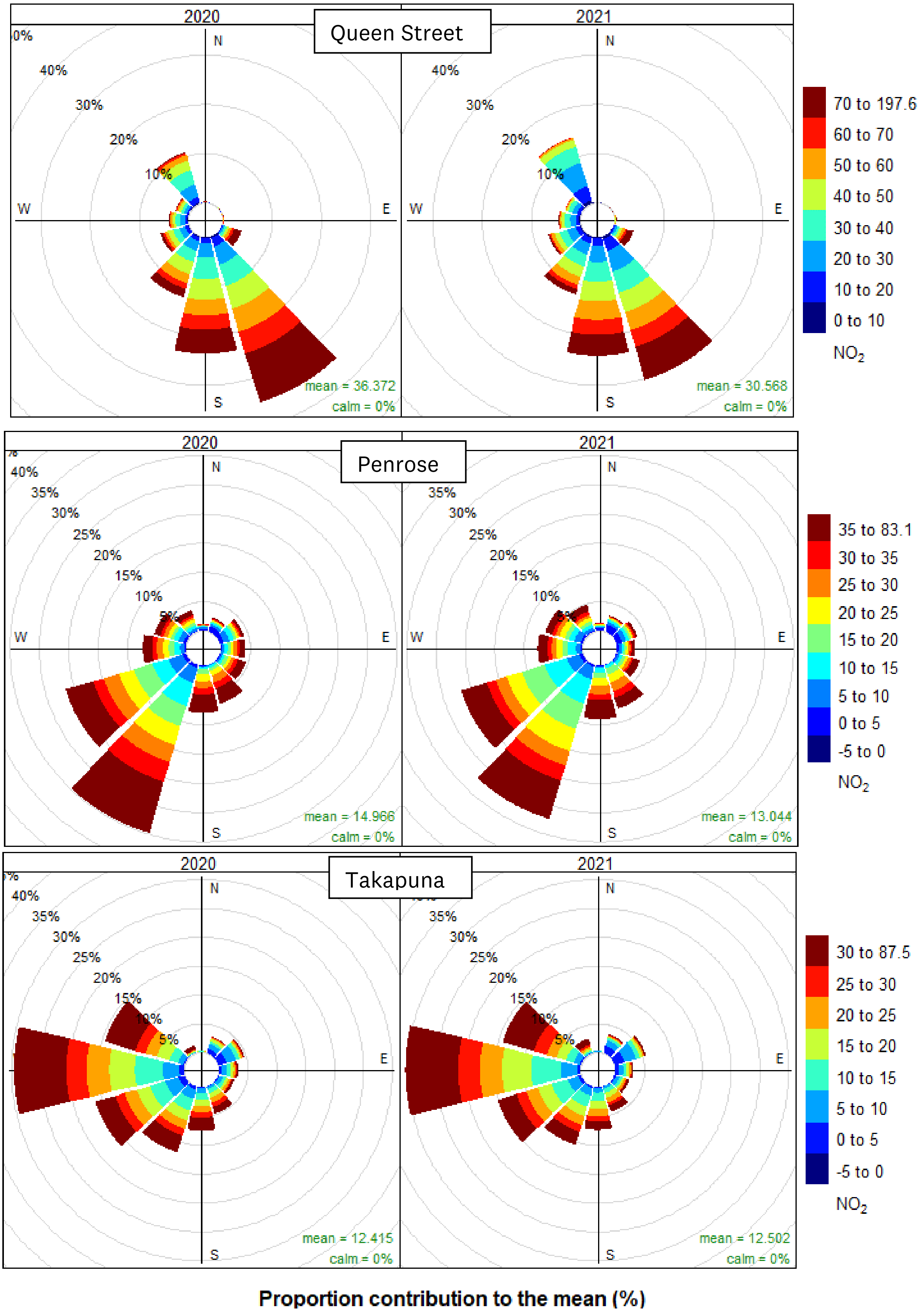

Figure 23. NO_2 pollution roses for Queen Street, Penrose, and Takapuna sites.

Higher NO_2 concentrations are associated with predominant prevailing wind direction as follows: Queen Street: southeast, Penrose and Takapuna: southwest. The plots on the left are for 2020 data while the right plots are for 2021 data.

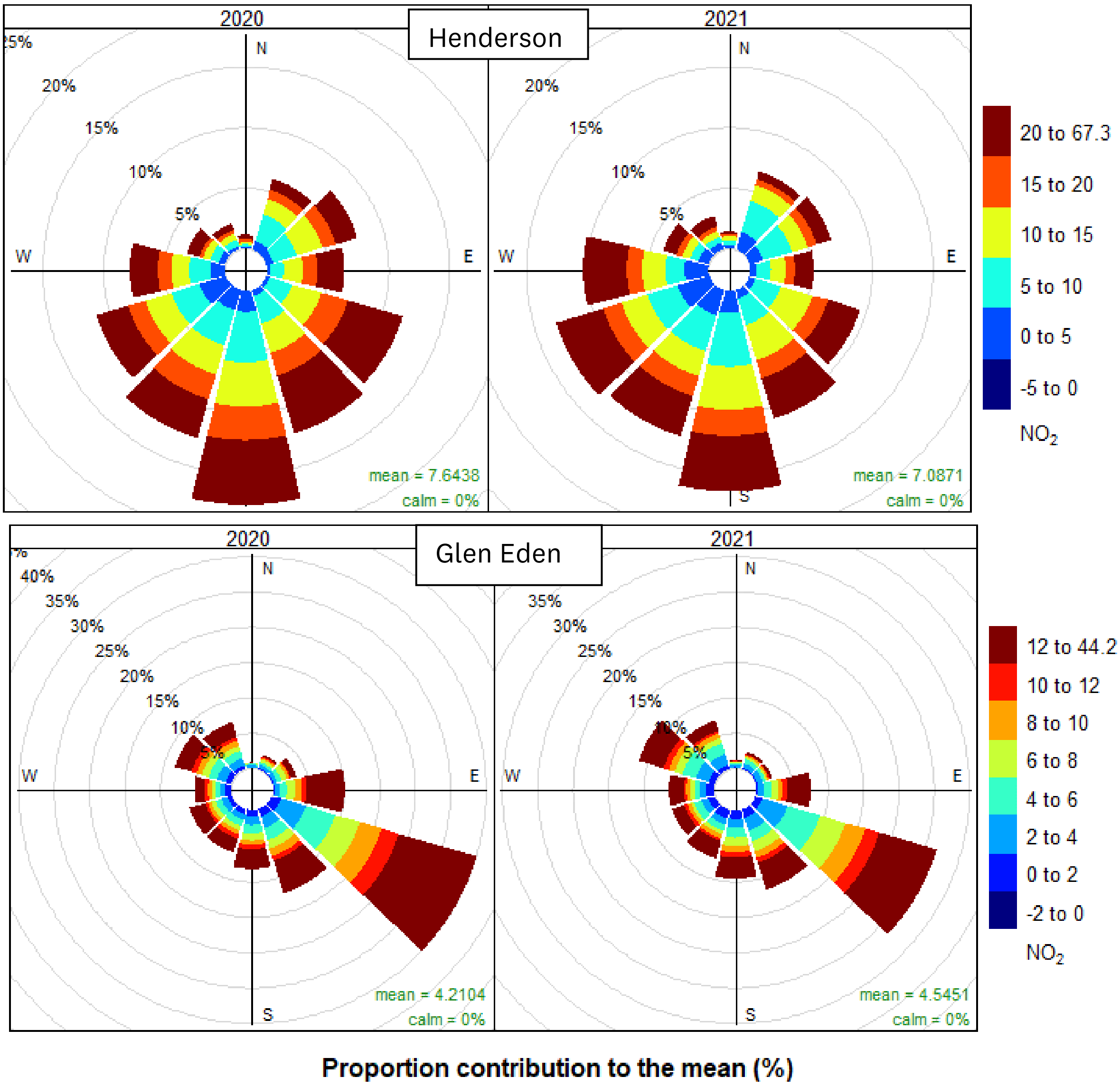

Figure 24. NO_2 pollution roses for Henderson and Glen Eden sites.

Higher NO_2 concentrations are associated with predominant prevailing wind direction as follows: Henderson: south, and Glen Eden: southeast. The plots on the left are for 2020 data while the right plots are for 2021 data.

3.2.4 Sulphur dioxide (SO_2)

The average SO_2 concentration of Auckland in 2021 significantly increased by 39% compared to 2020 (from 1.09 ± 1.99 µg/m^3 to 1.52 ± 1.99 µg/m^3) ($p<0.05$). The reason for this increase is not clear. Further investigation is needed. As found in 2020, the annual SO_2 mean concentration at Customs Street was higher than at the Penrose site. The increase in the 2021 SO_2 annual mean concentrations at both sites were significantly higher than the previous year ($p<0.05$) (see Appendix C). Figure 25 presents the variation of SO_2 annual concentrations for the two sites.

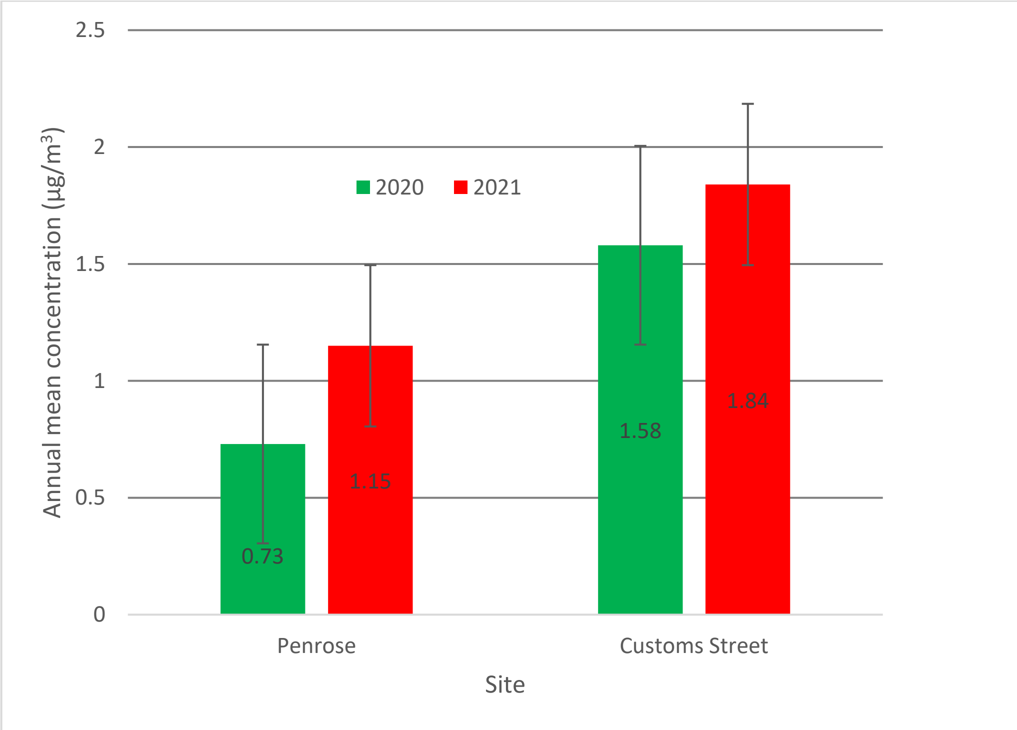

Figure 25. SO_2 annual mean concentrations at Customs Street and Penrose sites. Error bars represent the standard errors of the mean.

As with air particulates and NO_2, there were occasional hourly spikes in SO_2 mean concentrations at both sites. However, none of the sites exceeded the national standard and WHO guidelines (See Appendix G). A box and whisker diagram showing the distribution of hourly mean concentrations across the sites is presented in Figure 26.

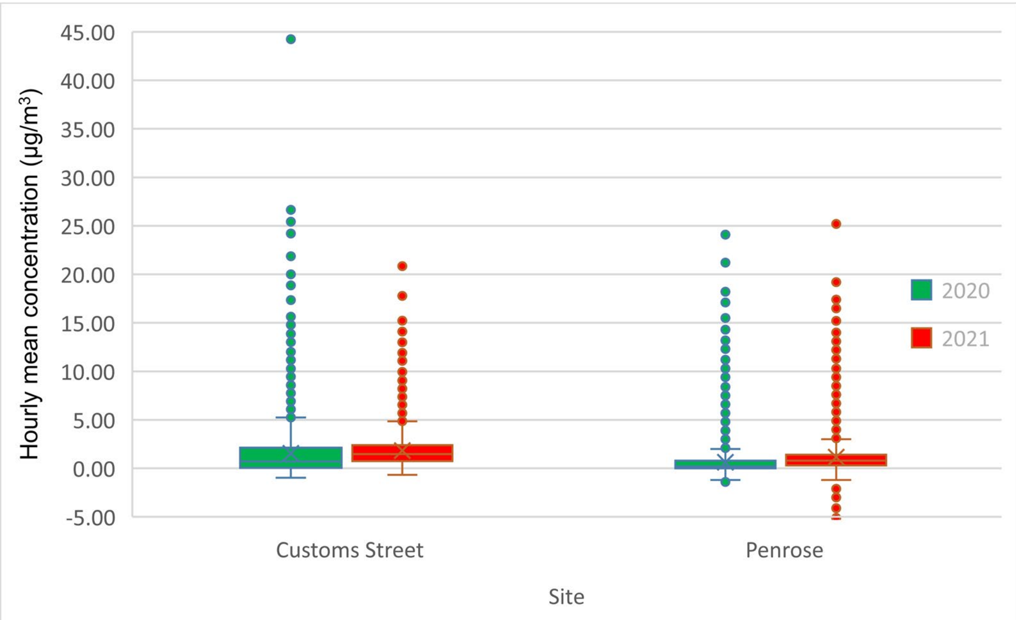

Figure 26. Boxplot of SO_2 hourly mean concentration measured at Customs Street and Penrose.

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

In general, SO_2 concentrations peak in the morning and late afternoon probably due to traffic (Figure 27) with the increase between 7am and 9am, and 5pm and 9pm. This was probably due to traffic patterns. Weekday SO_2 concentrations are slightly 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 28). Higher traffic volume is the likely contributing factor.

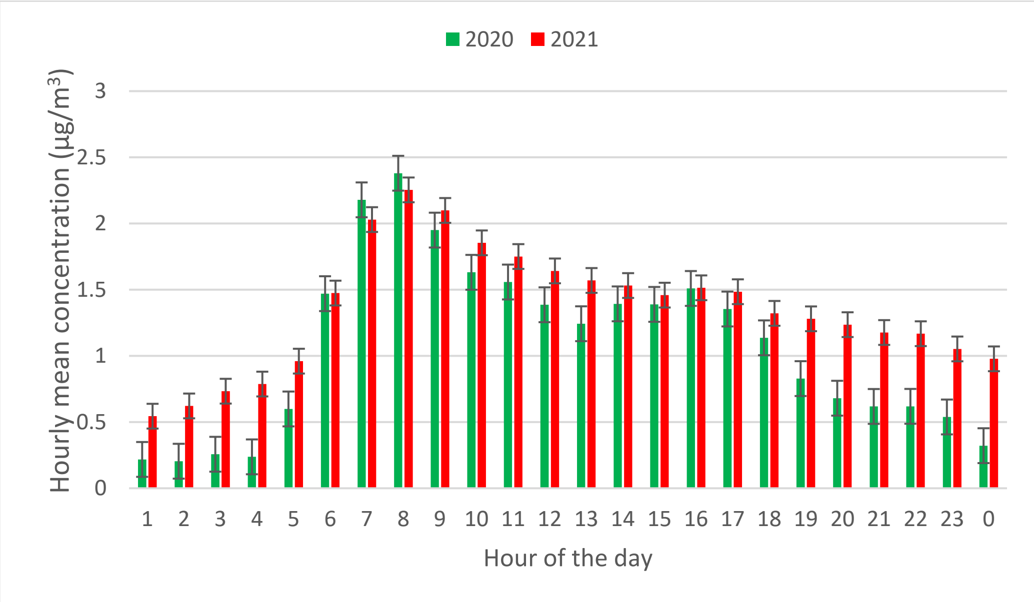

Figure 27. Time variations in SO_2 hourly mean concentrations. Error bars represent the standard errors of the mean.

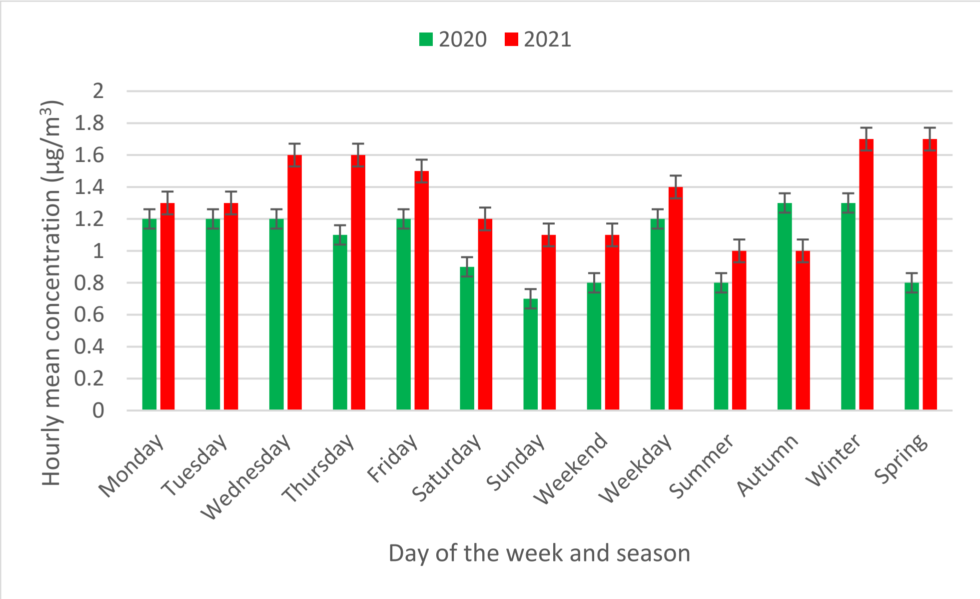

Figure 28. Temporal variations in Auckland SO_2 annual mean concentrations. Error bars represent the standard errors of the mean.

In the same manner as particulates and NO_2, SO_2 concentrations may vary from site to site depending on meteorological conditions and other factors. SO_2 pollution rose charts are important in showing which wind directions dominate the overall concentrations as well as providing information on the different concentration levels. Figure 29 shows that the highest SO_2 concentrations were at the Penrose site mostly from the southwest sector. It is interesting to note that the pattern of SO_2 pollution roses at the Penrose site in 2020 and 2021 was very similar.

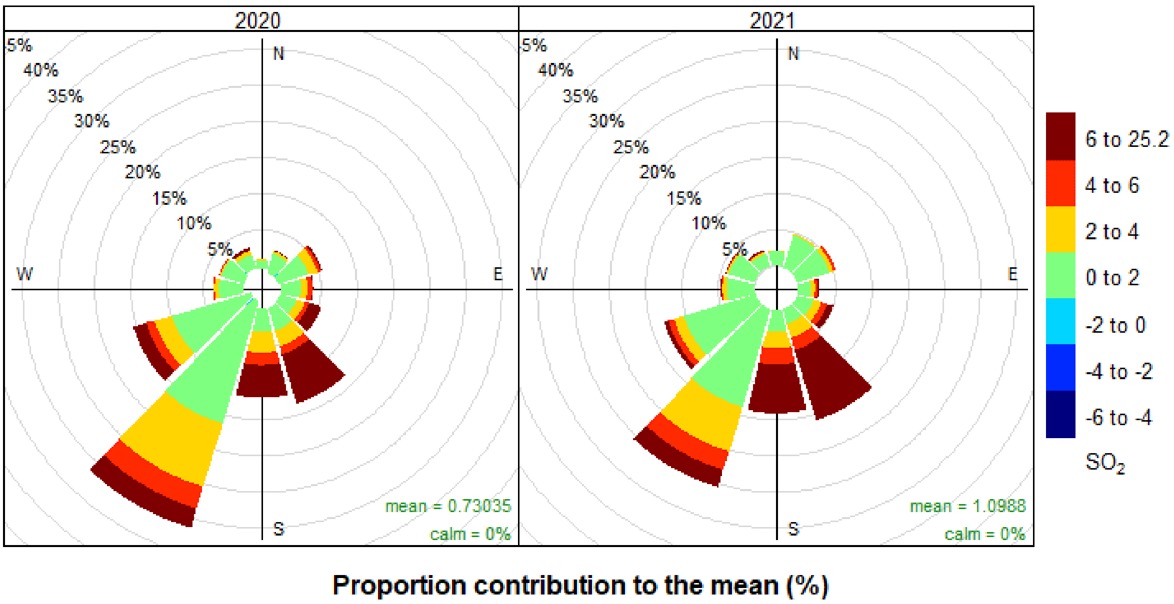

Figure 29. SO_2 pollution roses for Penrose site.

Higher SO_2 concentrations are associated with the southwest predominant prevailing wind direction. The plot on the left is for 2020 data while the right plot is for 2021 data.

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

3.2.5 Carbon monoxide (CO)

The average CO concentration at Khyber Pass Road site decreased by 8.3% compared to 2020 (from 0.24 ± 0.16 mg/m^3 to 0.22 ± 0.19 mg/m^3) ($p<0.05$). Interestingly even though there were occasional hourly and 8-hour running means spikes in CO concentrations, there was no exceedance of national standard and 2021 WHO air quality guideline (See Appendix H). Figure 30 compares the annual CO concentration for 2021 and 2020. A box and whisker diagram depicting the hourly mean concentrations is presented in Figure 31.

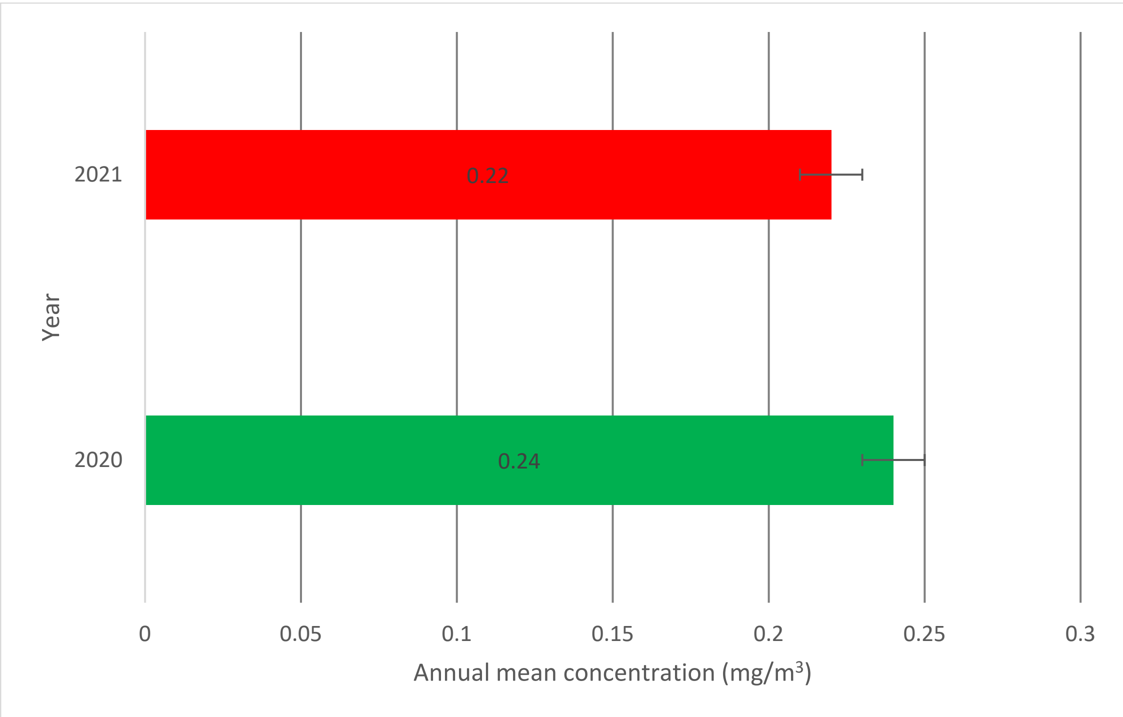

Figure 30. CO annual mean concentration. Error bars represent the standard errors of the mean.

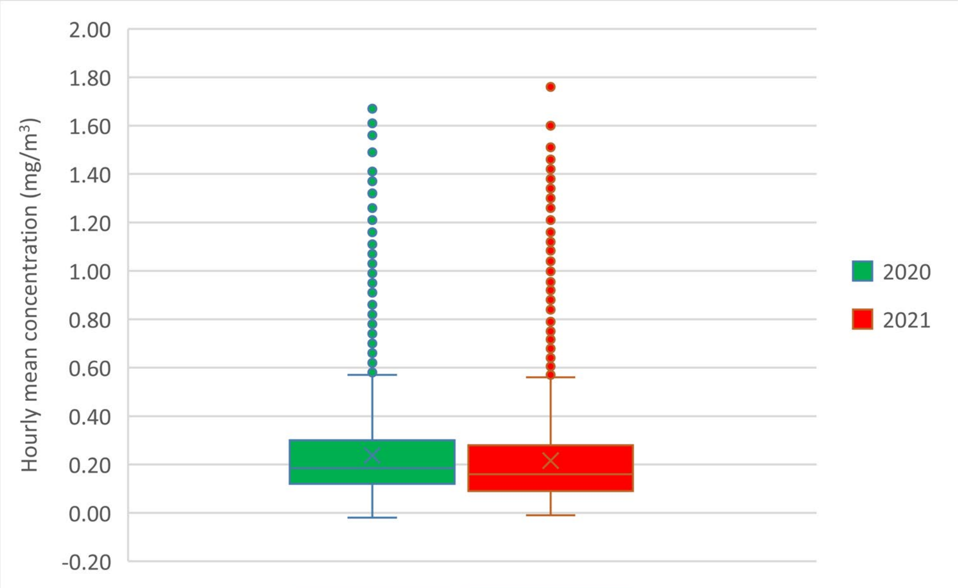

Figure 31. Boxplot of CO hourly mean concentration.

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

The highest CO concentrations were measured in winter. Concentrations of CO tend to be uniform in the weekday (See Figure 32). In general, CO concentrations were highest in the morning and late afternoon likely due to peak traffic, as presented in Figure 33 with the increase between 7am and 9am, and 5pm and 9pm. Weekday CO concentrations are significantly higher on weekdays than on weekends. Higher traffic volume is the likely contributing factor.

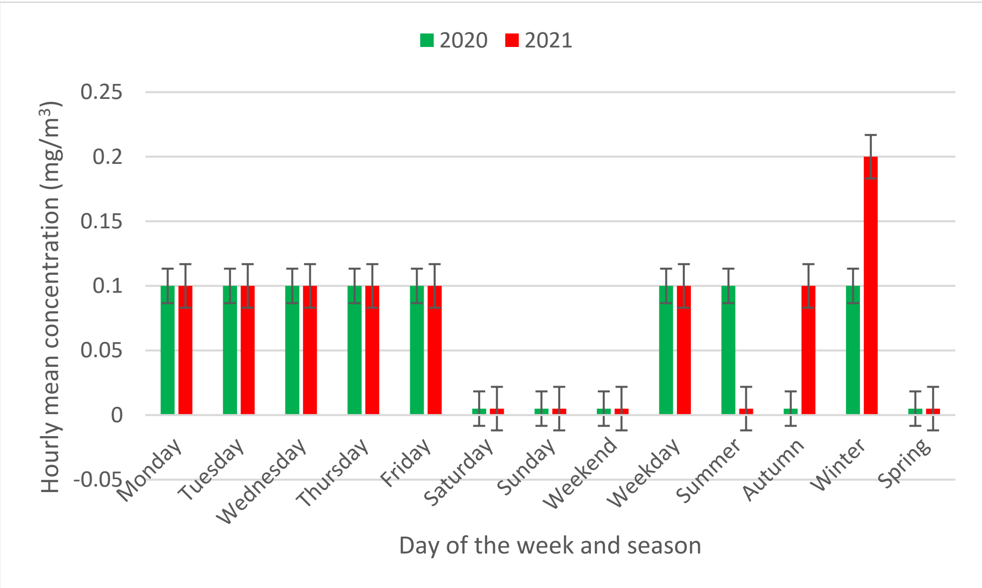

Figure 32. Temporal variations in CO annual mean concentrations. Error bars represent the standard errors of the mean.

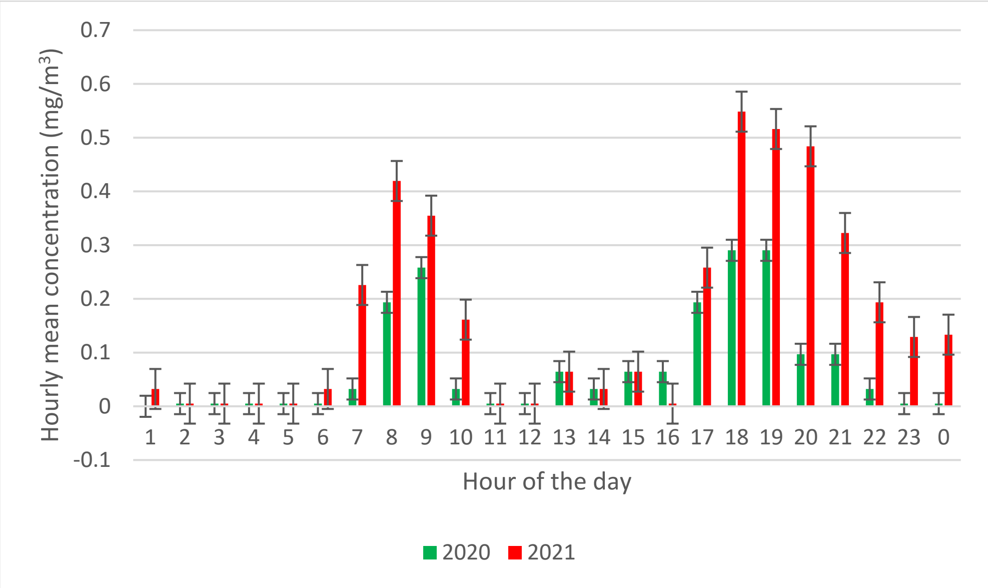

Figure 33. Time variations in CO hourly mean concentrations. Error bars represent the standard errors of the mean.

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 2021 decreased by 8.9% compared to 2020 (from 40.4 ± 0.16 µg/m^3 to 36.8 ± 13.8 µg/m^3) ($p<0.05$). Figure 34 compares the annual ozone concentrations for 2021 with 2020. As shown by Figure 35 (and Appendix I), there were occasional hourly mean spikes in O_3 concentrations, however, they did not cause any exceedance of national standard and 2021 WHO air quality guidelines. A box and whisker diagram depicting the hourly mean concentrations is given in Figure 35.

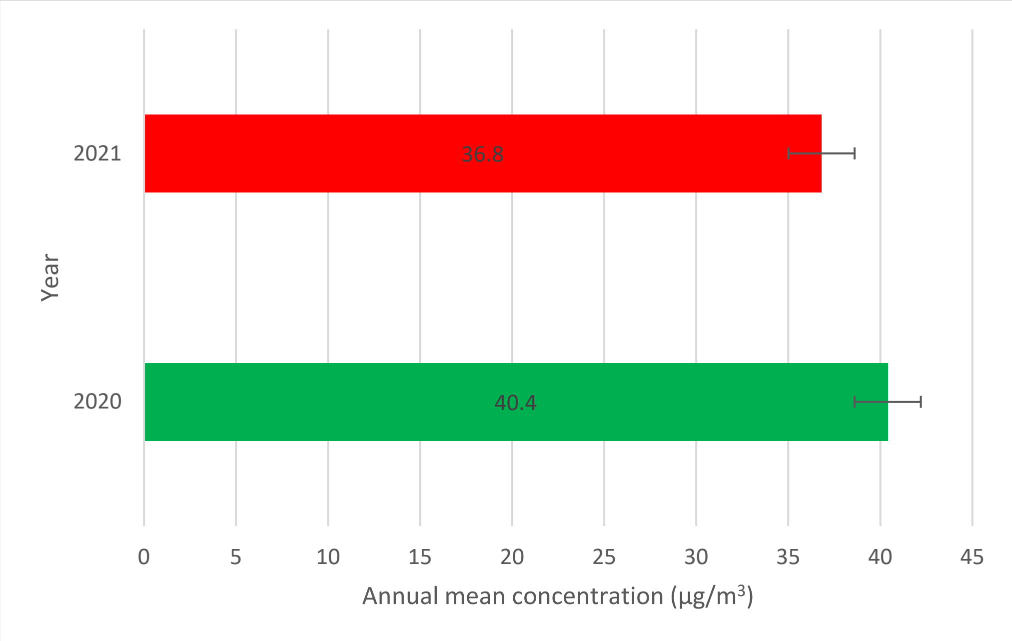

Figure 34. Ozone annual mean concentrations. Error bars represent the standard errors of the mean.

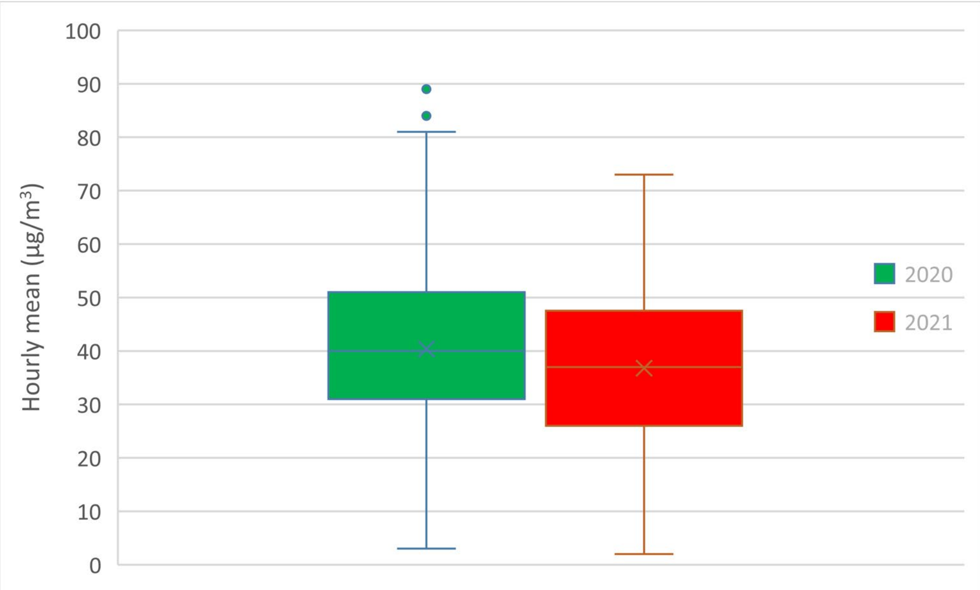

Figure 35. Boxplot of ozone hourly mean concentration.

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

The highest O_3 concentrations were measured in winter (Figure 36). In general, ozone concentrations were highest in the afternoon as shown in Figure 37, 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 were higher than on weekdays. It is important to note that O_3 concentrations increase with decreasing NO_2, a predictable inverse relationship given the relationship between NO_2 and O_3 in the presence of sunlight (Xie et al., 2014; Talbot and Crimmins, 2020).

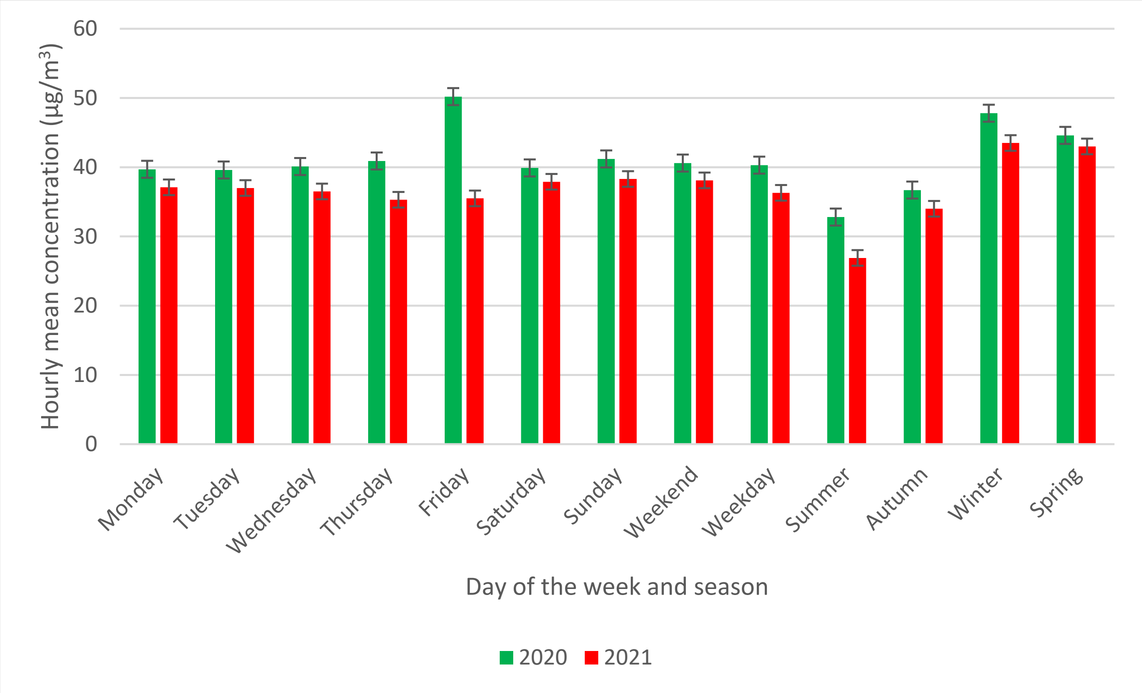

Figure 36. Temporal variations in ozone annual mean concentrations. Error bars represent the standard errors of the mean.

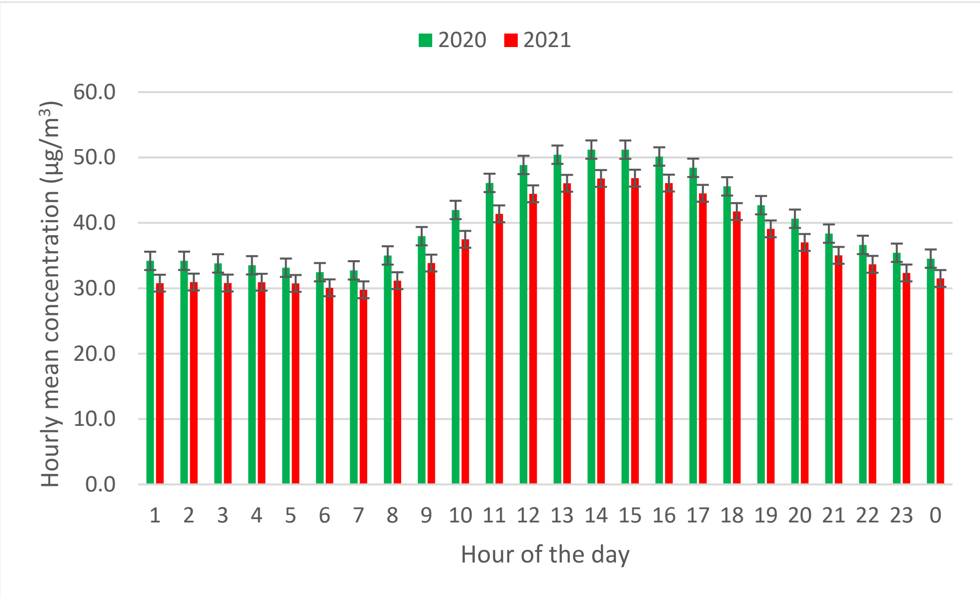

Figure 37. Time variations in ozone hourly mean concentrations. Error bars represent the standard errors of the mean.

3.2.7 Black carbon

The annual black carbon concentration measured at Customs Street in 2021 was significantly lower than the previous year (from 1339 ± 1390 to 1138 ± 1200 ng/m³) (p<0.0.5). On the contrary, the annual black carbon concentration recorded at Henderson was significantly higher than the previous year (from 552 ± 798 to 617 ± 1026 ng/m³) ($p<0.0.5$). The probable reason for the different behaviours at the two sites is not clear. Further investigation is needed. When data from the two sites are combined, the mean annual black carbon concentration for 2021 significantly decreased by 7.1% (from 932 ± 1191 ng/m³ to 866 ± 1142 ng/m³). Figures 38 and 39 present the variation and distribution of black carbon concentrations for the two sites.

Figure 38. Black carbon annual mean concentrations for Henderson and Customs Street sites. Error bars represent the standard errors of the mean.

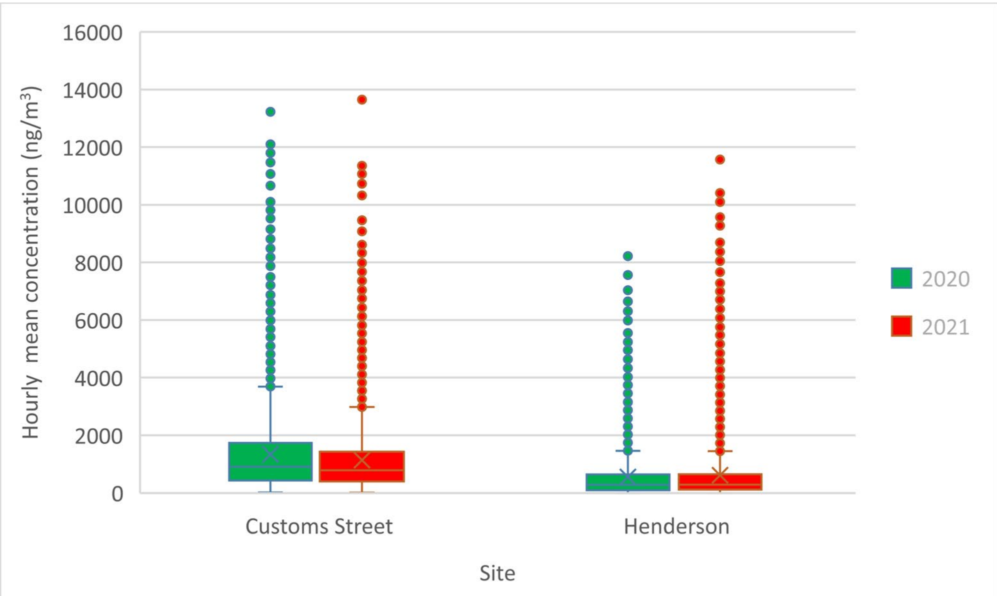

Figure 39. Boxplot of black carbon hourly mean concentration measured at two sites.

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

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 40). Black carbon concentrations on weekdays are slightly higher than on weekends. The highest black carbon concentrations were recorded in winter (See Appendix J). 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 the likely contributing factor.

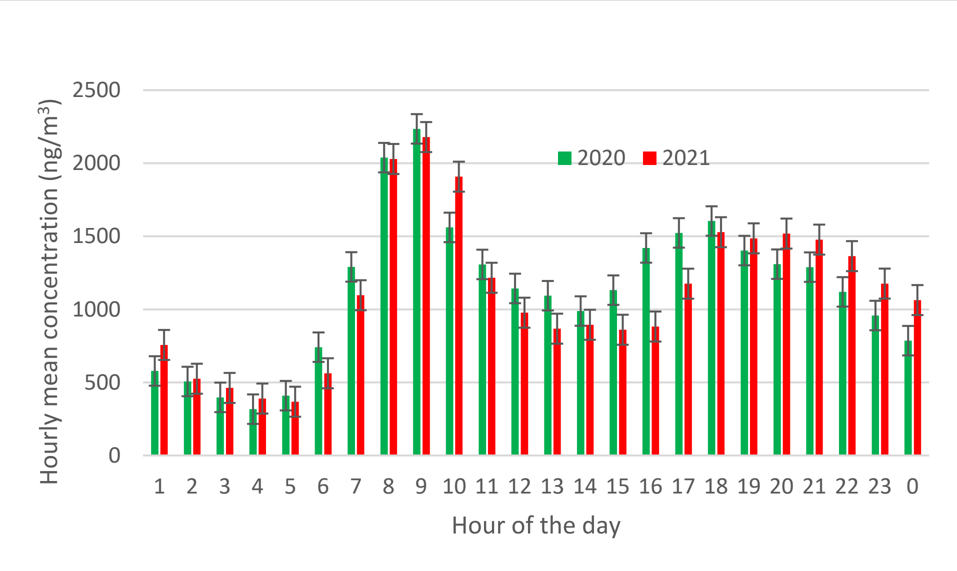

Figure 40. Time variations in black carbon hourly mean concentrations. Error bars represent the standard errors of the mean.

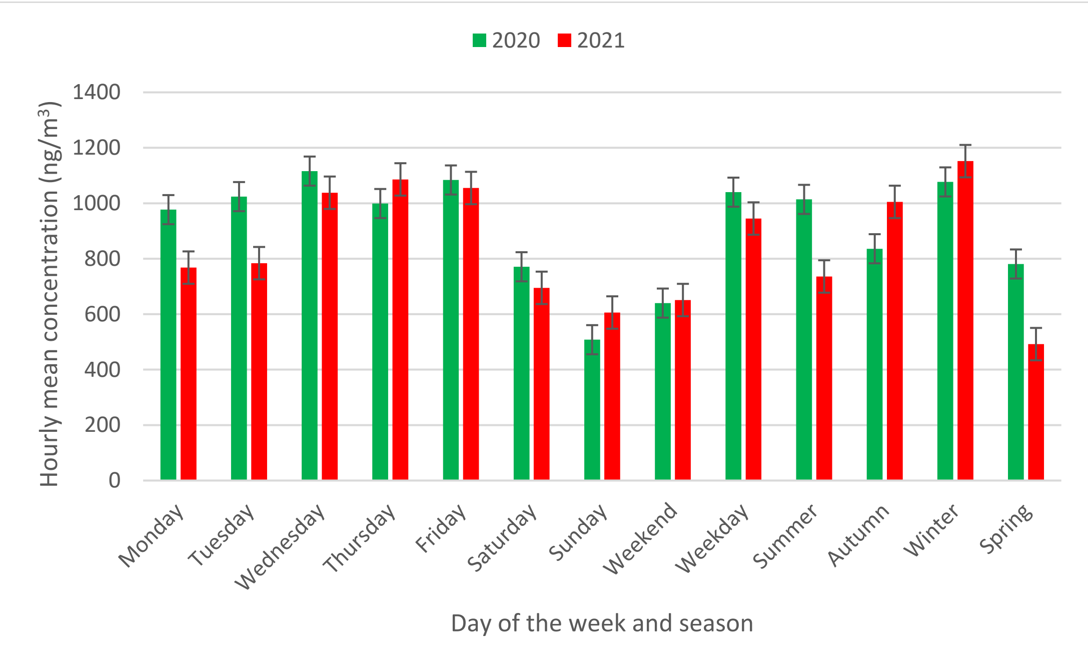

Figure 41. Temporal variations in black carbon annual mean concentrations. Error bars represent the standard errors of the mean.

3.2.8 Air quality index (AQI)

Air quality index (AQI) can be used as an indicator of the overall air quality of a given monitoring site. Auckland AQI model is based on the New South Wales/Victoria method as described by Reid and Rolfe (2014). It is calculated from the air quality data collected at Queen Street, Takapuna, Penrose, Glen Eden, Patumahoe, Henderson and Pakuranga. For each of the six criteria pollutants (PM_{10}, $PM_{2.5}$, NO_2, CO, SO_2 and O_3), AQI is the data value expressed as a percentage of the level specified by the NESAQ or the Auckland target ($PM_{2.5}$ only). A value of 100 represents the value of the standard or target has been reached. AQI is calculated using the formula below;

$$AQI = 100 \ * \ \text{Highest}\left\{\frac{PM_{10}}{50}, \frac{PM_{2.5}}{25}, \frac{NO_2}{200}, \frac{CO}{10}, \frac{SO_2}{350}, \frac{O_3}{150}\right\}$$

For example, if the measured pollutant 1-hour average concentration is 35 µg/m^3, and the goal/ NESAQ value is 50 µg/m^3, then AQI value is 70% [i.e., $\frac{35}{50}$ * 100]. A monitoring site's AQI for a given hour is the highest of all AQI values. AQI ratings or classes are as follows; 0-33 (very good), 34-66 (Good), 67-99 (Fair), 100-149 (Poor), 150-199 (Very poor), and 200+ (Hazardous).

The average AQI recorded in Auckland in 2021 slightly decreased by 0.34% compared to 2020 (from 26.39 ± 9.99% to 26.30 ± 11.31%) ($p<0.05$). Henderson's monitoring site had the lowest annual AQI mean of 22%, while Queen Street recorded the highest mean of 37%. Besides Queen Street and Henderson, all the monitored sites recorded annual mean AQI lower than the previous year. Apart from Henderson, all the differences in annual AQI levels observed at the sites were statistically significant ($p<0.05$) (See Appendix C). Figure 42 presents the variation of AQI annual mean levels for the six monitoring sites.

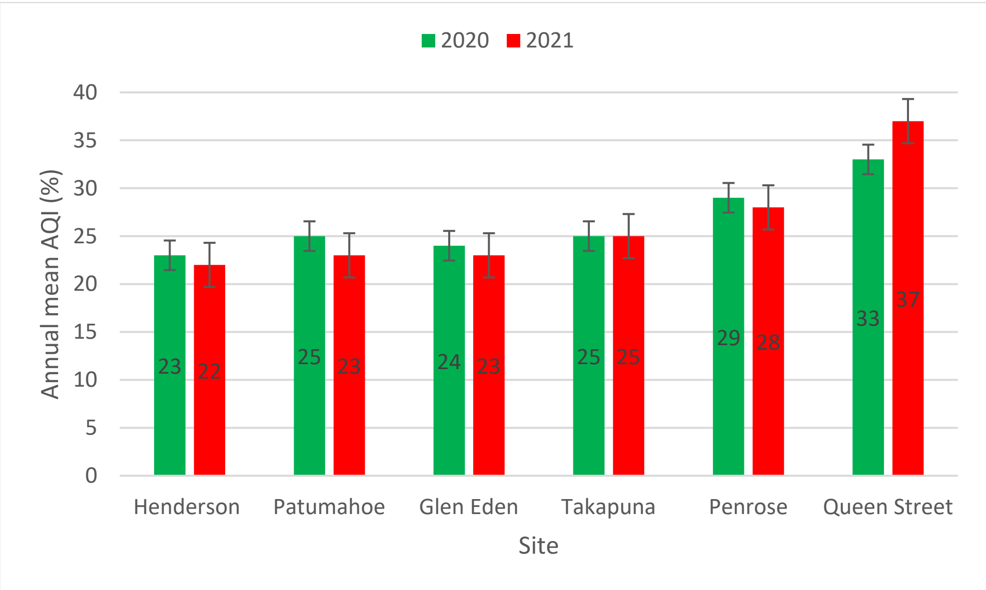

Figure 42. AQI annual mean levels for six sites – arranged in increasing order from left to right. Error bars represent the standard errors of the mean.

Weekday AQI levels are identical to weekend levels. The highest AQI levels were recorded in summer (See Appendix J). The spikes in average AQI values for 2021 summer and 2020 winter could be due to increased source contribution from motor vehicles and home heating, respectively. AQI levels appeared to increase later in the week with the highest levels mostly on Wednesday to Friday (See Figure 43). Unlike the previous year, there was little variation in the mean hourly AQI levels across the hours of the day (Figure 44).

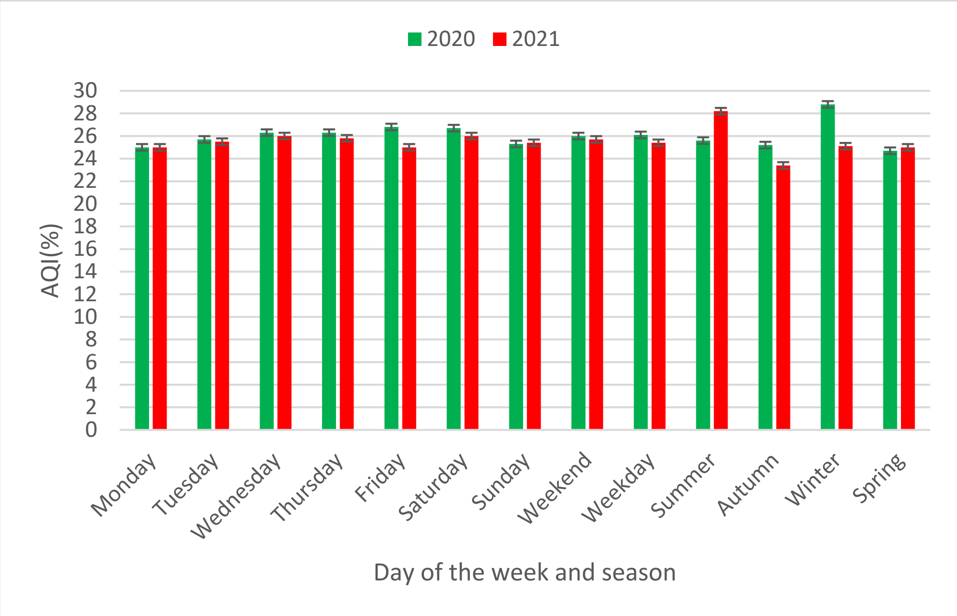

Figure 43. Temporal variations in Auckland's AQI annual mean concentrations. Error bars represent the standard errors of the mean.

Figure 44. Time variations in Auckland's AQI hourly mean concentrations. Error bars represent the standard errors of the mean.

3.2.9 Volatile organic compounds (VOCs)

All average BTEX concentrations in 2021 from the three monitoring sites were either below the limit of detection, or where available, were below ambient air quality guidelines. The average benzene, toluene and, m-, p-Xylene concentrations in 2021 at all the sites were less than the previous year. As shown in Figure 45, the average benzene concentration at Crowhurst Street was 2.4 µg/m³, and this is below the Auckland Unitary Plan annual target of 3.6 µg/m³. There are no formal guidelines or standards in New Zealand for toluene, ethylbenzene, and xylene concentrations in ambient air.

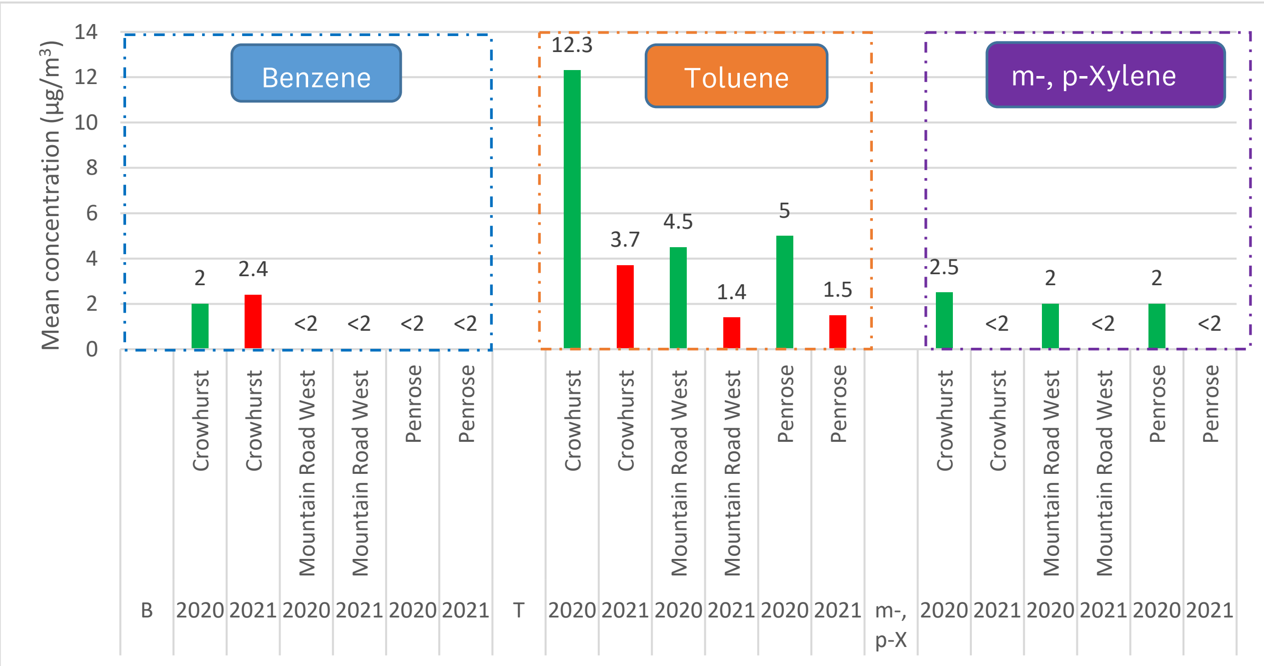

Figure 45. Average concentrations of benzene, toluene and, m-, p-Xylene (for 2020 and 2021).

Results below Limit of Detection (LOD) are displayed as <2. Red bars represent 2021 data. Note due to COVID-19 lockdown in 2021. Passive sampling badges were exposed for only two months instead of three.

3.2.10 Total Suspended particulate (TSP) and lead (Pb) content

Penrose's TSP mean in 2021 decreased by 11.6% compared to 2020 (from 14.7 ± 2.89% to 13 ± 1.74 µg/m³) ($p<0.05$). As at the time of writing this report, the results from the lead (Pb) content analysis at the Hills Laboratory had not arrived. Therefore, a comparison with the 2020 average Pb concentration of 0.0023 µg/m³ could not be conducted.

3.2.11 Impact of COVID-19 restrictions on Auckland's air quality

Auckland came under the level 4 lockdown from midnight 17 August and moved to level 3 from midnight 21 September 2021. The government changed the alert level to level 3 step 1 (3.1) at midnight 5 October and then to level 3 step 2 (3.2) at midnight 9 November. Assessment of the impact of the restrictions on air quality was conducted by Xie (2021a, 2021b) and Boamponsem (2021).

Boamponsem (2021) analysed the mean hourly concentration of pollutants during COVID-19 alert level 4, week one lockdown (18-24 August 2021), and compared with 2020 lockdown (26 March-1 April 2020) and mean concentrations of the previous two years (18-24 August 2019 and 2020). Xie (2021b) analysed pollutants concentrations averaged over periods of pre-level 4 (1-17 August 2021), level 4 (18 August-21 September 2021), level 3 (22 September-5 October 2021), level 3.1 (6 October-9 November 2021), level 3.2 (10-24 November 2021) and normal (10-24 November). To adjust for the influence of meteorological conditions, Xie (2021b) also compared pollutants concentrations averaged over the same period (e.g., 18 August-21 September for level 4) of previous years (up to five years from 2016).

They found that monitored air pollutants concentrations responded to these changes in restriction levels. Here are the key findings:

- The extent of the impact of the COVID-19 alert level 4 lockdown (week one) depended on the contaminant and the monitoring site. Concentrations of particulate matter (PM_{10} and $PM_{2.5}$), NO_2, and ozone were significantly lower than the previous two years' average.
- Generally, average concentrations of particulate matter, ozone (O_3), and black carbon were slightly higher than the 2020 week one lockdown. However, the average concentration of NO_2 was slightly lower than the 2020 week one lockdown.
- There was no clear impact of the lockdown on SO_2, and CO concentrations.
- During level 4 lockdown, across the region, NO_2 concentrations which are primarily associated with vehicle emissions, dropped sharply by 43% of normal levels (compared to averages of previous five years data) and remained below normal values in level 3.2 (Xie, 2021b)
- PM_{10} and $PM_{2.5}$ concentrations did not show a consistent pattern due to the prevalence of non-traffic sources. The city centre (Queen Street) site showed a marked drop in NO_2 by 58% in level 4 and stayed below normal values in level 3.2 (Xie, 2021b).

4 Conclusions

Auckland Council is responsible for the management of air quality in the region. The council is required to monitor air quality under the Resource Management Act 1991 and the National Environmental Standards for Air Quality (NESAQ). To achieve this, the council continuously collects air quality data to assess compliance and provide information to aid policy development and evaluation. Auckland Council is required to publicly report any breach. The data the council collects enables us to quantify ambient air quality in the region and note 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 2021 data and assesses it against the relevant National Environmental Standard for Air Quality (NESAQ), Auckland Unitary Plan air quality target, and the revised 2021 WHO air quality guidelines.

Here are the key findings:

- No breach of national air quality standards occurred in 2021.
- The average PM_{10} concentration of Auckland in 2021 increased by 1.3% compared to 2020. However, this increase did not exceed the new 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 annual guideline by 24%.
- The average $PM_{2.5}$ concentration of Auckland in 2021 increased by 6.7% compared to 2020. This increase was over the 2021 WHO air quality guideline of 5 $\mu g/m^3$. The annual $PM_{2.5}$ averages for Penrose, Takapuna, and Queen Street sites were higher than the more stringent WHO air quality guideline. Auckland's target for 24-hour average PM2.5 was exceeded on one occasion during winter at Pakuranga
- Overall, concentrations of particulate matter peak in the afternoon and night hours and mostly increase later in the week with the highest concentrations typically occurring on Wednesday to Friday.
- The annual mean NO_2 concentration for Auckland in 2021 is the lowest recorded since 2006. The annual mean concentration significantly decreased by 16.7% compared to 2020. However, Auckland's overall annual average NO_2 concentration exceeded the 2021 WHO air quality guideline of 10 $\mu g/m^3$. On 26 occasions, the 24-hour average NO_2 levels in Auckland exceeded the 2021 WHO air quality guideline.
- The average SO_2 concentration of Auckland in 2021 significantly increased by 39% compared to 2020. As found in 2020, the annual SO_2 mean concentration at Customs Street was higher than at the Penrose site.
- As in the previous year, the highest air particulates and NO_2 levels were recorded at the city centre sites (Queen Street and Customs Street).

- The average CO concentration at the Khyber Pass Road site decreased by 8.3% compared to 2020. There was no exceedance of the 2021 WHO air quality guideline for CO.
- The average O_3 concentration at Patumahoe in 2021 decreased by 8.9% compared to 2020. Though there were occasional hourly spikes in O_3 mean concentrations, none was above the 2021 WHO air quality guidelines.
- All average BTEX concentrations in 2021 from the three monitoring sites were either below the limit of detection or where available, were below ambient air quality guidelines.
- In general, most air pollutants peak in the morning and late afternoon probably due to traffic, with the increase between 7am and 9am, and 5pm and 9pm.
- All key air pollutants were highest in winter probably due to the use of solid fuels for home heating.
- Except for O_3, weekday (Monday to Friday) air pollutants concentrations are slightly higher than weekends (Saturday and Sunday) due to increased traffic.
- There was no clear impact of the lockdown on SO_2, and CO concentrations.
- During level 4 lockdown, across the region, NO_2 concentrations which are primarily associated with vehicle emissions, dropped sharply by 43% of normal levels (compared to averages of the previous five years' data) and remained below normal values in level 3.2. PM_{10} and $PM_{2.5}$ concentrations did not show a consistent pattern due to the prevalence of non-traffic sources. The city centre (Queen Street) site showed a marked drop in NO_2 by 58% in level 4 and stayed below normal values in level 3.2.

5 References

Ancelet, T., Davy, P., Trompetter, W. and Markwitz, A. (2014). Sources of particulate matter pollution in a small New Zealand city. *Atmospheric Pollution Research* 5, 572-580.

Auckland Council Research and Evaluation Unit (2021). The health of Tāmaki Makaurau / Auckland's natural environment in 2020. Available at https://www.knowledgeauckland.org.nz/publications/te-oranga-o-te-taiao-o-t%C4%81maki-makaurau-the-health-of-t%C4%81maki-makaurau-auckland-s-natural-environment-in-2020-a-synthesis-of-auckland-council-s-state-of-the-environment-reporting/.

Baldwin, N., Gilani, O. Raja, S. Batterman, S., Ganguly, R. Hopke, P., Berrocal, V., Robins, T. and Hoogterp, S. (2015). Factors affecting pollutant concentrations in the near-road environment. *Atmospheric Environment* 115, 223-235.

Bluett, J, Smit, R, and Aguiar, M. (2016). Understanding trends in roadside air quality, (September), 171.

Boamponsem, L (2021). Auckland air quality report – August 2021. Available at https://www.knowledgeauckland.org.nz/publications/auckland-air-quality-report-august-2021/

Boamponsem, L.K, De Freitas, C.R. and Williams, D. (2017). Source apportionment of air pollutants in the Greater Auckland Region of New Zealand using receptor models and elemental levels in the lichen, *Parmotrema reticulatum*. Atmospheric Pollution Research, 8(1), 101-113.

Bond, Tami, S. Doherty, D. Fahey, P. Forster. et al., (2013). Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres*, 118, 5380-5552.

Carslaw, David, and K. Ropkins. (2012). Openair – An R Package for Air Quality Data Analysis. Environmental Modelling & Software 27-28 (January), 52-61.

Carslaw, K. S., O. Boucher, D. V. Spracklen, G. W. Mann, J. G. L. Rae, S. Woodward, and M. Kulmala. (2010). A Review of Natural Aerosol Interactions and Feedbacks within the Earth System. *Atmospheric Chemistry and Physics* 10 (4): 1701-37. https://doi.org/10.5194/acp-10-1701-2010

Crimmins, P (2018). Auckland Air Emissions Inventory 2016 – industry. Auckland Council technical report, TR2018/019.

Davy, P and Trompetter, W. (2021). The rise of non-tailpipe motor vehicle emissions in a southern hemisphere city. *Air Quality and Climate Change* Volume 55 No.1, 44-45.

Davy, P. (2021) Composition and long-term trends for Biomass combustion contributions to urban air pollution in Auckland. Biomass Burning/Health SIG Virtual Workshop, 16 November 2021.

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

Davy, P., Ancelet, T., Trompetter, W. and Markwitz, A. (2016). Source apportionment and trend analysis of air particulate matter in the Auckland Region, Wellington: GNS Science Consultancy Report 2016/194.

Chappell, P.R. (2013). The Climate and Weather of Auckland, second ed. from. https://niwa.co.nz/static/Auckland%20ClimateWEB.pdf , (Accessed: 1 March 2022)

Dirks, Kim, J. Scarfe, N. Talbot, R. Marshall, and J. Salmond. (2017). A Statistical Analysis of the Relationship between Brown Haze and Surface Air Pollution Levels on Respiratory Hospital Admissions in Auckland, New Zealand. Climate 5 (4).

EFCA. (2019). Ambient ultrafine particles: evidence for policy makers. White paper prepared by the 'Thinking outside the box' team, European Federation of Clean Air and Environmental Protection Associations, Version 1, 25 October 2019. Available at https://efca.net/files/WHITE%20PAPER-UFP%20evidence%20for%20policy%20makers%20(25%20OCT).pdf

EPA Victoria (2018). Air pollution in Victoria – a summary of the state of knowledge August 2018. Available at www.epa.vic.gov.au . (Accessed: 18 January 2022)

European Union (2021). Scientific Committee toolbox. Available at https://ec.europa.eu/health/scientific_committees/opinions_layman/en/indoor-air-pollution/glossary/index.htm#abc. (Accessed: 18 January 2022)

Font, Anna, T. Baker, I. Mudway, E. Purdie, C. Dunster, and G. Fuller. (2014). Degradation in Urban Air Quality from Construction Activity and Increased Traffic Arising from a Road Widening Scheme. Science of The Total Environment 497-498 (November): 123-32.

Janssen, NA, Nicole, G. Hoek, M. Simic-Lawson, et al., (2011). Black Carbon as an Additional Indicator of the Adverse Health Effects of Airborne Particles Compared with PMx. *Environmental Health Perspectives* 119 (12): 1691-99. https://doi.org/10.1289/ehp.1003369 .

Kuschel, G, Metcalfe, J, Wilton, E, Guria, J, Hales, S, Rolfe, K, and Woodward, A. (2012). Updated Health and Air Pollution in New Zealand Study Volume 1: Summary report (Vol. 1). Available at https://environment.govt.nz/publications/updated-health-and-air-pollution-in-new-zealand-study-2012-technical-report/

Lai, HK, Berry, SD, Verbiest, MEA, Tricker, PJ, Atatoa Carr, PE, Morton, SMB, and Grant, CC. (2017). Emergency department visits of young children and long-term exposure to neighbourhood smoke from household heating – The Growing Up in New Zealand child cohort study. *Environmental Pollution*, 231, 533-540. https://doi.org/10.1016/j.envpol.2017.08.035.

Longely, Ian, J. Salmond, K. Dirks, D. Welch, D. Shepherd, S. Grange, G. Olivares, G. Miskell. (2014). Personal Exposure to Noise and Air Pollution (PENAP) in the Queen Street Valley, Auckland. Auckland Council technical report, TR2014/036.

Metcalfe, J., Wickham, L and Sridhar, S (2018). Auckland air emissions inventory 2016 – home heating. Prepared by Emission Impossible Ltd for Auckland Council. Auckland Council technical report, TR2018/018.

MfE and Stats NZ (2021). New Zealand's Environmental Reporting Series: Our air 2021. Available at www.environment.govt.nz, (Accessed: 18 January 2022)

Ministry for the Environment (MfE). (2009). Good-Practice Guide for Air Quality Monitoring and Data Management. Ministry for the Environment report, April 2009.

Ministry for the Environment (MfE). (2014). 2011 user's guide to the revised National Environmental Standards for Air Quality: Updated 2014.

Ministry for the Environment and Statistics New Zealand (2014). New Zealand's Environmental Reporting Series: 2014 Air domain report.

Moore, C (2019). Wark worth to Wells ford – Air Quality Assessment, July 2019. Jacobs New Zealand Limited.

New South Wales Ambient Air Quality Annual Compliance Report 2020 (2021), State of NSW and Department of Planning, Industry and Environment.

Payne, RJ, Dise, NB, Field, CD, Dore, AJ, Caporn, SJM, and Stevens, CJ. (2017). Nitrogen deposition and plant biodiversity: past, present, and future. https://doi.org/10.1002/fee.1528.

Peeters, S. (2018). Auckland air emissions inventory 2016 – sea transport. Prepared by M&P Consulting Limited for Auckland Council. Auckland Council technical report, TR2018/017.

Petersen, J and Gillies, M. (2014). The ambient air quality monitoring network in the Auckland region 2013. Auckland Council technical report, TR2014/035.

Petersen, J and Harper, B. (2005). Auckland Region Air Quality Monitoring Network. Auckland Regional Council, technical publication, TP296, 2005.

Reid, N. (2014). Benzene, 1,3 butadiene and other volatile organic compounds in Auckland, 2001-2013. Auckland Council technical report, TR2014/037.

Reid, N and Rolfe, K. (2014). An air quality index for Auckland: review of some international techniques and example data. Auckland Council technical report, 2014/031.

Rolfe, K. (2013). Review of Auckland's ambient air quality monitoring programme 2012. Prepared by Kevin Rolfe and Associates Ltd for Auckland Council. Auckland Council working report, WR2013/010. Draft, February 2013.

Sridhar, S. (2013). Auckland's air quality monitoring plan. Prepared by Emission Impossible Ltd for Auckland Council. Auckland Council technical report, TR2013/053.

Sridhar, S and Metcalfe, J. (2019). Auckland air emissions inventory 2016 – transport (revised). Prepared by Emission Impossible Ltd for Auckland Council. Auckland Council technical report, TR2018/016-2.

Talbot, N and Crimmins, P. (2020). Trends in Auckland's air quality 2006-2018. Auckland Council technical report, TR2020/004.

Talbot, N., Reid, N and Crimmins, P. (2017). Auckland ambient air quality trends for $PM_{2.5}$ and PM_{10} – 2006-2015. Auckland Council technical report, TR2017/029.

Talbot, N and Lehn, R. (2018). The impacts of transport emissions on air quality in Auckland's city centre. Auckland Council technical report, TR2018/028.

United States Environmental Protection Agency (US EPA). (2008). Integrated Science Assessment (ISA) for Oxides of Nitrogen and Sulfur – Ecological Criteria (Final Report, Dec 2008). Washington, DC. Retrieved from https://www.epa.gov/isa/integrated-science-assessment-isa-oxides-nitrogen-oxides-sulfur-and-particulate-matter.

United States Environmental Protection Agency (US EPA). (2010). Integrated Science Assessment for Carbon monoxide. Available at https://www.epa.gov/isa/integrated-science-assessment-isa-carbon-monoxide. (Accessed: 18 January 2022)

United States Environmental Protection Agency (US EPA). (2013). Integrated Science Assessment for Ozone and Related Photochemical Oxidants. Federal Register (Vol. EPA 600/R-). Research Triangle Park, NC. Available at https://www.epa.gov/isa/integrated-science-assessment-isa-ozone-and-related-photochemical-oxidants. (Accessed: 18 January 2022)

United States Environmental Protection Agency (US EPA). (2017). Integrated Science Assessment for Sulfur Oxides – Health Criteria. Research Triangle Park, NC. Available at http://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=310044. (Accessed: 18 January 2022).

United States Environmental Protection Agency (US EPA). (2016). Integrated Science Assessment for Oxides of Nitrogen – Health Criteria. Available at https://www.epa.gov/isa/integrated-science-assessment-isa-nitrogen-dioxide-health-criteria (Accessed: 18 January 2022).

United States Environmental Protection Agency (US EPA). (2021). Particulate Matter (PM) Basics. Available at: https://www.epa.gov/pm-pollution/particulate-matter-pm-basics#PM . (Accessed: 17 January 2022).

US National Oceanic and Atmospheric Administration (2021). Relative Humidity (RH) – Definition. https://graphical.weather.gov/definitions/defineRH.html . (Accessed: 18 January 2022).

World Health Organization (WHO). (2013). WHO/Europe Air Quality – Review of Evidence on Health Aspects of Air Pollution – REVIHAAP Project: Final Technical Report.

World Health Organization (WHO). (2021). WHO global air quality guidelines: particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Available at https://apps.who.int/iris/handle/10665/345329, (Accessed: 18 January 2022).

Xie, S. (2021a). Auckland air pollution levels during COVID-19 restrictions in August-November 2021. Research and Evaluation Unit (RIMU), Auckland Council.

Xie, S (2021b). Auckland air pollution levels during COVID-19 restriction level 4 in August 2021 – week one. Research and Evaluation Unit, Auckland Council.

Xie, S, Crimmins, P , Metcalfe, J, Sridhar, S, Wickham, L and Peeters, S. (2019). Auckland air emissions inventory 2016. Auckland Council technical report, TR2019/024.

Xie, S., Sridhar, S and Metcalfe, J. (2014). Auckland air emissions inventory 2006. Auckland Council technical report, TR2014/015.

Xie, Shanju, P. Davy, Sridhar, S, and Metcalfe, J. (2016). Quantifying Trends of Particulate Matter Emissions from Motor Vehicles in Auckland (New Zealand Collection) – Informit. Air Quality and Climate Change 50 (2).

Xie, S, Sridhar, S, Metcalfe. J. (2014). Auckland Air Emissions Inventory 2006. Auckland Council technical report, TR2014/015.

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Appendix A: Sources of air contaminants in Auckland

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

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

Appendix B: Meteorological parameters descriptive statistics

Ambient temperature					
Site	Year	Annual mean (°C)	Std. Deviation	Significant?*	Change**
Glen Eden	2020	15.3	4.1	Yes	↑
	2021	15.6	4.3		
Penrose	2020	16.3	3.8	Yes	↑
	2021	16.7	3.9		
Queen Street	2020	16.9	3.6	Yes	↑
	2021	17.2	3.7		
Pakuranga	2020	16.0	4.5	Yes	↑
	2021	15.4	5.0		
Takapuna	2020	16.0	3.8	Yes	↑
	2021	16.2	3.9		
Henderson	2020	15.7	4.2	Yes	↑
	2021	16.0	4.3		
Auckland	2020	16.0	4.1	Yes	↑
	2021	16.2	4.2		
Ambient relative humidity					
Site	Year	Annual mean(%)	Std. Deviation	Significant? *	Change**
Glen Eden	2020	71.8	13.5	No	↗
	2021	72.6	13.0		
Penrose	2020	69.0	12.2	No	↗
	2021	69.8	12.3		
Queen Street	2020	61.3	12.3	No	↗
	2021	64.7	12.5		
Pakuranga	2020	69.8	13.4	Yes	↑
	2021	70.4	12.9		
Takapuna	2020	69.1	12.2	No	↗
	2021	70.4	11.9		
Henderson	2020	70.5	13.4	No	↗
	2021	71.3	13.4		
Auckland	2020	68.0	13.4	Yes	↑
	2021	69.4	13.0		

** ↑ Increased
↗ Increased but not significant
* Mean difference

Appendix C: Mean difference comparison between 2021 and 2020: t-test results

Site	Pollutant	p-value	F-value	Significant?	Change*
Penrose	SO_2	0.000	27.6	Yes	↑
Customs Street		0.000	352.6	Yes	↑
Auckland		0.000	82.0	Yes	↑
Customs Street	Black carbon	0.000	126.0	Yes	↓
Henderson		0.000	51.7	Yes	↑
Auckland		0.000	54.3	Yes	↓
Khyber Pass Road	CO	0.000	80.5	Yes	↓
Patumahoe	O_3	0.388	0.7	No	↘
Patumahoe	NO_2	0.367	0.8	No	↗
Penrose		0.000	22.8	Yes	↓
Queen Street		0.000	65.3	Yes	↓
Customs Street		0.000	634.0	Yes	↓
Glen Eden		0.464	0.5	No	↗
Khyber Pass Road		0.000	450.6	Yes	↓
Henderson		0.000	31.6	Yes	↓
Takapuna		0.541	0.4	No	↗
Auckland		0.000	1955.1	Yes	↓
Patumahoe	PM_{10}	0.002	9.3	Yes	↓
Penrose		0.001	11.2	Yes	↓
Queen Street		0.000	352.9	Yes	↑
Glen Eden		0.018	5.6	Yes	↓
Pakuranga		0.000	16.9	Yes	↑
Papatoetoe		0.000	88.8	Yes	↑
Khyber Pass Road		0.750	0.1	No	↘
Henderson		0.000	34.5	Yes	↑
Takapuna		0.014	6.0	Yes	↑
Auckland		0.000	274.8	Yes	↓
Queen Street	$PM_{2.5}$	0.000	400.4	Yes	↑
Penrose		0.007	7.2	Yes	↓
Patumahoe		0.000	52.8	Yes	↑
Takapuna		0.000	48.7	Yes	↑
Auckland		0.000	403	Yes	↑
Patumahoe	AQI	0.000	83.0	Yes	↓
Penrose		0.000	50.4	Yes	↓
Queen Street		0.000	87.6	Yes	↑
Glen Eden		0.001	10.4	Yes	↓
Henderson		0.000	58.9	Yes	↓
Takapuna		0.572	0.3	No	↗
Auckland		0.000	156.2	Yes	↓
Newmarket and Penrose	Benzene, Toluene and m-, p-Xylene	n/a	n/a	n/a	↓

Site	Pollutant	p-value	F-value	Significant?	Change*
Penrose	TSP	n/a	n/a	n/a	↓
*	↓	Decreased			
	↑	Increased			
	↗	Increased but not significant			
	↘	Decreased but not significant			
	n/a	Not applicable			

Appendix D: Calendar plots for PM_{10} 24 hour mean concentration

(The colours represent four categorical scale (μg/m³) as: lowest, low, high, and highest)

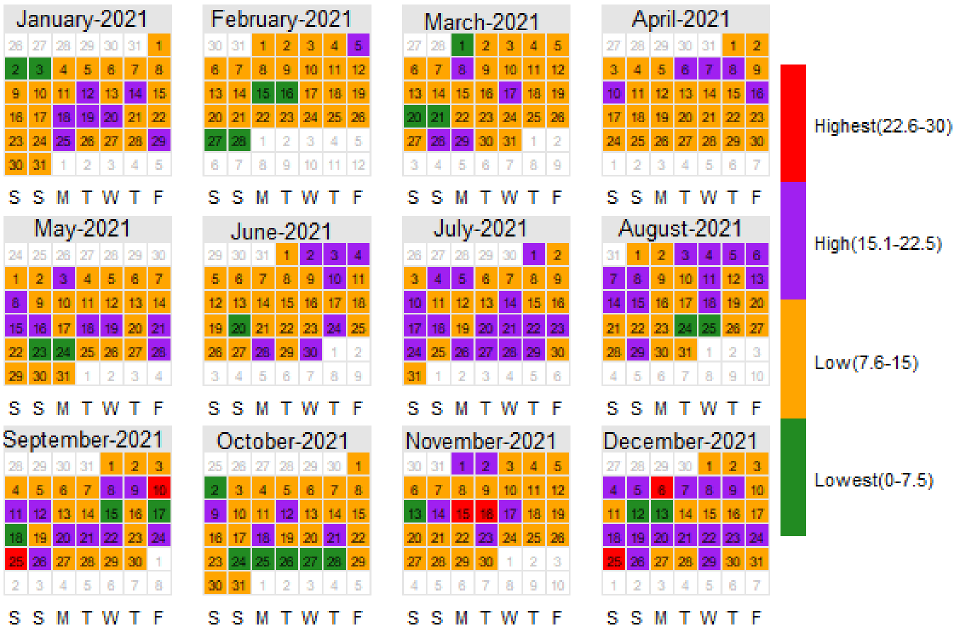

Figure D1. Calendar plot for PM_{10} concentrations in 2021 – nine sites combined.

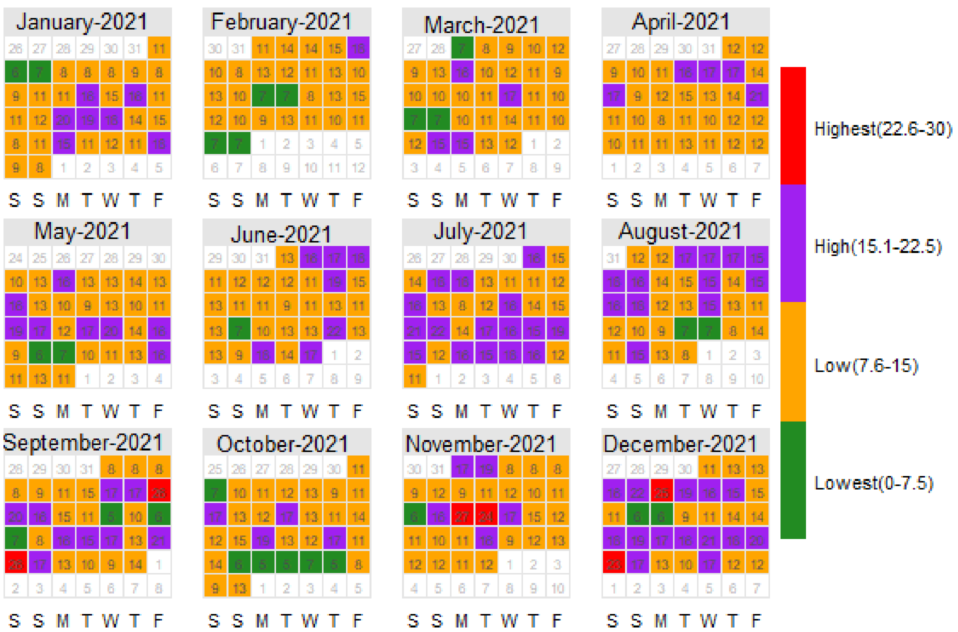

Figure D2. Calendar plot for PM_{10} concentrations in 2021 (nine sites combined). The numbers show the PM_{10} concentration in μg/m³.

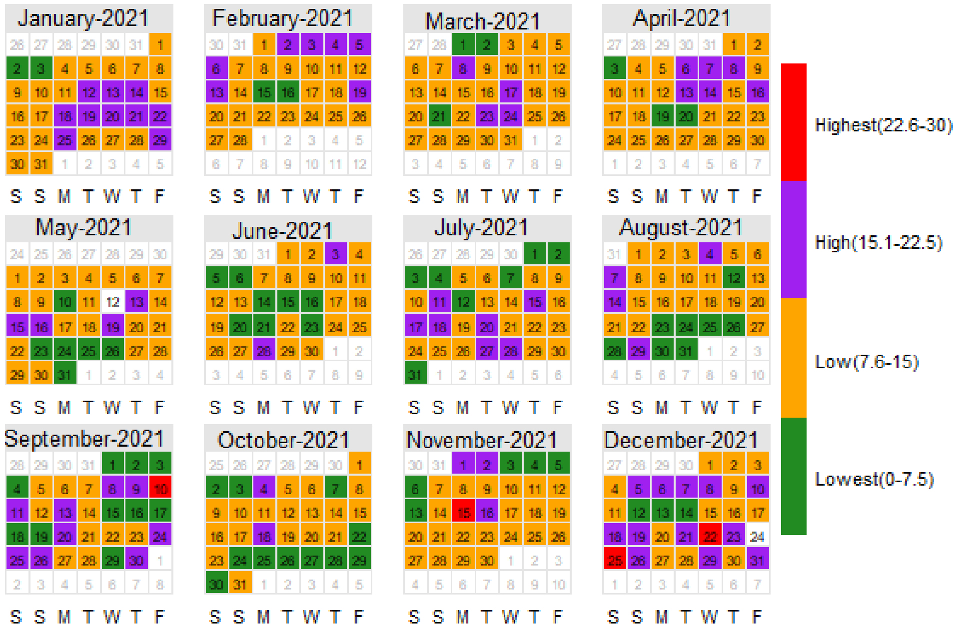

Figure D3. Calendar plot for PM_{10} concentrations in Patumahoe.

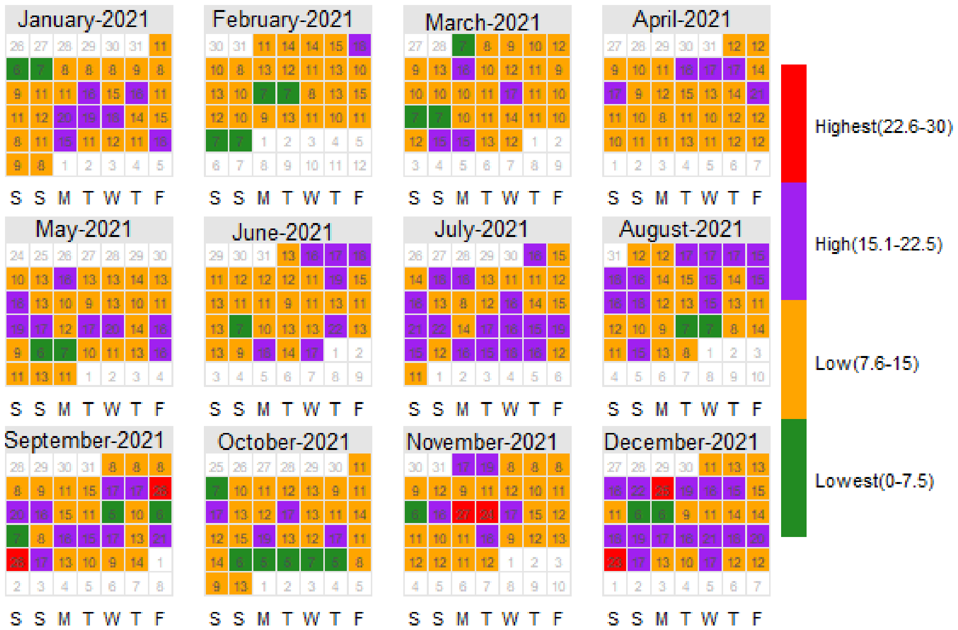

Figure D4. Calendar plot for PM_{10} concentrations in Patumahoe site. The numbers show the PM_{10} concentration in µg/m^3.

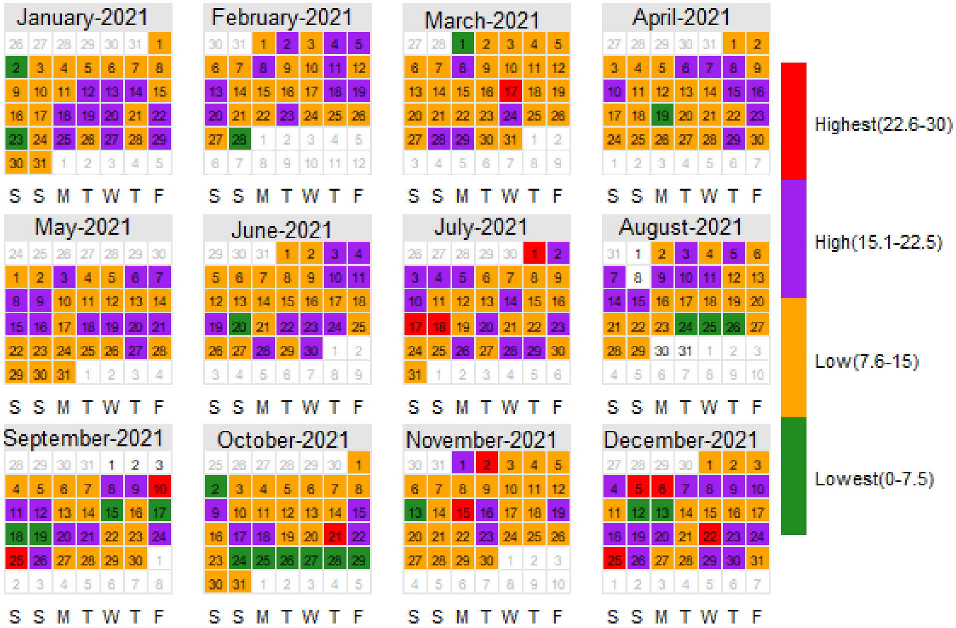

Figure D5. Calendar plot for PM_{10} concentrations in Penrose.

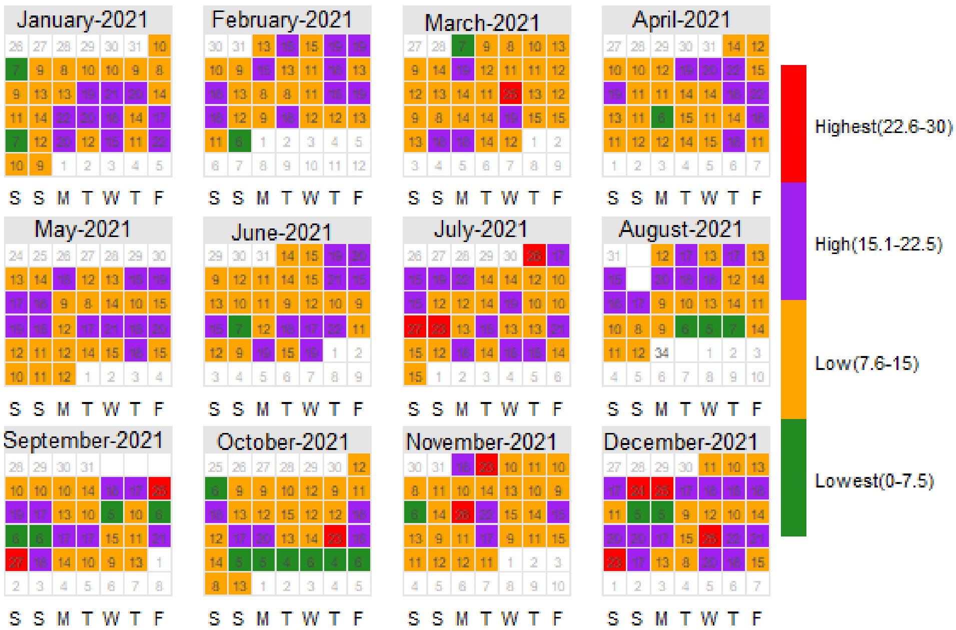

Figure D6. Calendar plot for PM_{10} concentrations in Penrose site. The numbers show the PM_{10} concentration

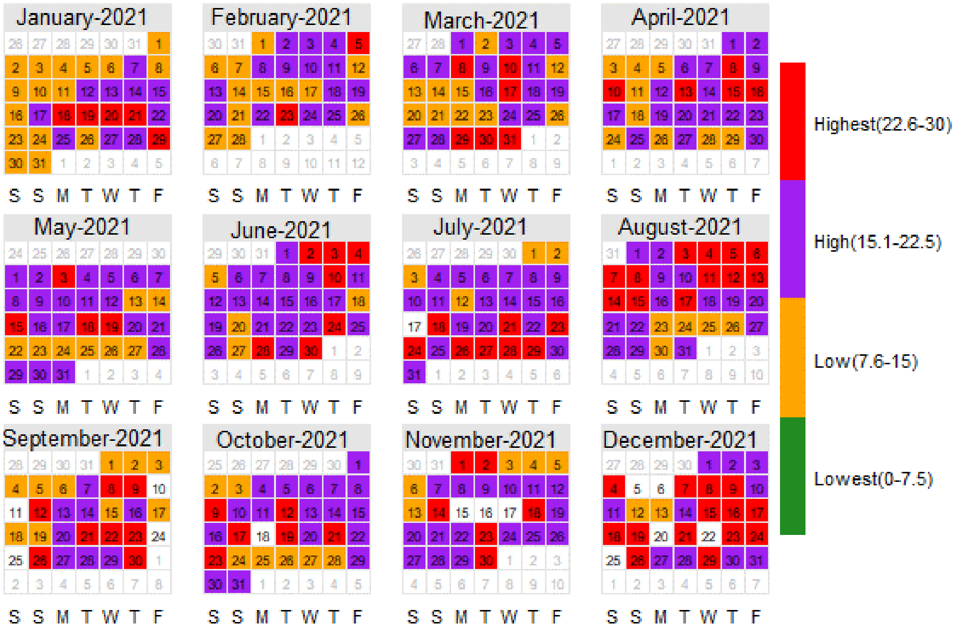

Figure D7. Calendar plot for PM_{10} concentrations in Queen.

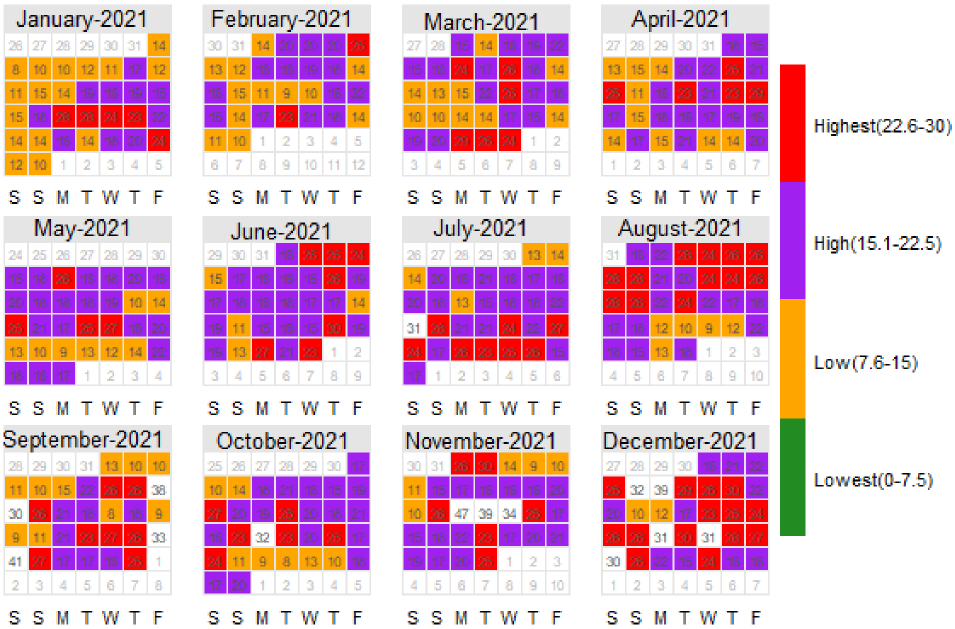

Figure D8. Calendar plot for PM_{10} concentrations in Queen site. The numbers show the PM_{10} concentration

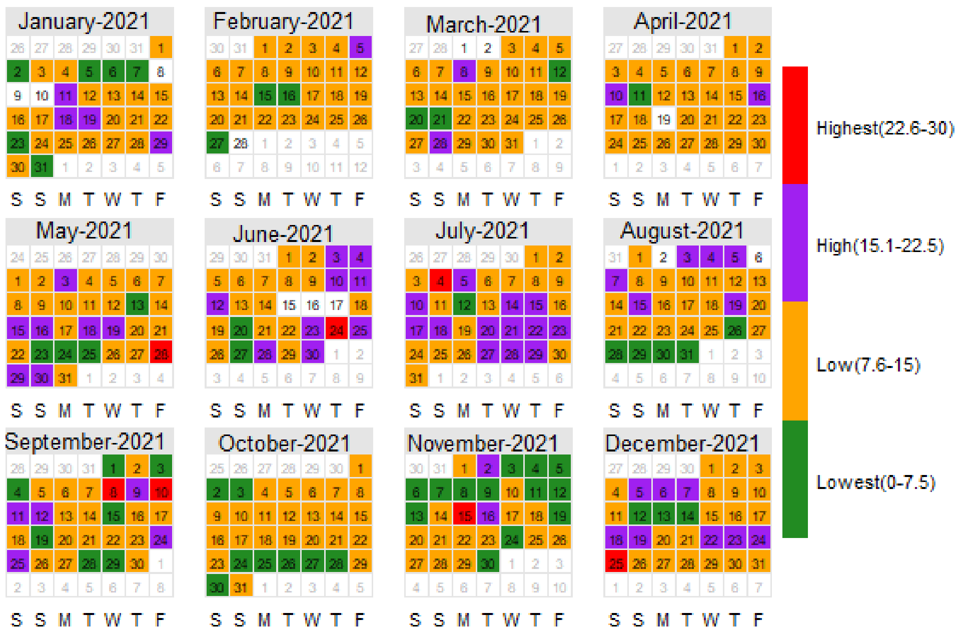

Figure D9. Calendar plot for PM_{10} concentrations in Glen Eden site.

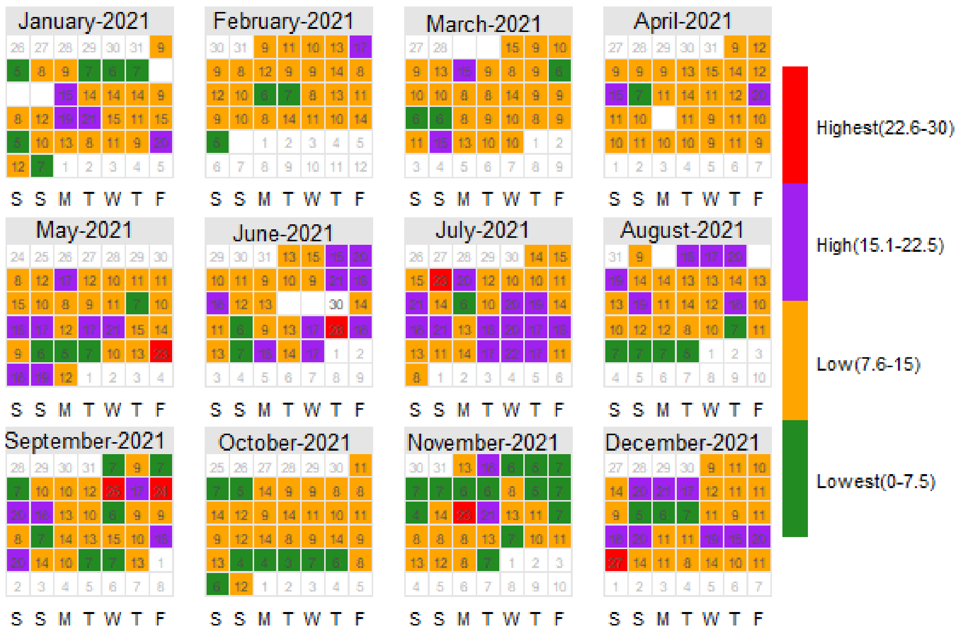

Figure D10. Calendar plot for PM_{10} concentrations in Glen Eden site. The numbers show the PM_{10} concentration in $\mu g/m^3$.

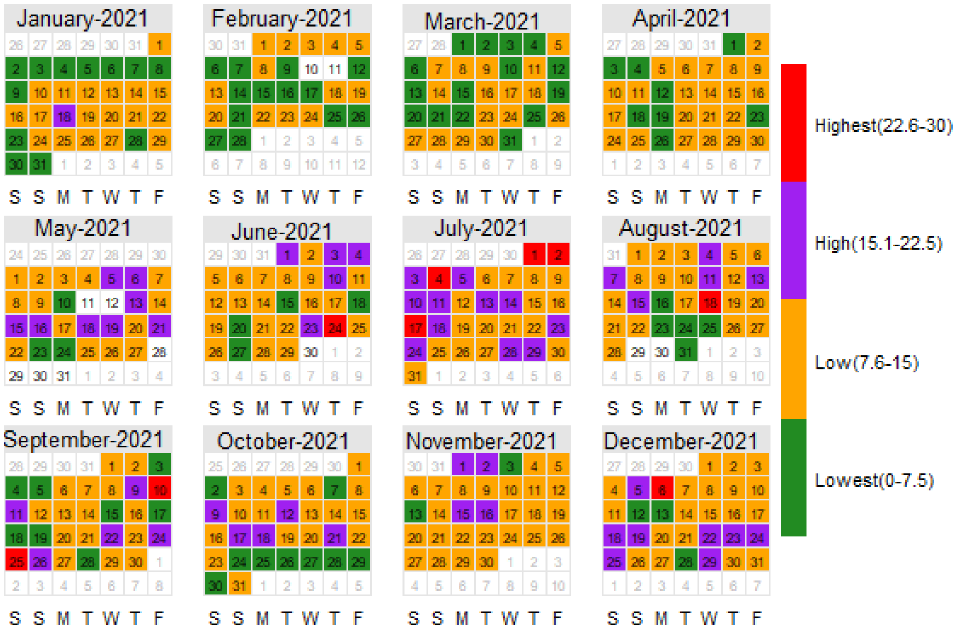

Figure D11. Calendar plot for PM_{10} concentrations in Pakuranga.

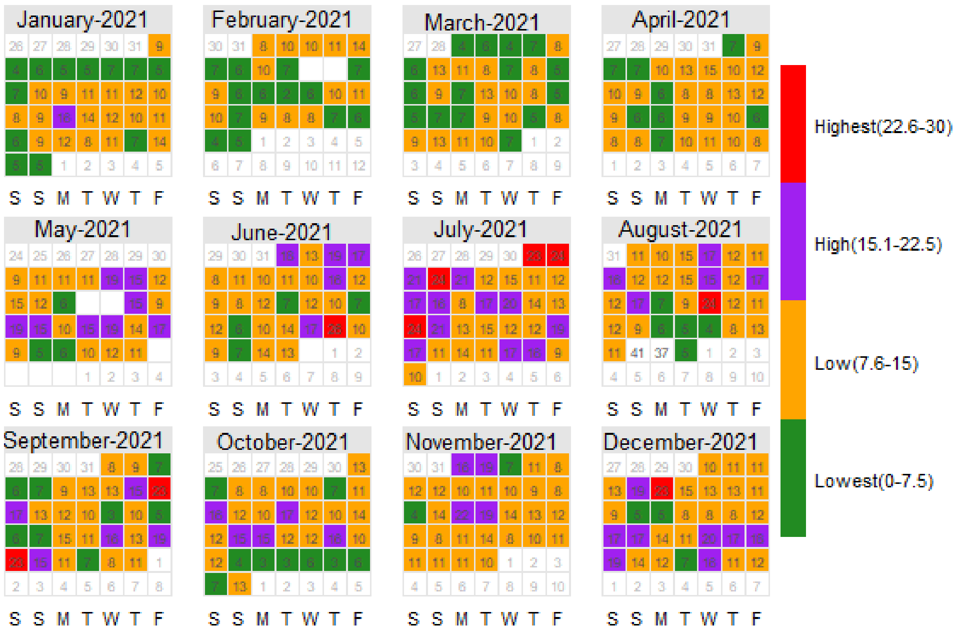

Figure D12. Calendar plot for PM_{10} concentrations in Pakuranga site. The numbers show the PM_{10} concentration

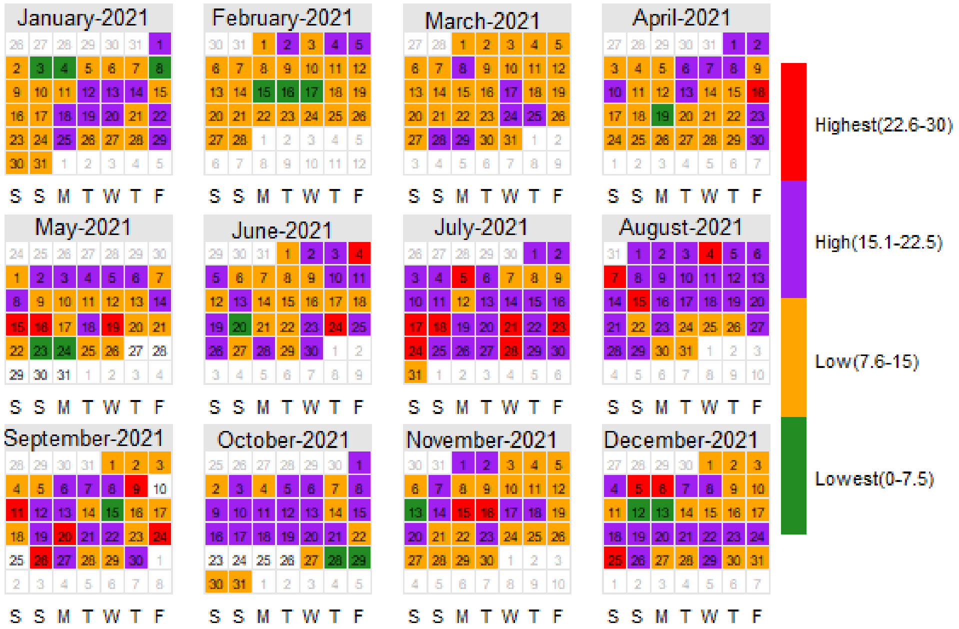

Figure D13. Calendar plot for PM_{10} concentrations in Papatoetoe

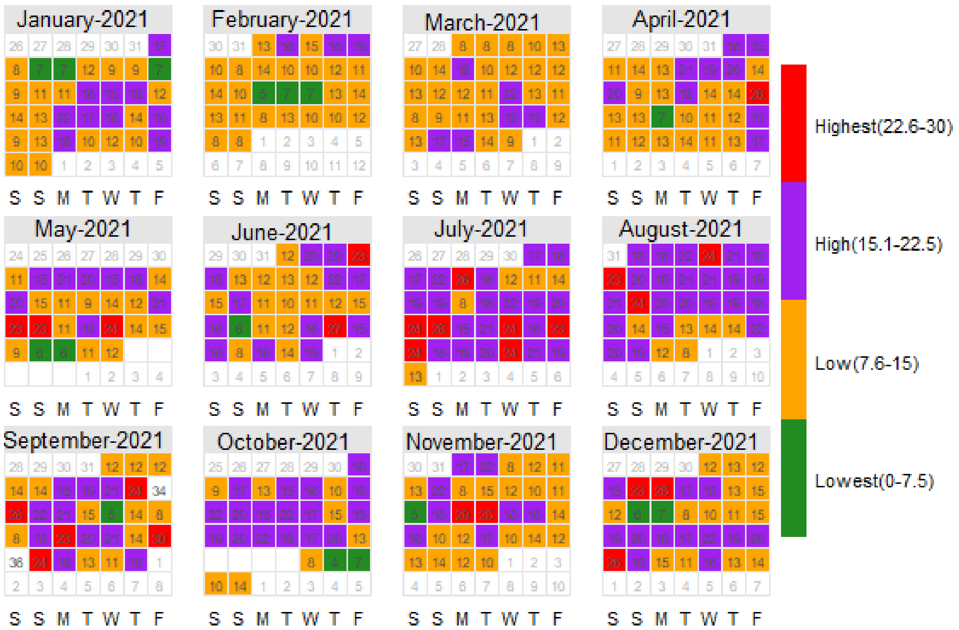

Figure D14. Calendar plot for PM_{10} concentrations in Papatoetoe site. The numbers show the PM_{10} concentration

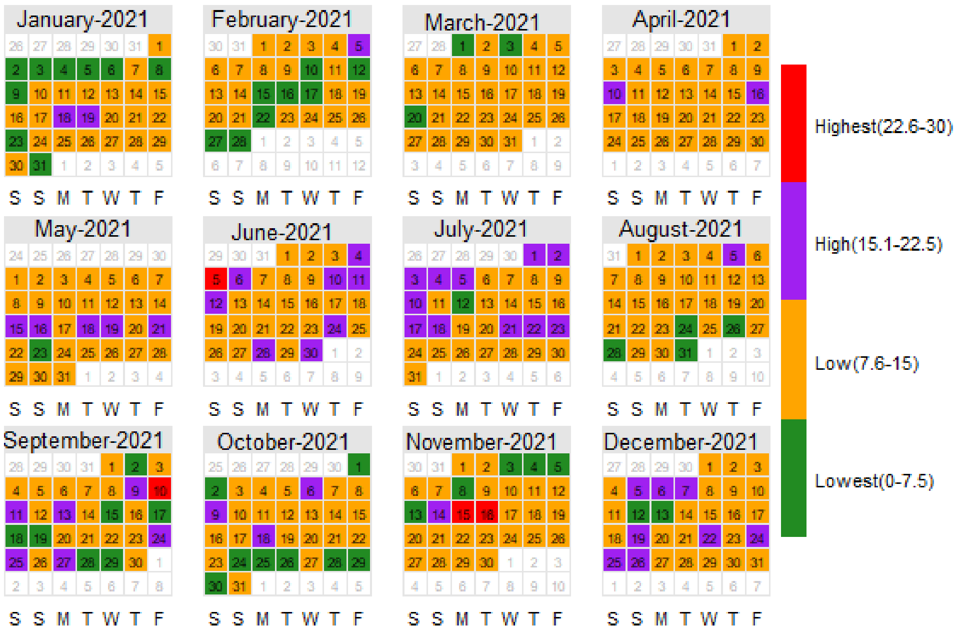

Figure D15. Calendar plot for PM_{10} concentrations in Henderson.

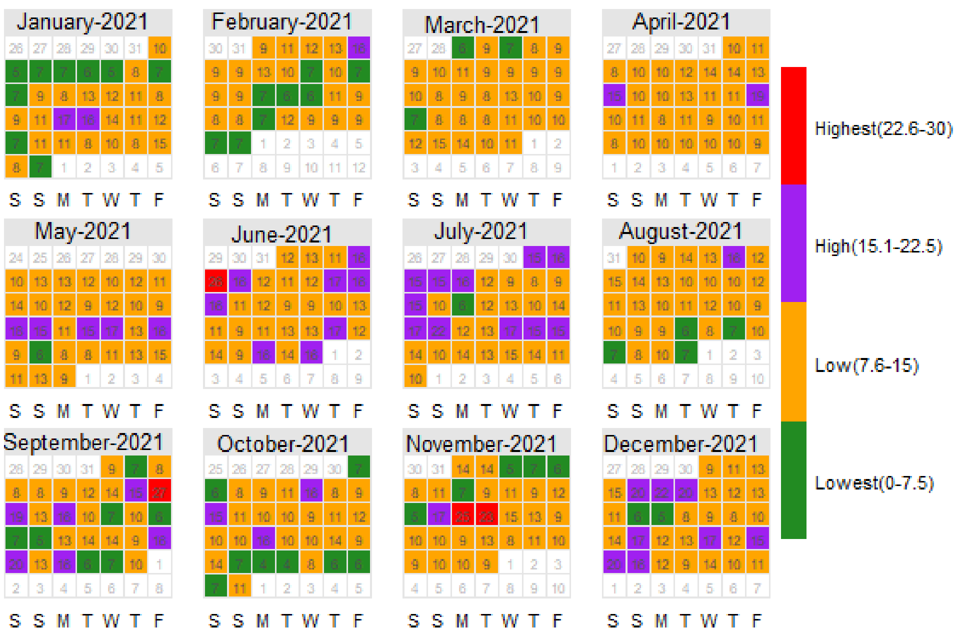

Figure D16. Calendar plot for PM_{10} concentrations in Henderson site. The numbers show the PM_{10} concentration

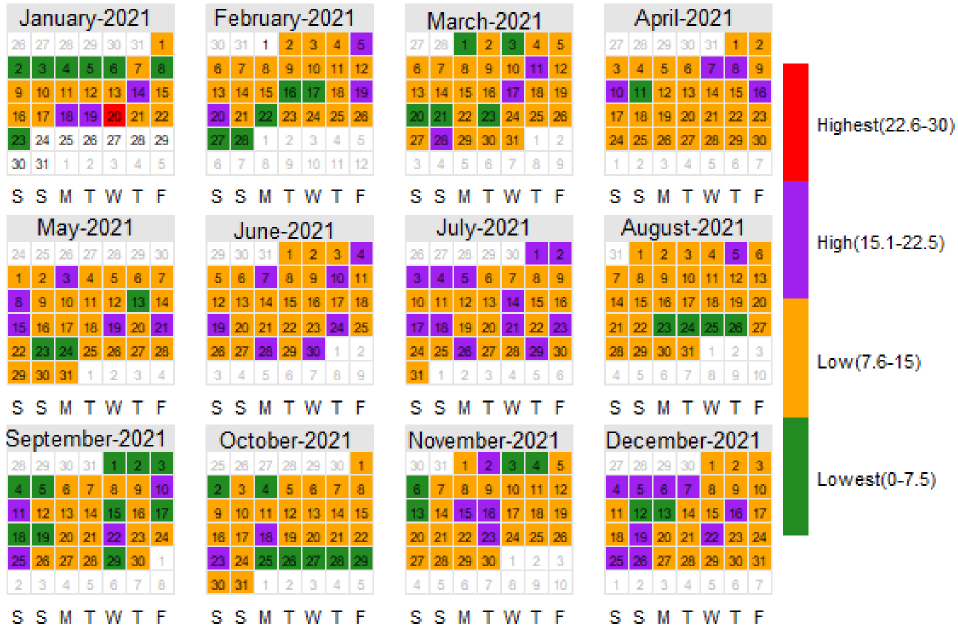

Figure D17. Calendar plot for PM_{10} concentrations in Takapuna.

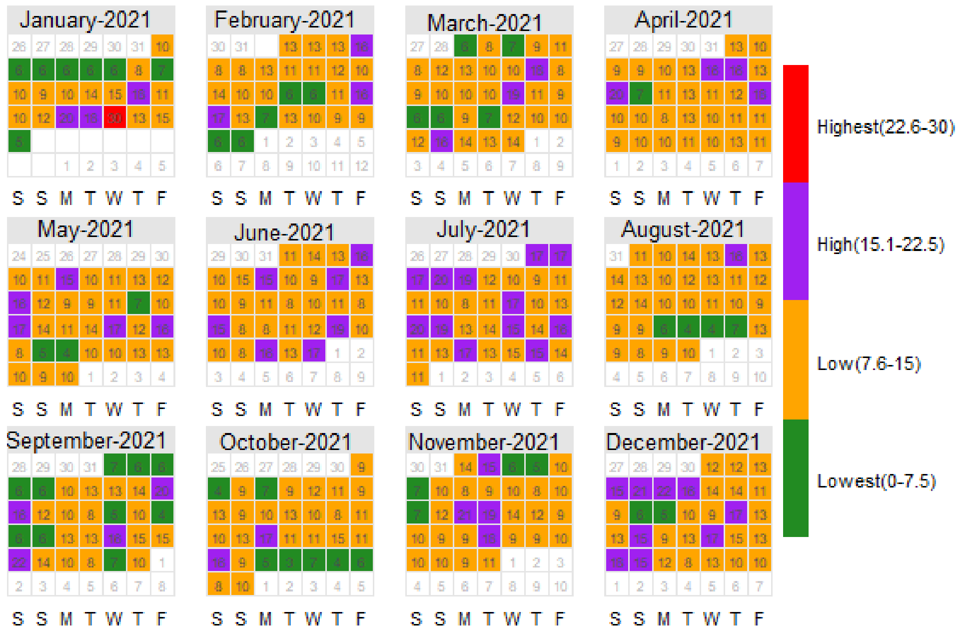

Figure D18. Calendar plot for PM_{10} concentrations in Takapuna site. The numbers show the PM_{10} concentration in $\mu g/m^3$.

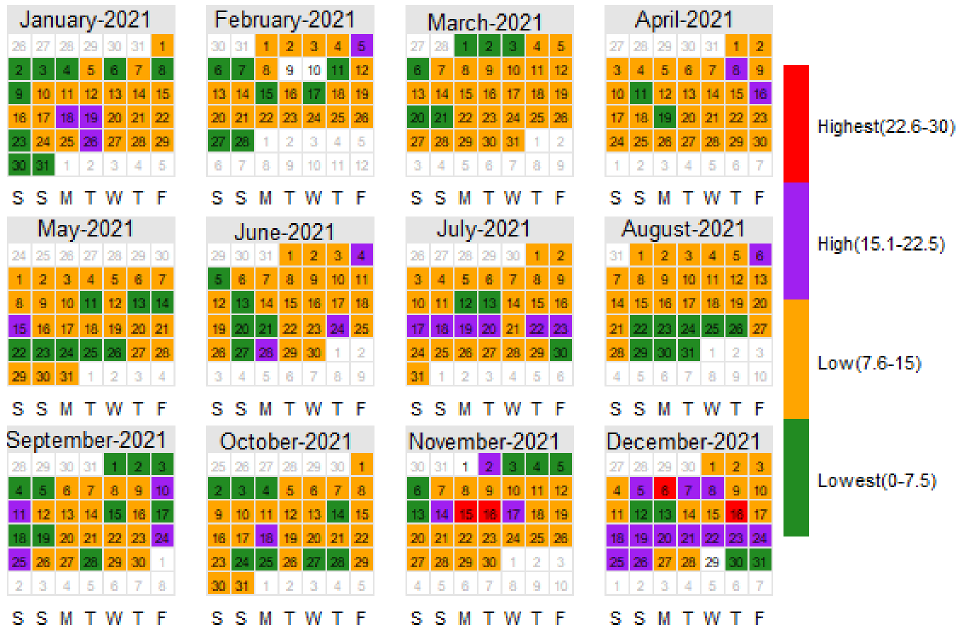

Figure D19. Calendar plot for PM_{10} concentrations in Khyber Pass Road.

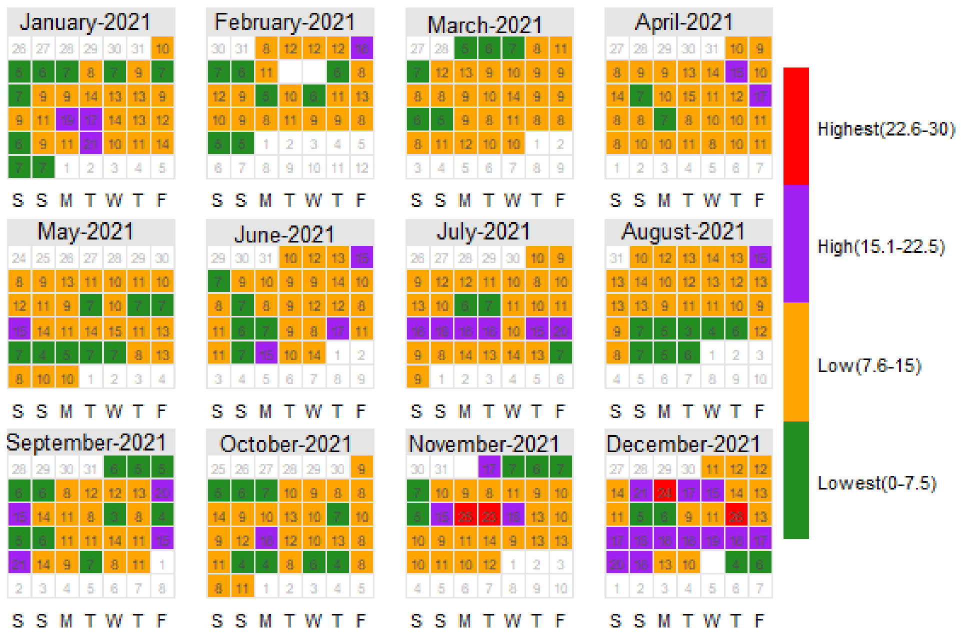

Figure D20. Calendar plot for PM_{10} concentrations in Khyber Pass Road site. The numbers show the PM_{10} concentration

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

(The colours represent four categorical scale (µg/m³) as: lowest, low, high, and highest)

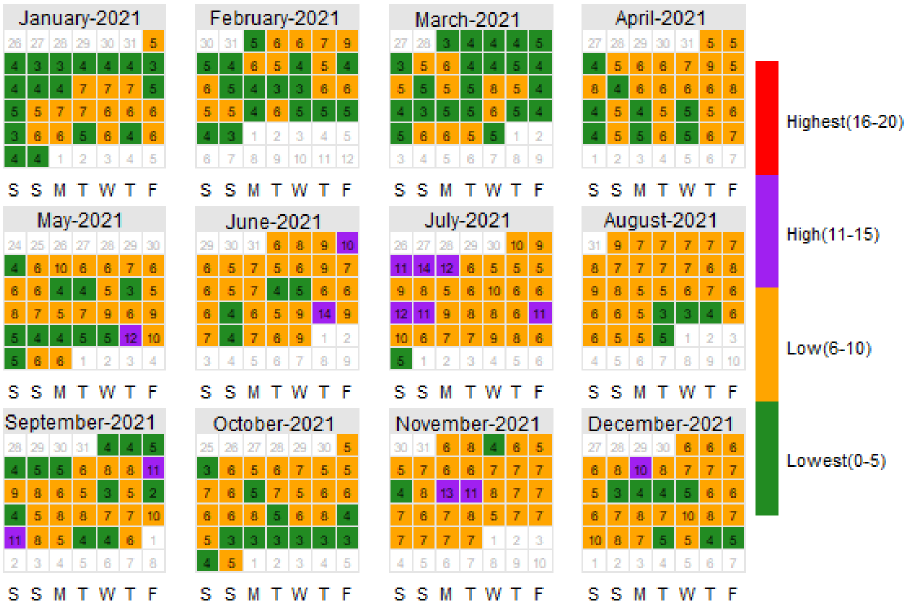

Figure E1. Calendar plot for Auckland $PM_{2.5}$ concentrations in 2021 (four sites combined).

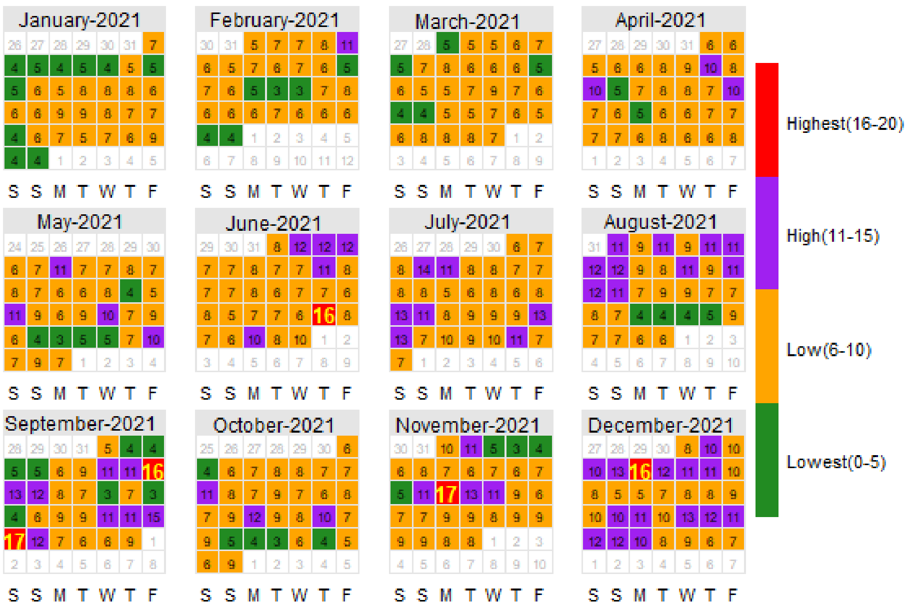

Figure E2. Calendar Plot for $PM_{2.5}$ Queen Street concentrations in 2021 with annotations highlighting those days where the concentration of $PM_{2.5}$ were equal or greater than the 2021 WHO guideline of 15 µg/m³. The numbers show the $PM_{2.5}$ concentration in µg/m³.

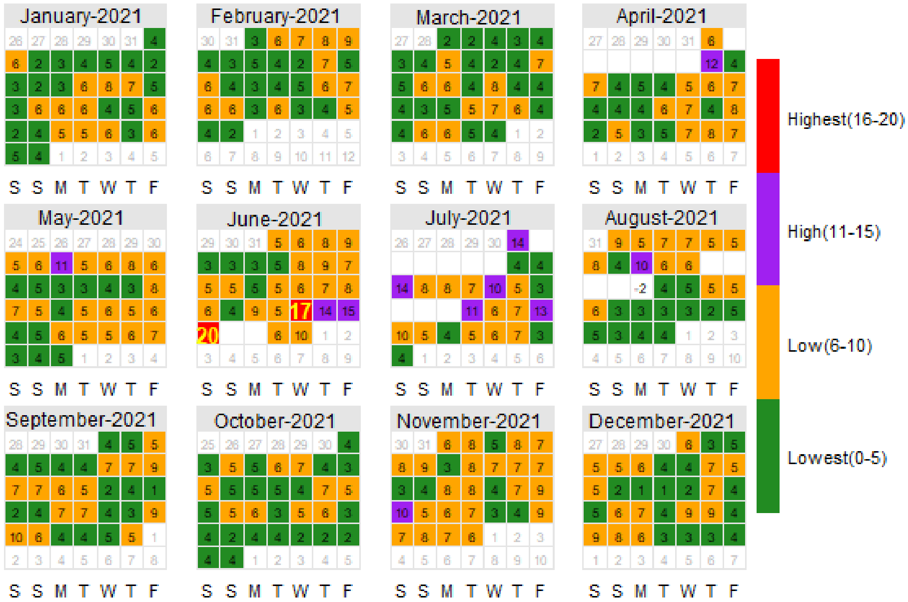

Figure E3. Calendar Plot for $PM_{2.5}$ Penrose concentrations in 2021 with annotations highlighting those days where the concentration of $PM_{2.5}$ were equal or greater than the 2021 WHO guideline of 15 µg/m^3. The numbers show the $PM_{2.5}$ concentration in µg/m^3.

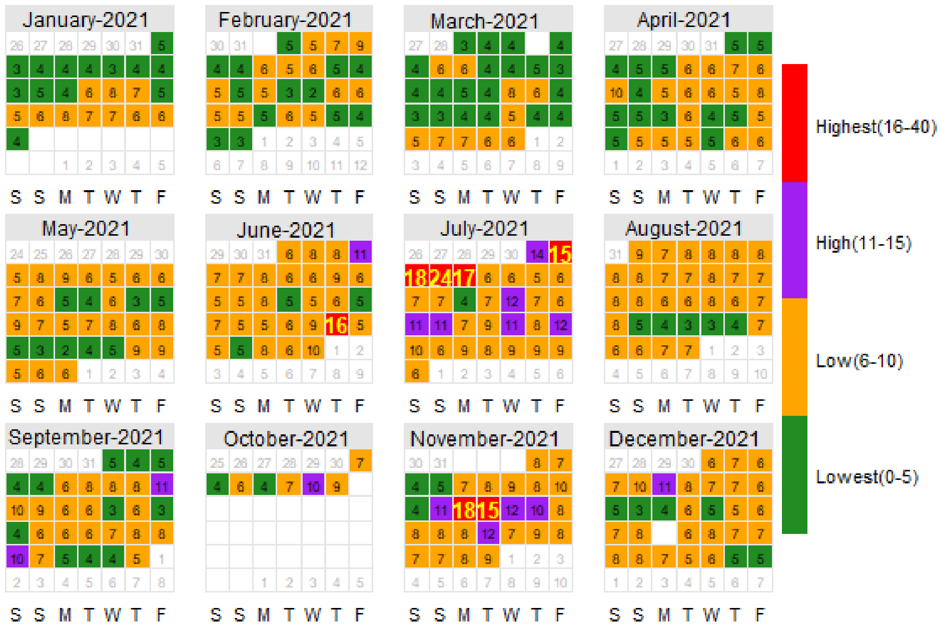

Figure E4. Calendar Plot for $PM_{2.5}$ Takapuna concentrations in 2021 with annotations highlighting those days where the concentration of $PM_{2.5}$ were equal or greater than the 2021 WHO guideline of 15 µg/m^3. The numbers show the $PM_{2.5}$ concentration in µg/m^3.

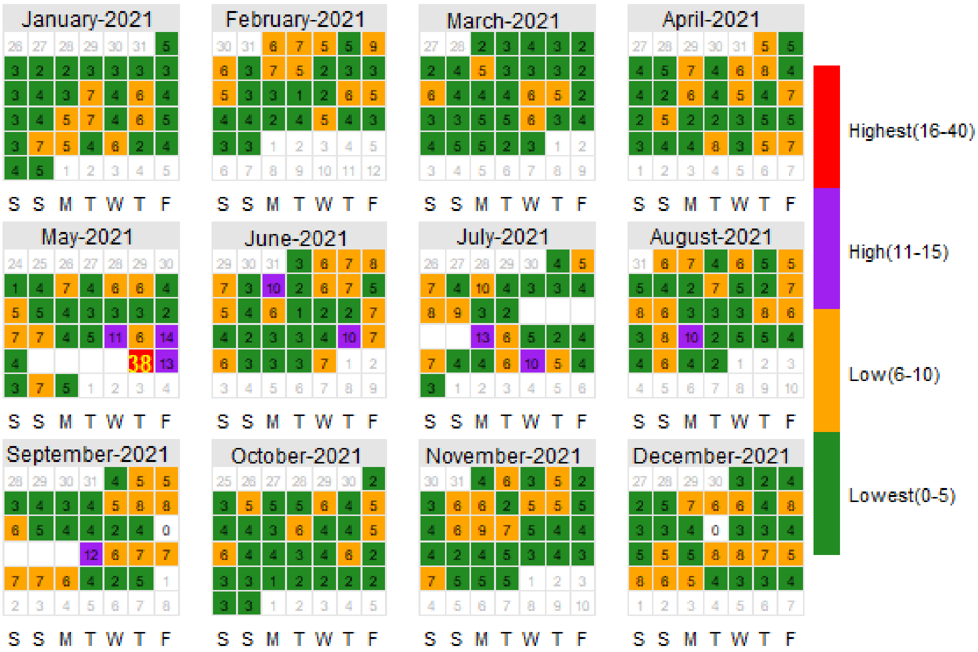

Figure E5. Calendar Plot for $PM_{2.5}$ Patumahoe concentrations in 2021 with annotations highlighting those days where the concentration of $PM_{2.5}$ were equal or greater than the 2021 WHO guideline of 15 $\mu g/m^3$. The numbers show the $PM_{2.5}$ concentration in $\mu g/m^3$.

Appendix F: Calendar plots for NO_2 24-hour and 1-hour mean

(The colours represent four categorical scale ($\mu g/m^3$) as: lowest, low, high, and highest)

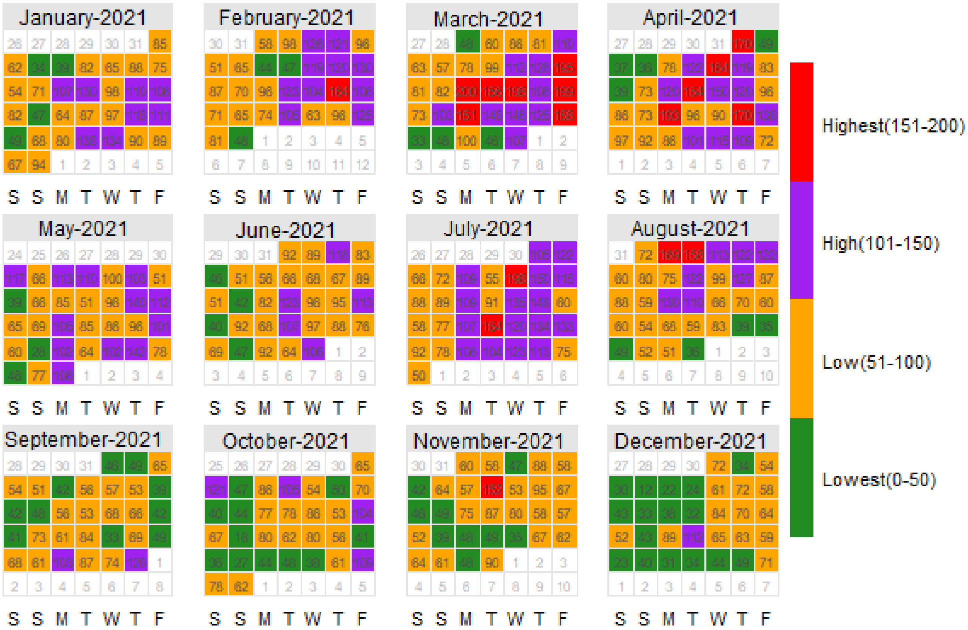

Figure F1. Calendar Plot for NO_2 overall Auckland (eight sites combined) concentrations in 2021. The numbers show the NO_2 maximum 1-hour mean concentration in $\mu g/m^3$.

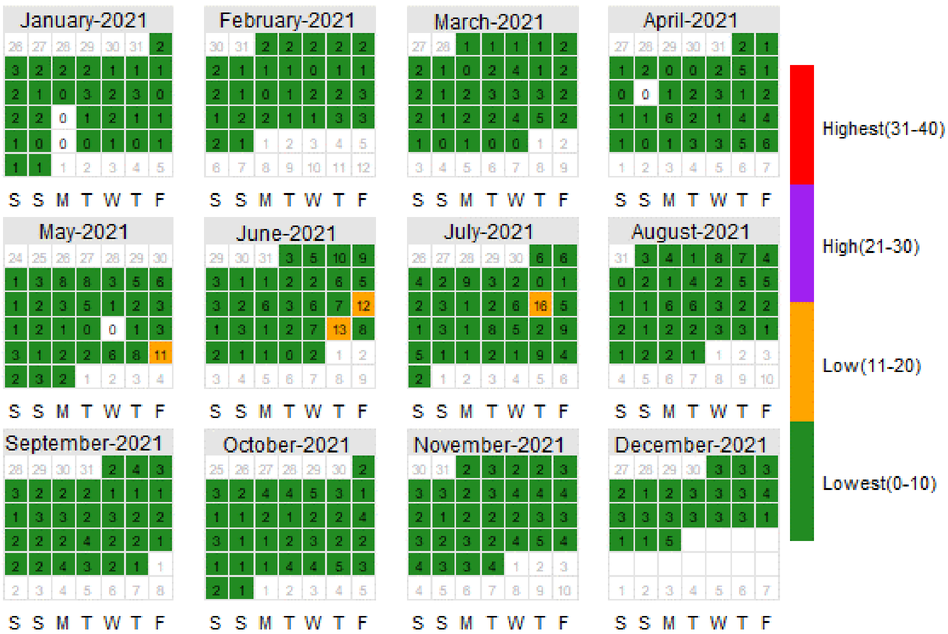

Figure F2. Calendar Plot for NO_2 overall Patumahoe concentrations in 2021. The numbers show the NO_2 maximum 24-hour mean concentration in $\mu g/m^3$. No exceedance of WHO guideline.

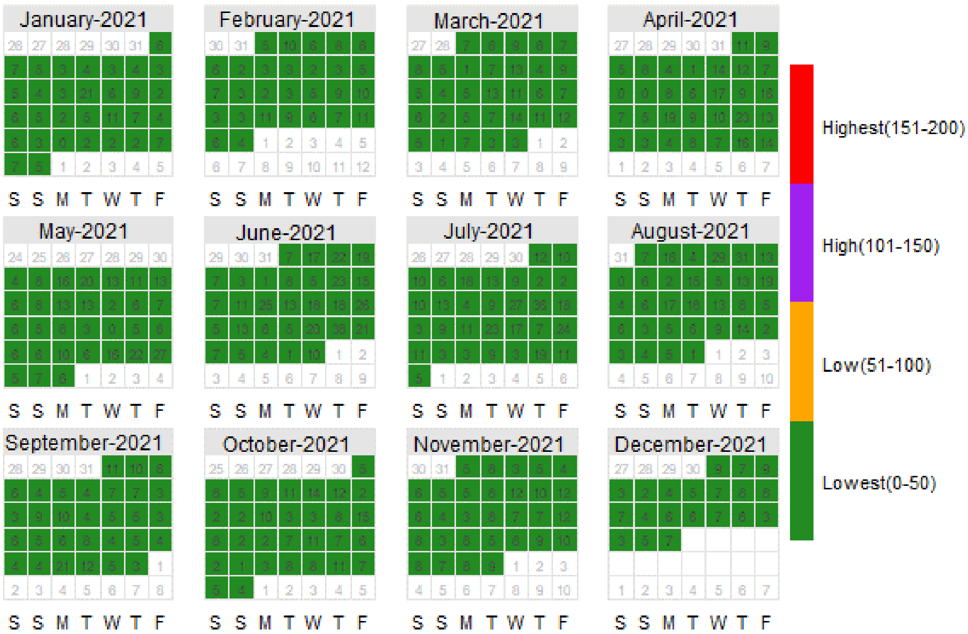

Figure F3. Calendar Plot for NO_2 overall Patumahoe concentrations in 2021. The numbers show the NO_2 maximum 1-hour mean concentration in µg/m^3. No exceedance of WHO guideline.

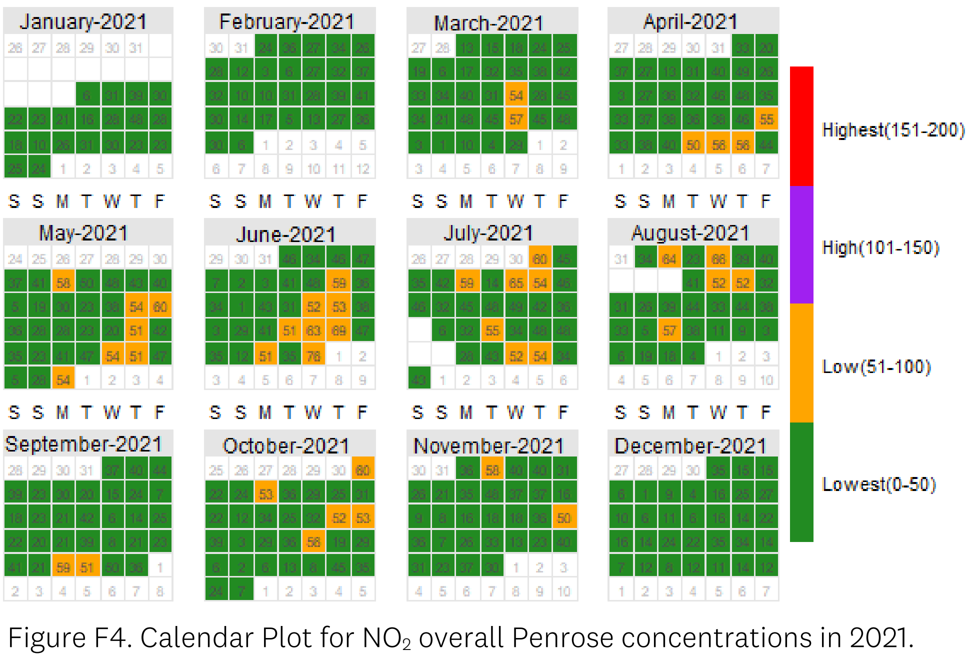

Figure F4. Calendar Plot for NO_2 overall Penrose concentrations in 2021. The numbers show the NO_2 maximum 1-hour mean concentration in µg/m^3. No exceedance of WHO guideline of 200 µg/m^3.

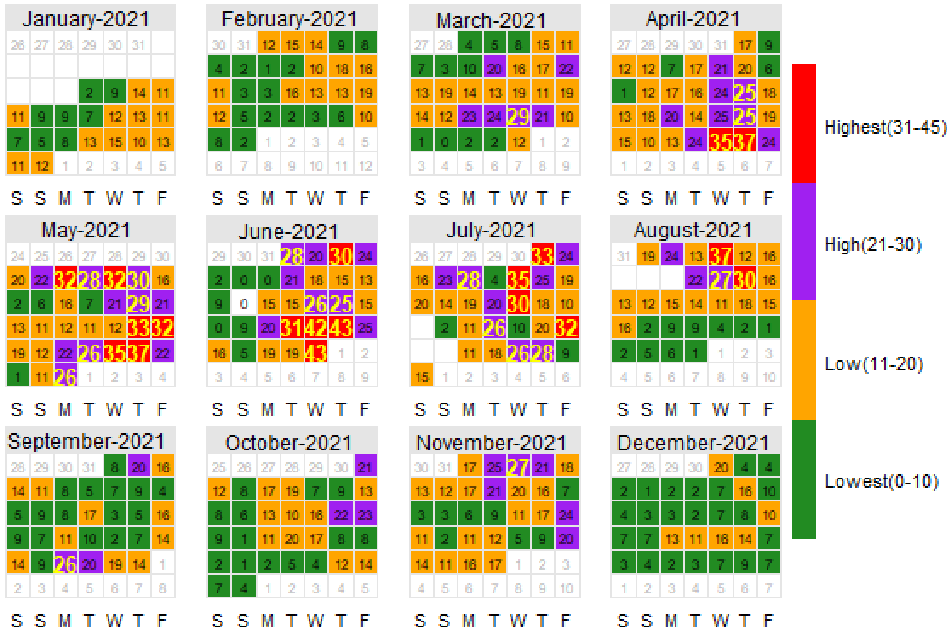

Figure F5. Calendar Plot for NO_2 overall Penrose concentrations in 2021 with annotations highlighting those days where the concentration of NO_2 were equal or greater than the 2021 WHO guideline of 25 µg/m³. The numbers show the NO_2 concentration in µg/m³.

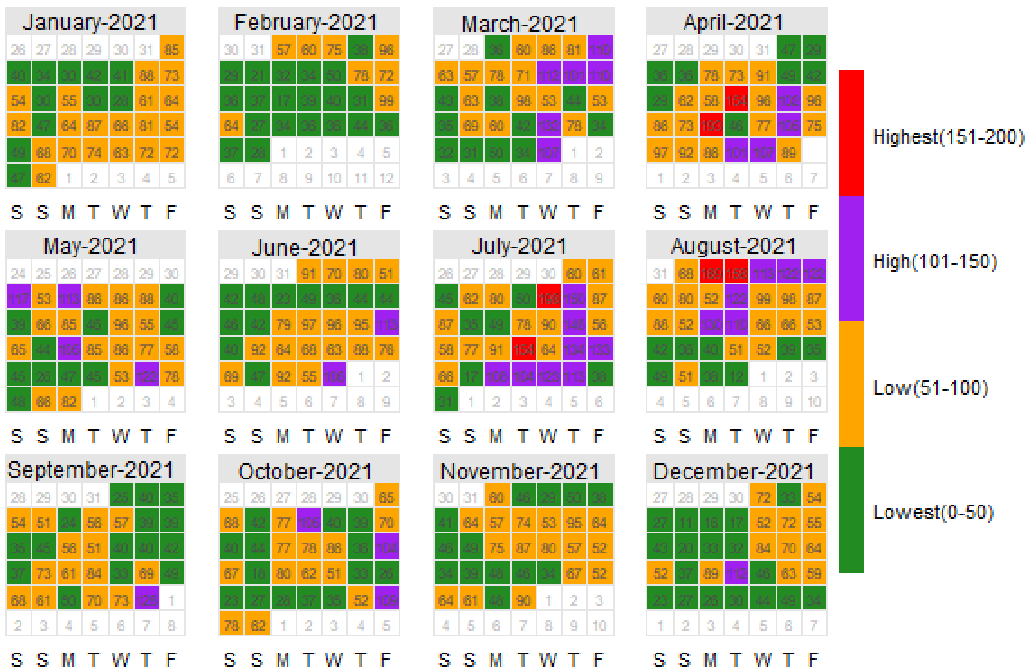

Figure F6. Calendar Plot for NO_2 overall Queen Street concentrations in 2021. The numbers show the NO_2 maximum 1-hour mean concentration in µg/m³. No exceedance of WHO guideline of 200 µg/m³.

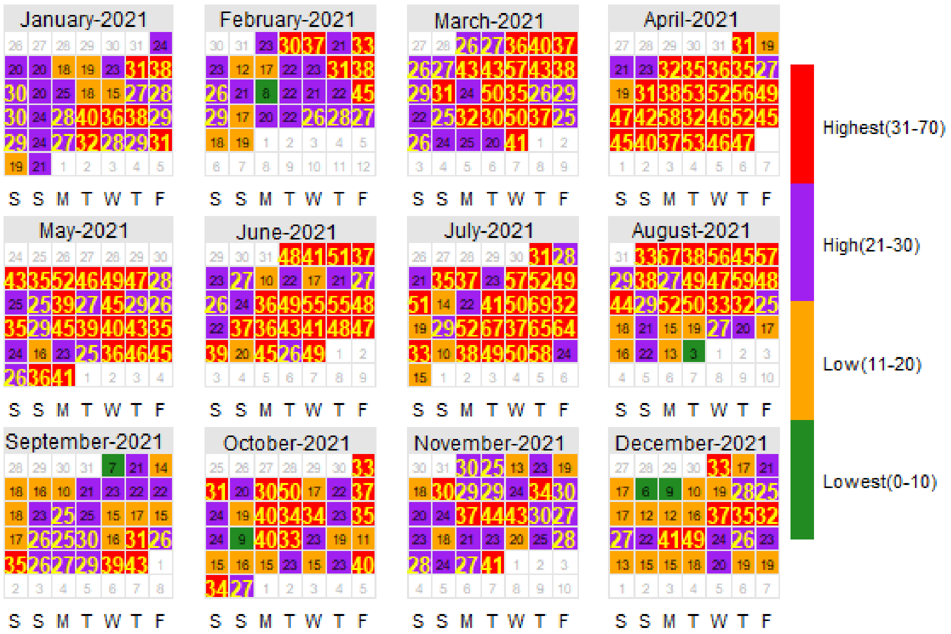

Figure F7. Calendar Plot for NO_2 overall Queen Street concentrations in 2021 with annotations highlighting those days where the concentration of NO2 were equal or greater than the 2021 WHO guideline of 25 µg/m³. The numbers show the NO_2 concentration in µg/m³.

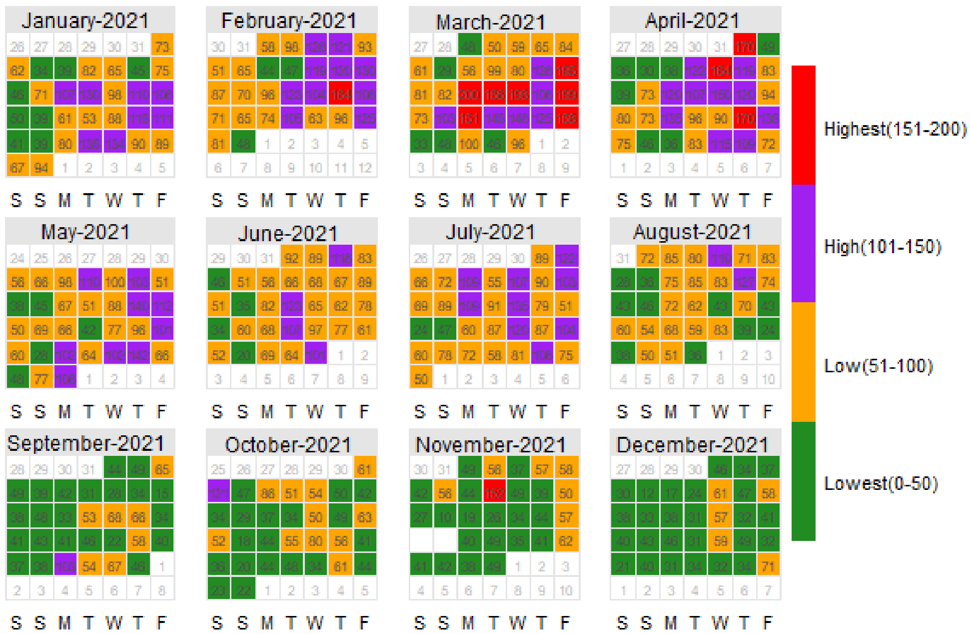

Figure F8. Calendar Plot for NO_2 overall Customs Street concentrations in 2021. The numbers show the NO_2 maximum 1-hour mean concentration in µg/m³. No exceedance of WHO guideline of 200 µg/m³.

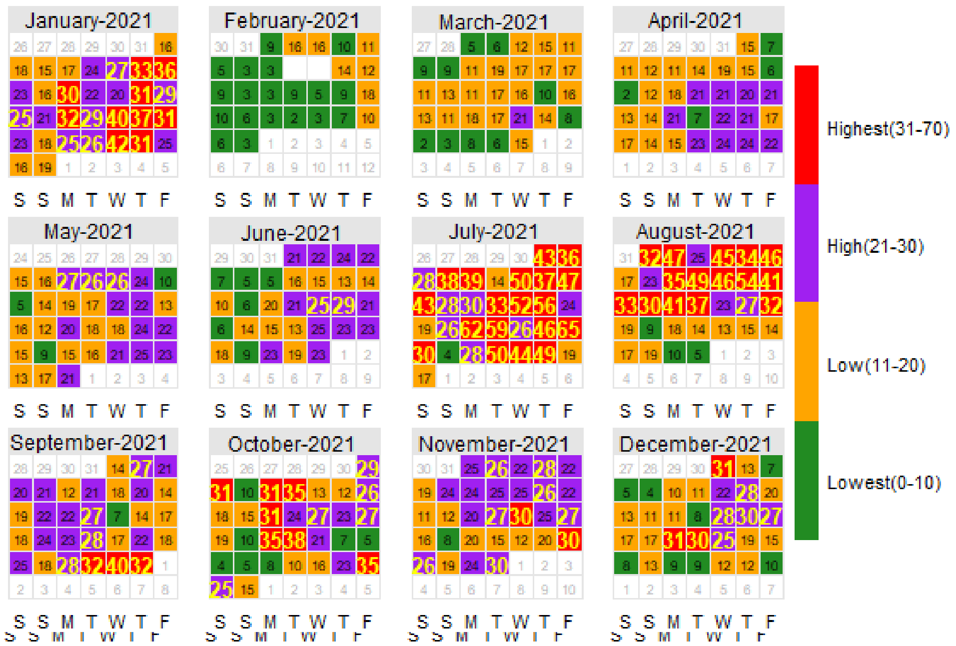

Figure F11. Calendar Plot for NO_2 overall Khyber Pass Road concentrations in 2021 with annotations highlighting those days where the concentration of NO2 were equal or greater than the 2021 WHO guideline of 25 µg/m^3. The numbers show the NO_2 concentration in µg/m^3.

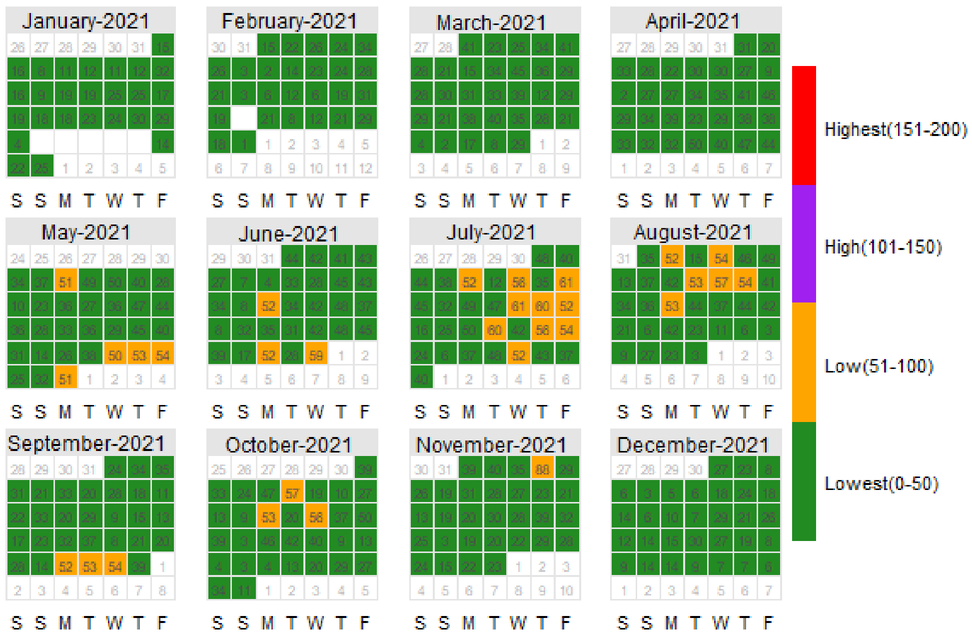

Figure F12. Calendar Plot for NO_2 overall Takapuna concentrations in 2021. The numbers show the NO_2 maximum 1-hour mean concentration in µg/m^3. No exceedance of WHO guideline of 200 µg/m^3.

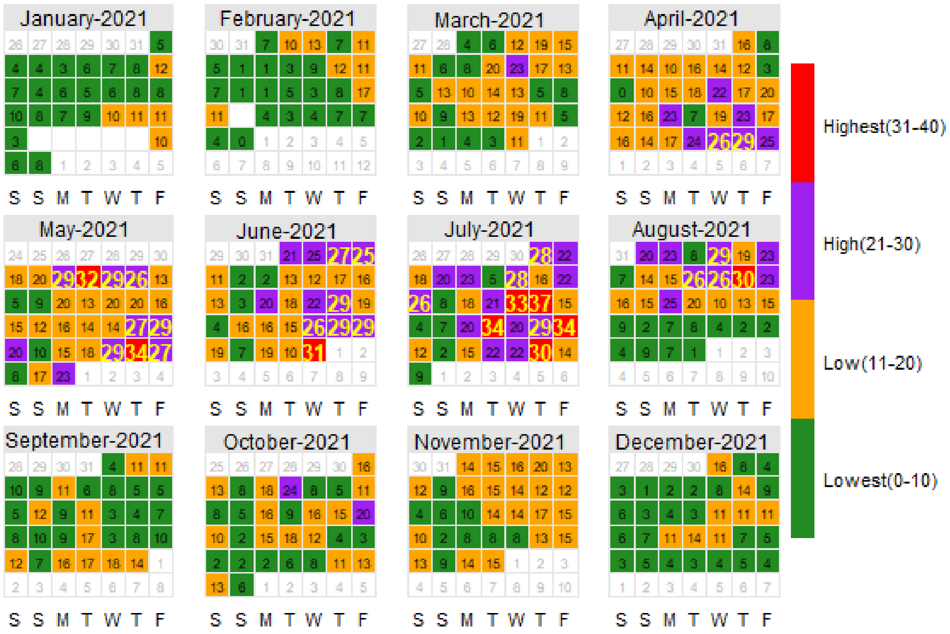

Figure F13. Calendar Plot for NO_2 overall Takapuna concentrations in 2021 with annotations highlighting those days where the concentration of NO2 were equal or greater than the 2021 WHO guideline of 25 µg/m^3. The numbers show the NO_2 concentration in µg/m^3.

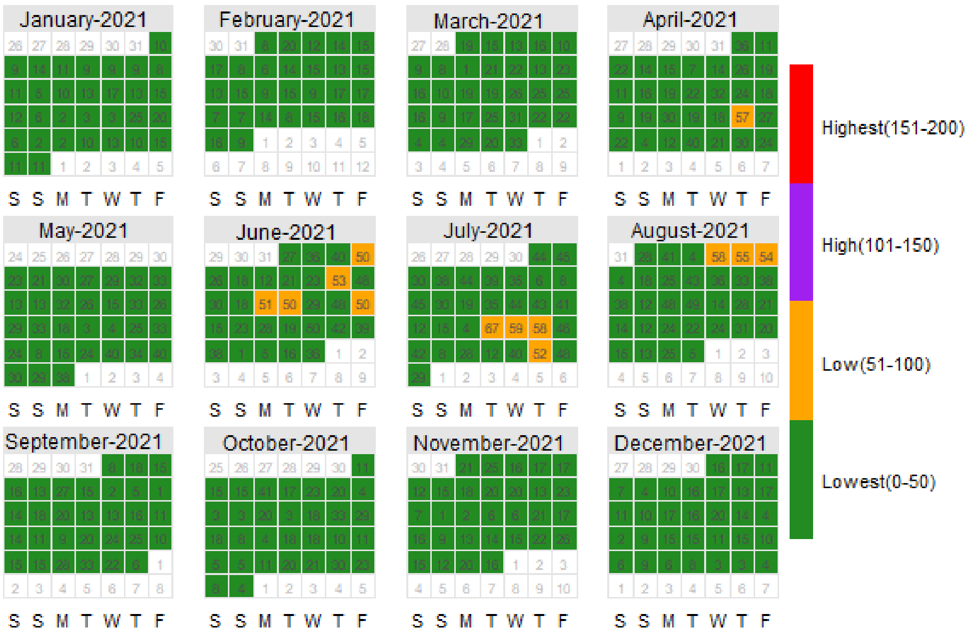

Figure F14. Calendar Plot for NO_2 overall Henderson concentrations in 2021. The numbers show the NO_2 maximum 1-hour mean concentration in µg/m^3. No exceedance of WHO guideline of 200 µg/m^3.

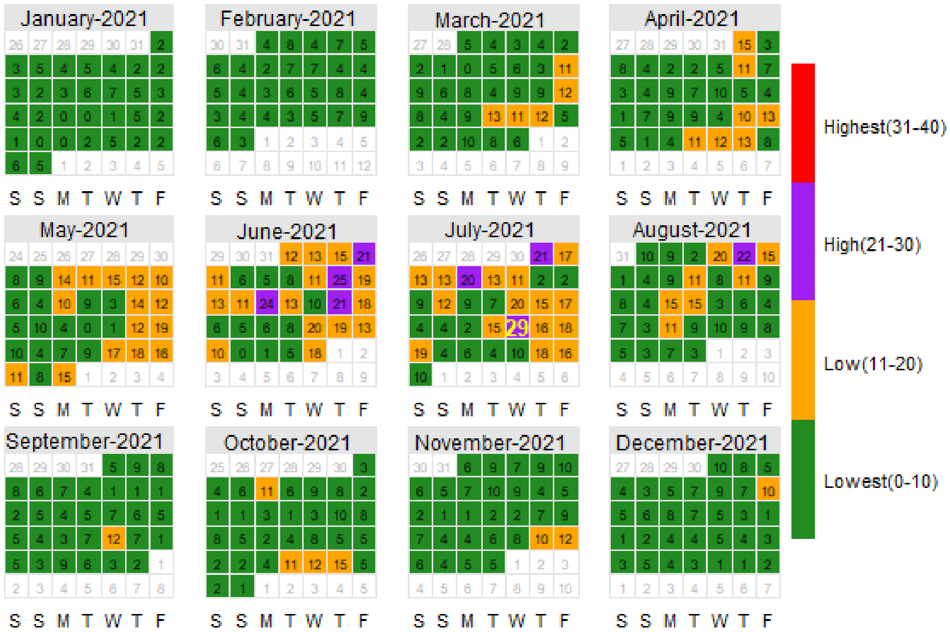

Figure F15. Calendar Plot for NO_2 overall Henderson concentrations in 2021 with annotations highlighting those days where the concentration of NO2 were equal or greater than the 2021 WHO guideline of 25 µg/m^3. The numbers show the NO_2 concentration in µg/m^3.

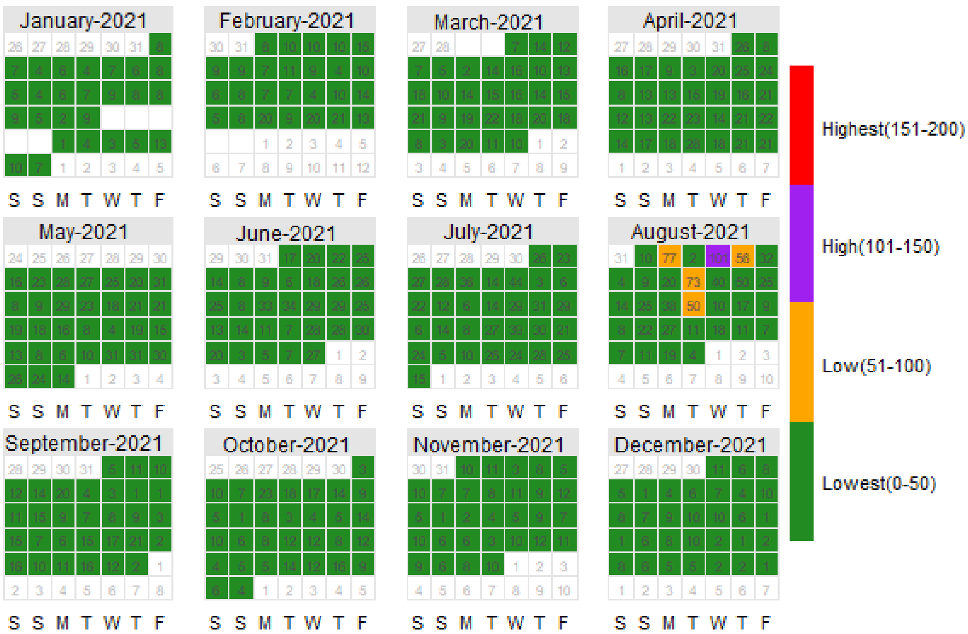

Figure F16. Calendar Plot for NO_2 overall Glen Eden concentrations in 2021. The numbers show the NO_2 maximum 1-hour mean concentration in µg/m^3. No exceedance of WHO guideline of 200 µg/m^3.

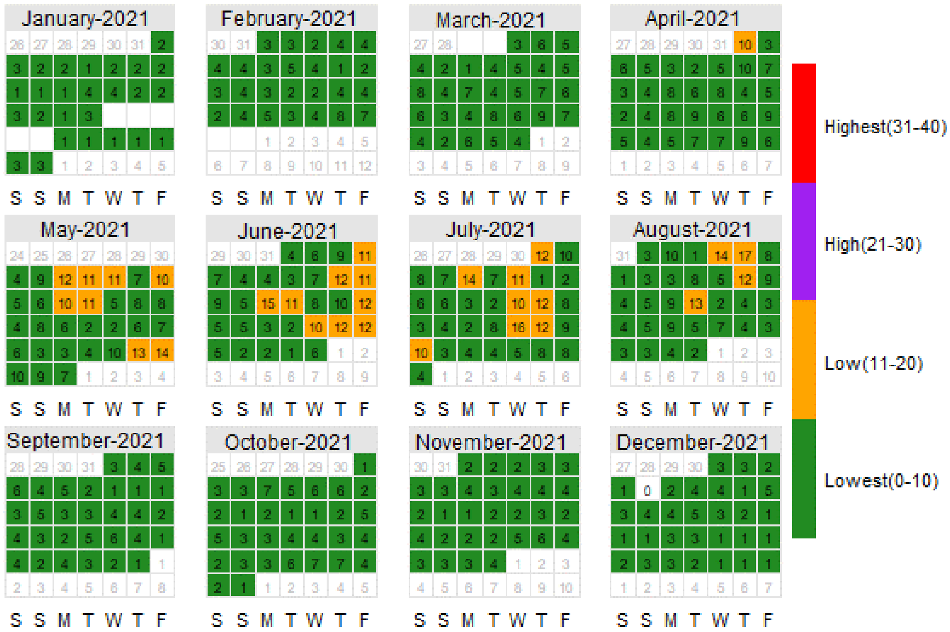

Figure F17. Calendar Plot for NO_2 overall Glen Eden concentrations in 2021. No day's concentrations of NO_2 were equal or greater than the 2021 WHO guideline of 25 µg/m^3. The numbers show the NO_2 concentration in µg/m^3.

Appendix G: Calendar plots for SO_2 24-hour mean concentration

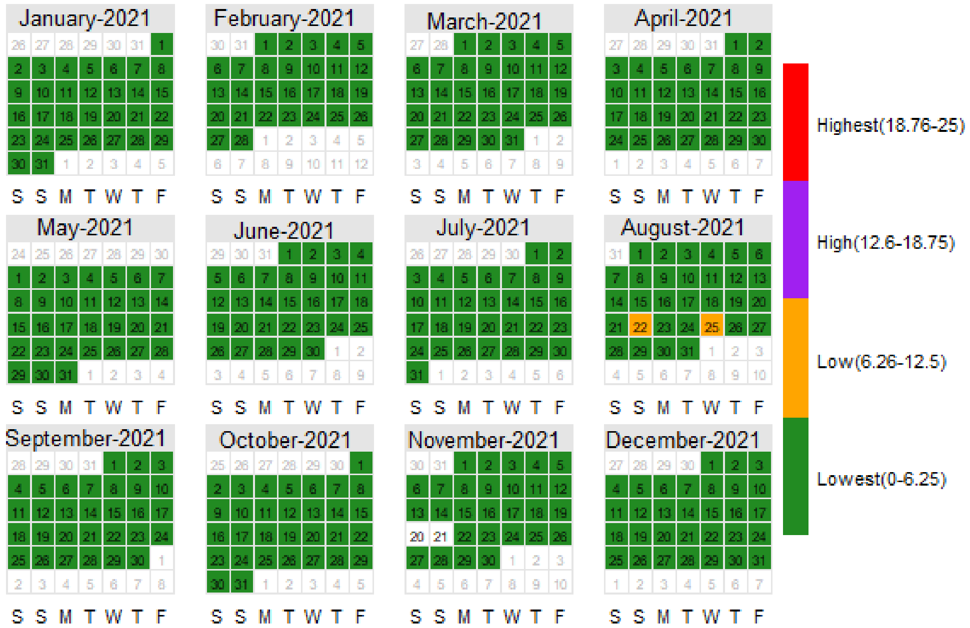

Figure G1. Calendar Plot for Customs Street SO_2 concentrations in 2021. The numbers show the SO_2 24-hour mean concentration in µg/m^3. No exceedance of national standard and WHO guideline.

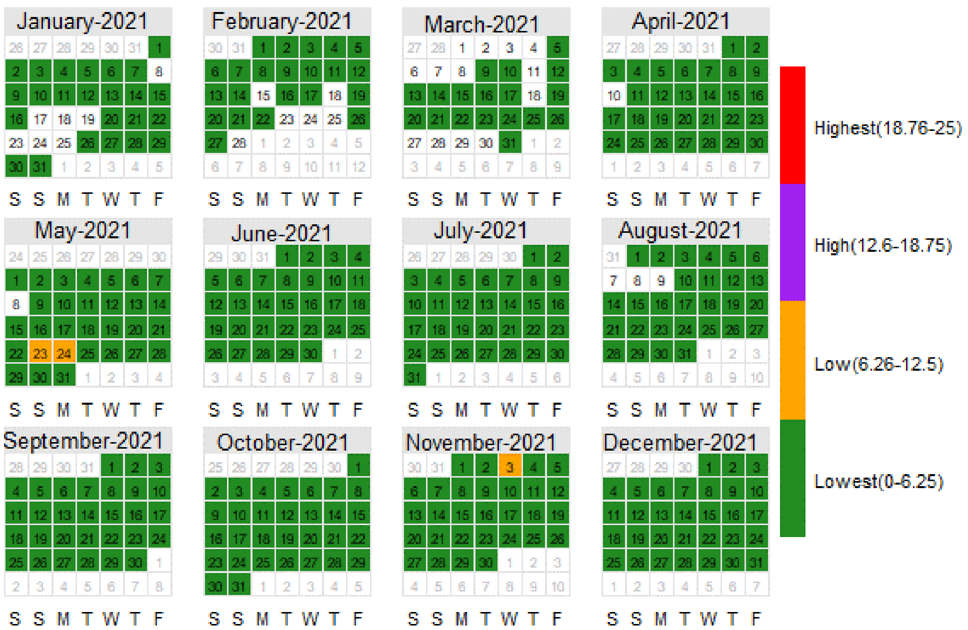

Figure G2. Calendar Plot for Penrose SO_2 concentrations in 2021. The numbers show the SO_2 24-hour mean concentration in µg/m^3. No exceedance of national standard and 2021 WHO guideline.

Appendix H: Calendar plots for CO 1-hour and 8-hour running mean

(The colours represent four categorical scale (mg/m³) as: lowest, low, high, and highest)

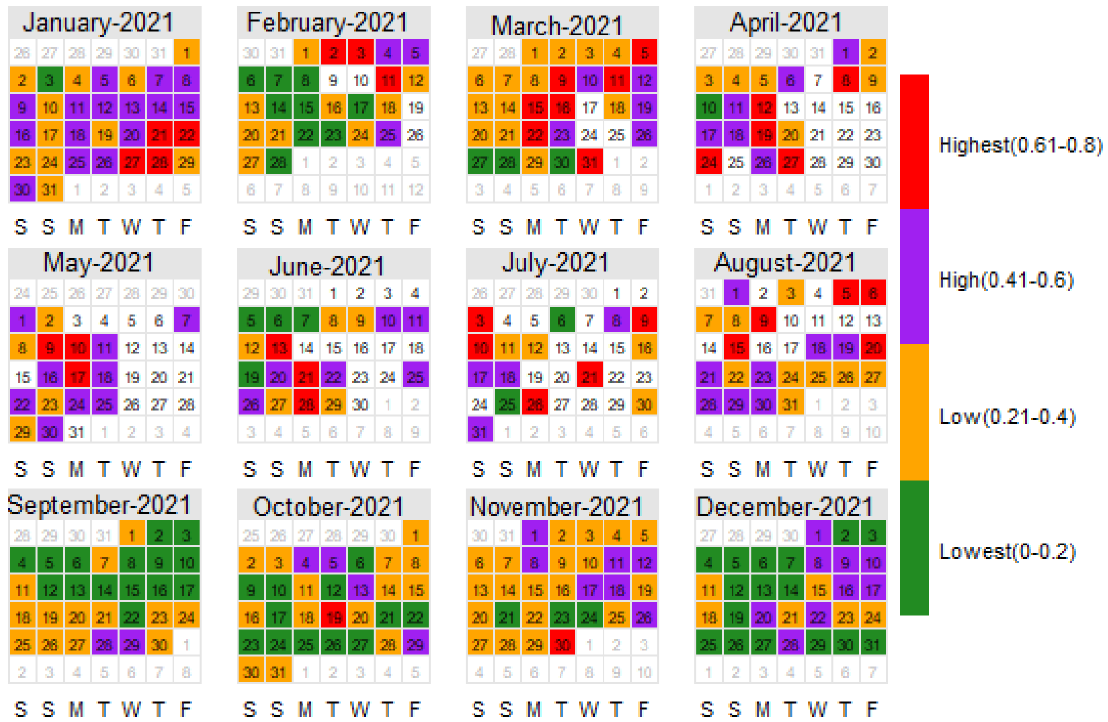

Figure H1. Calendar Plot for Khyber Pass Road 1-hour maximum mean CO concentrations in 2021.

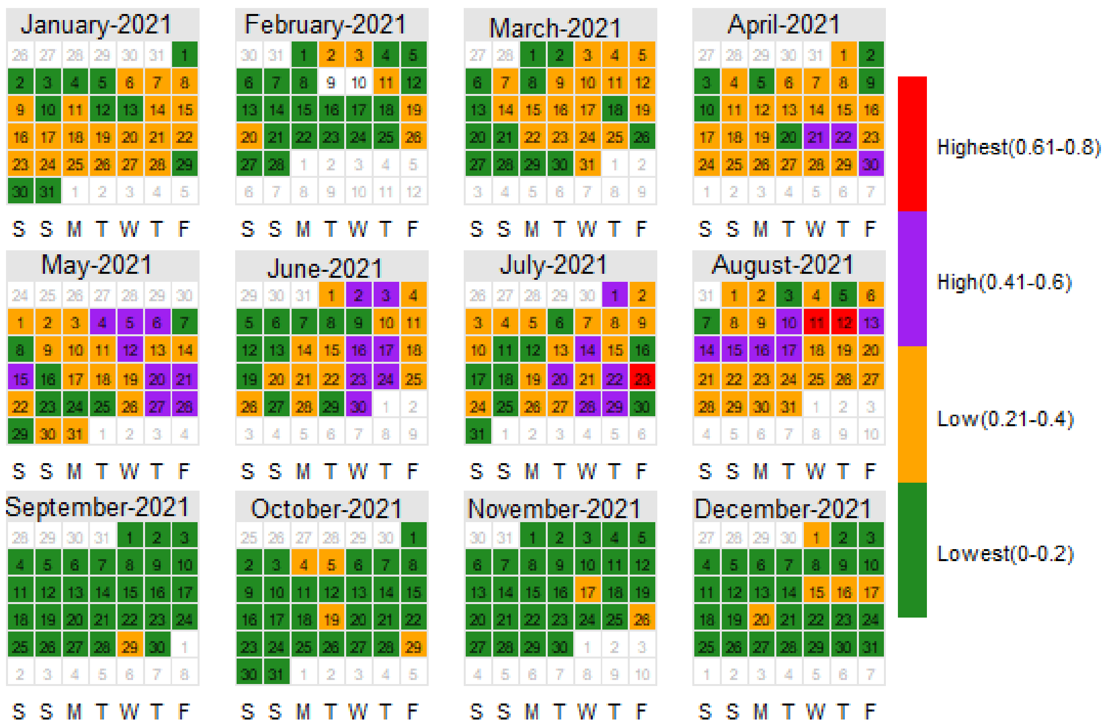

Figure H2. Calendar Plot for Khyber Pass Road CO concentrations in 2021. The numbers show CO 8-hour running mean concentration in mg/m³.

Appendix I: Calendar plots for O_3 1-hour and 8-hour running mean

(The colours represent four categorical scale (μg/m³) as: lowest, low, high, and highest)

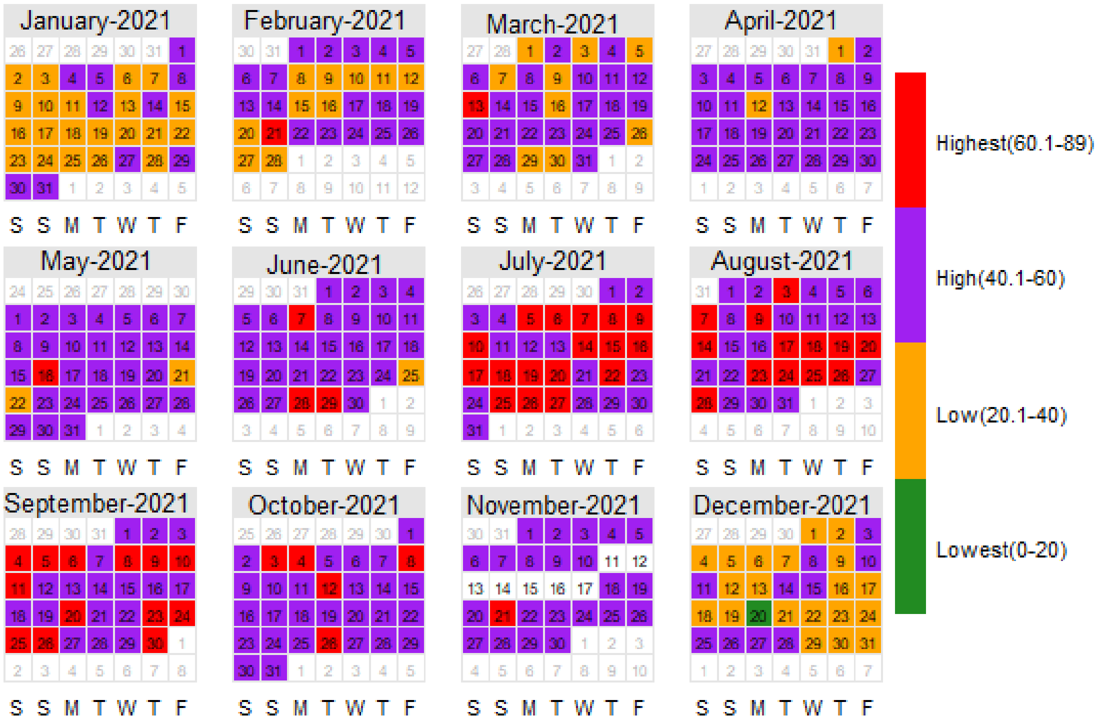

Figure I1. Calendar Plot for Patumahoe 1-hour maximum mean O_3 concentrations in 2021.

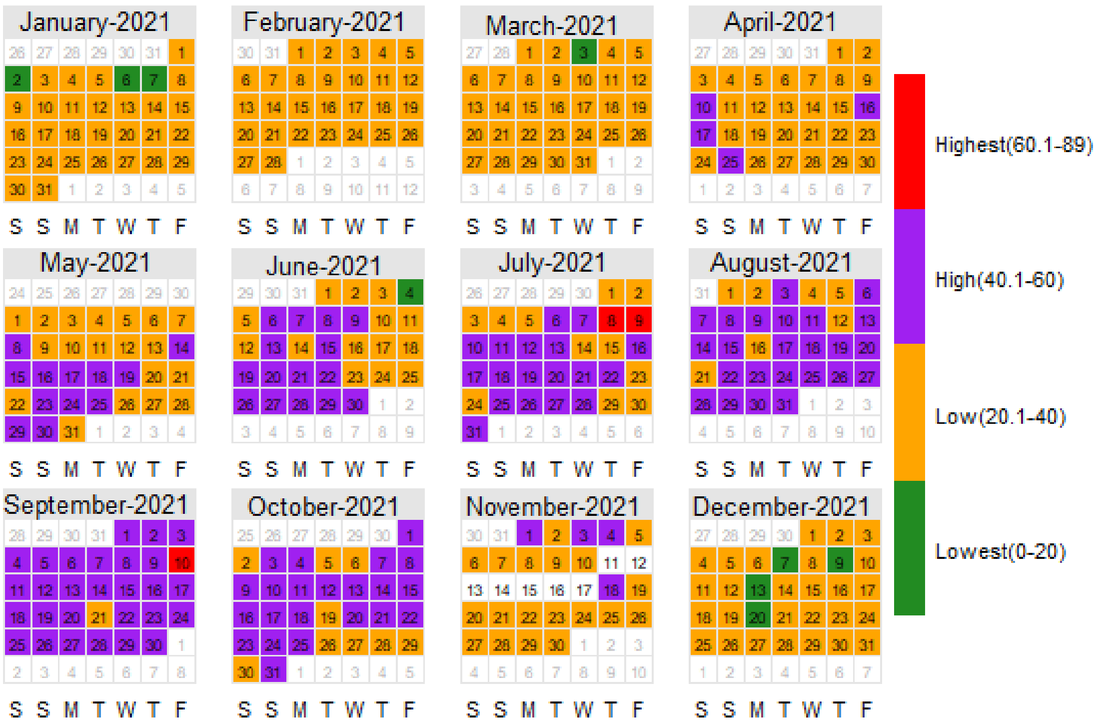

Figure I2. Calendar Plot for Patumahoe O_3 concentrations in 2021. The numbers show O_3 8-hour running mean concentration in μg/m³.

Appendix J: Calendar plots for black carbon max 1-hour mean

(The colours represent four categorical scale (ng/m^3) as: lowest, low, high, and highest)

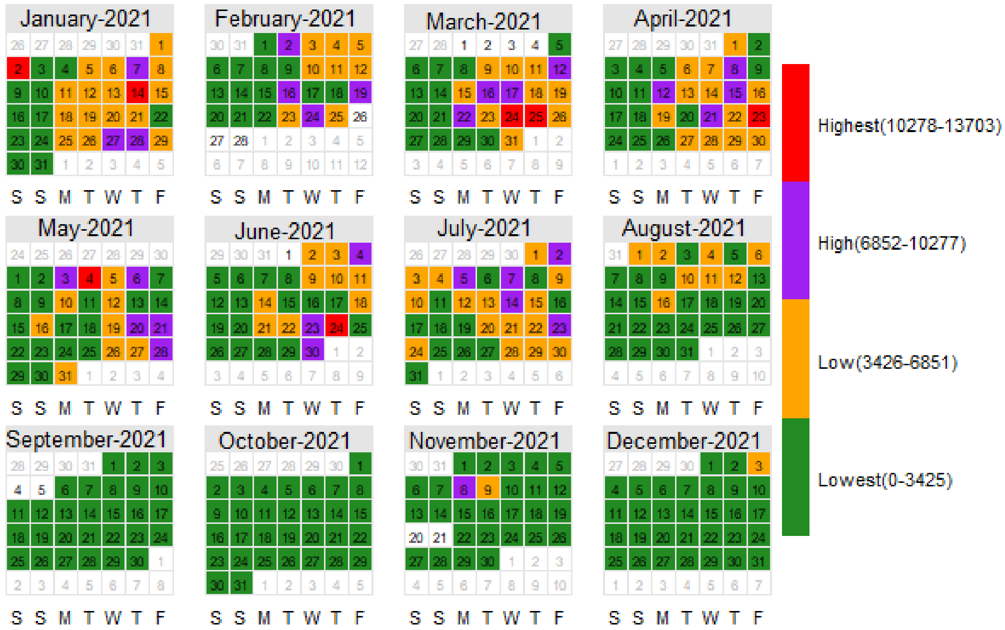

Figure J1. Calendar Plot for Customs Street black carbon concentrations in 2021. The numbers show the black carbon 1-hour maximum mean concentration in ng/m^3.

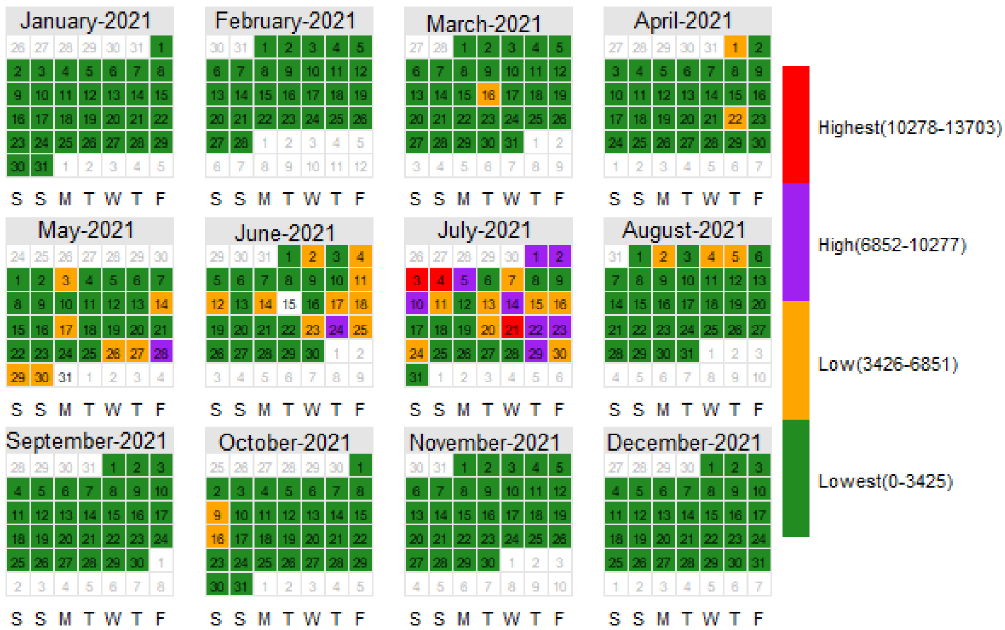

Figure J2. Calendar Plot for Henderson black carbon concentrations in 2021. The numbers show the black carbon 1-hour maximum mean concentration in ng/m^3.

Appendix K: Calendar plots for AQI 24-hour mean value

(The colours represent four categorical scale as: very good, good, fair, and poor)

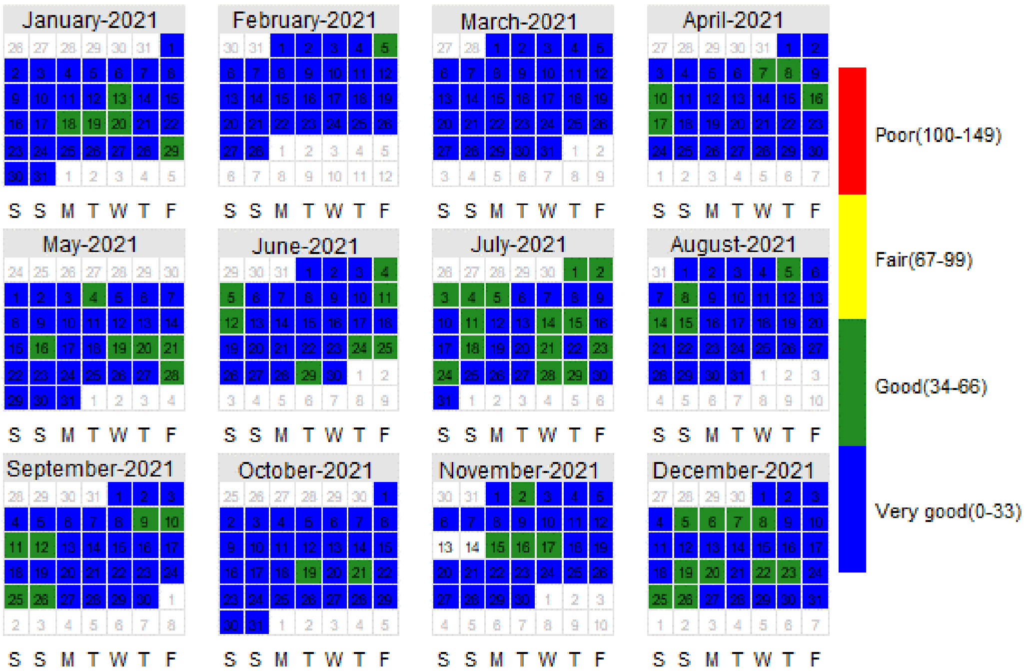

Figure K1. Calendar Plot for Auckland (six sites combined) AQI values in 2021.

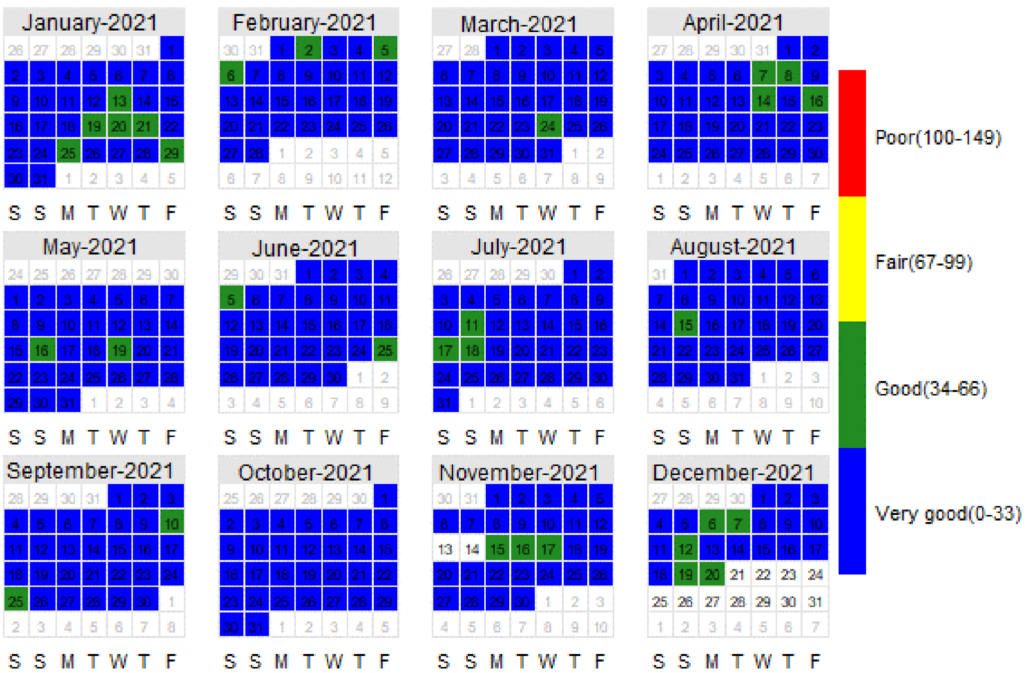

Figure K2. Calendar Plot for Patumahoe AQI values in 2021.

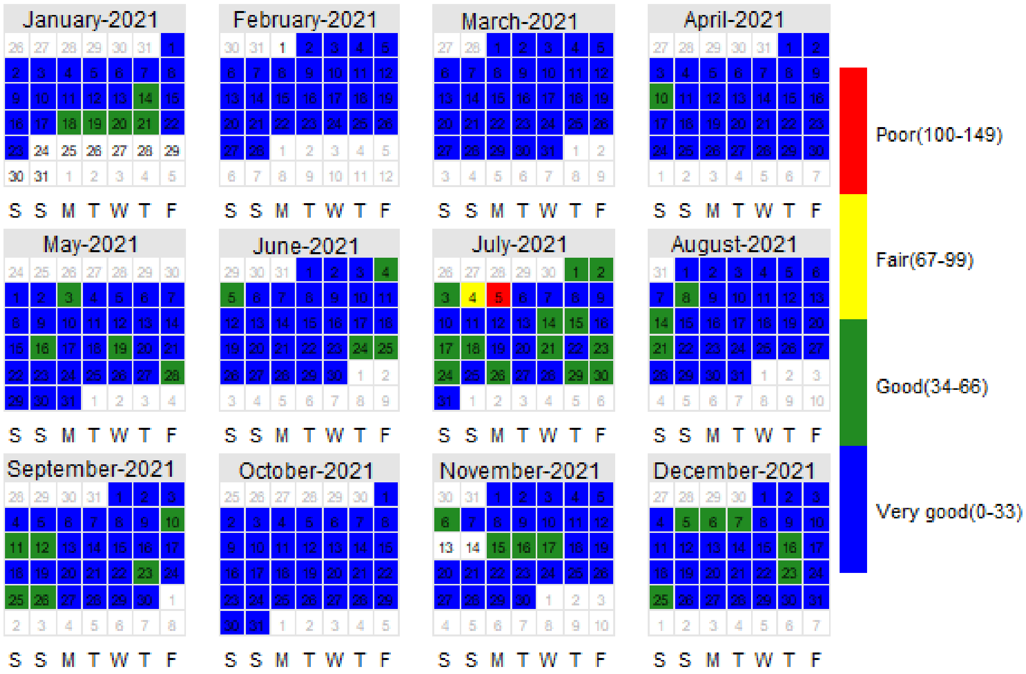

Figure K3. Calendar Plot for Takapuna AQI values in 2021.

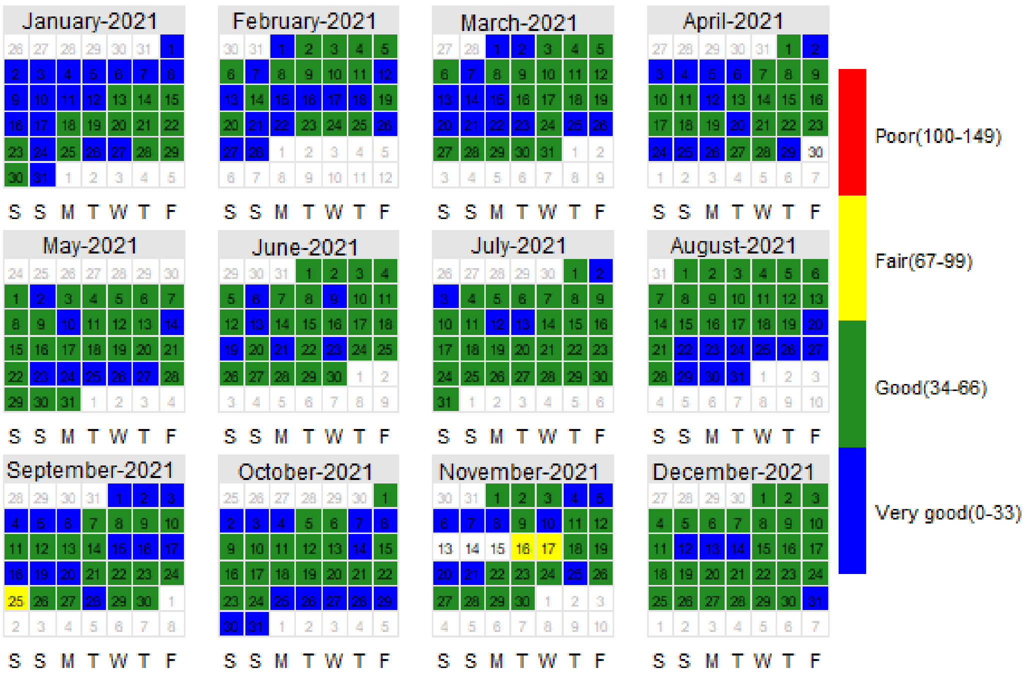

Figure K4. Calendar Plot for Queen Street AQI values in 2021.

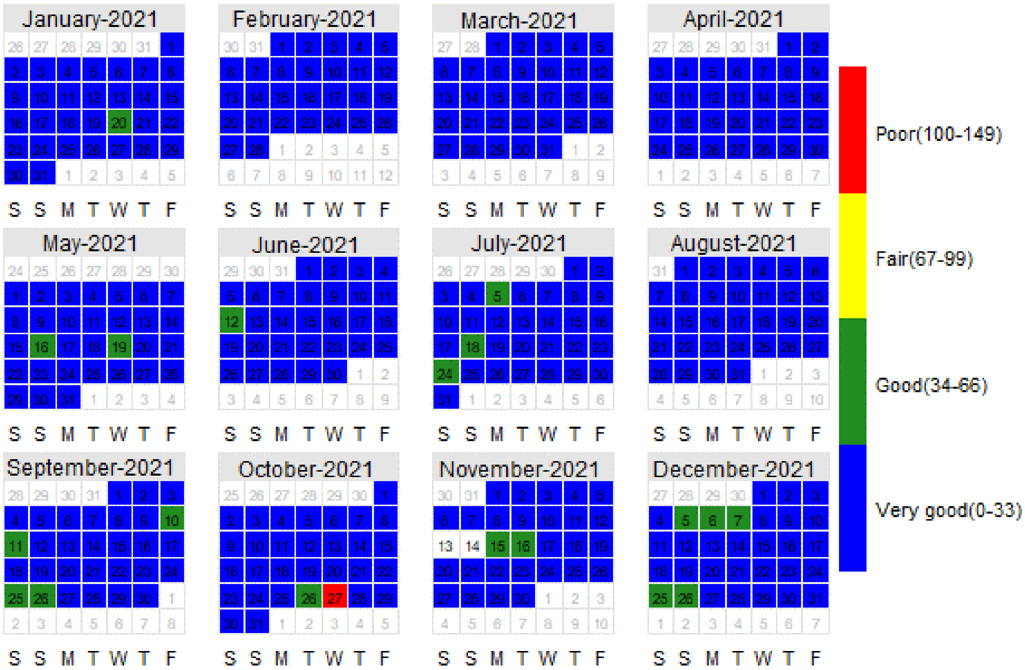

Figure K5. Calendar Plot for Henderson AQI values in 2021.

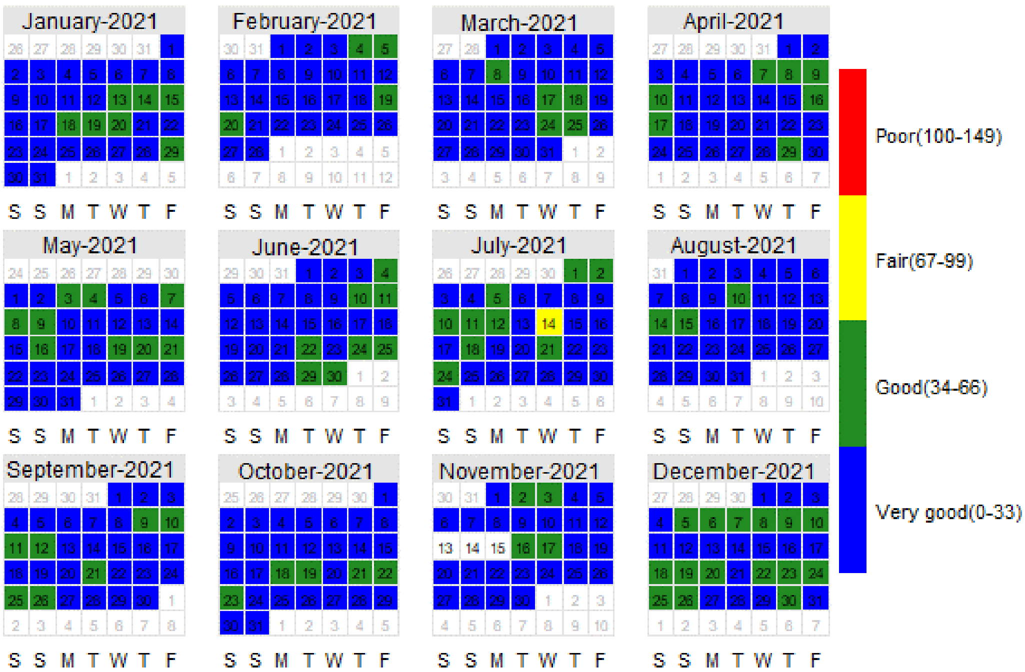

Figure K6. Calendar Plot for Penrose AQI values in 2021.

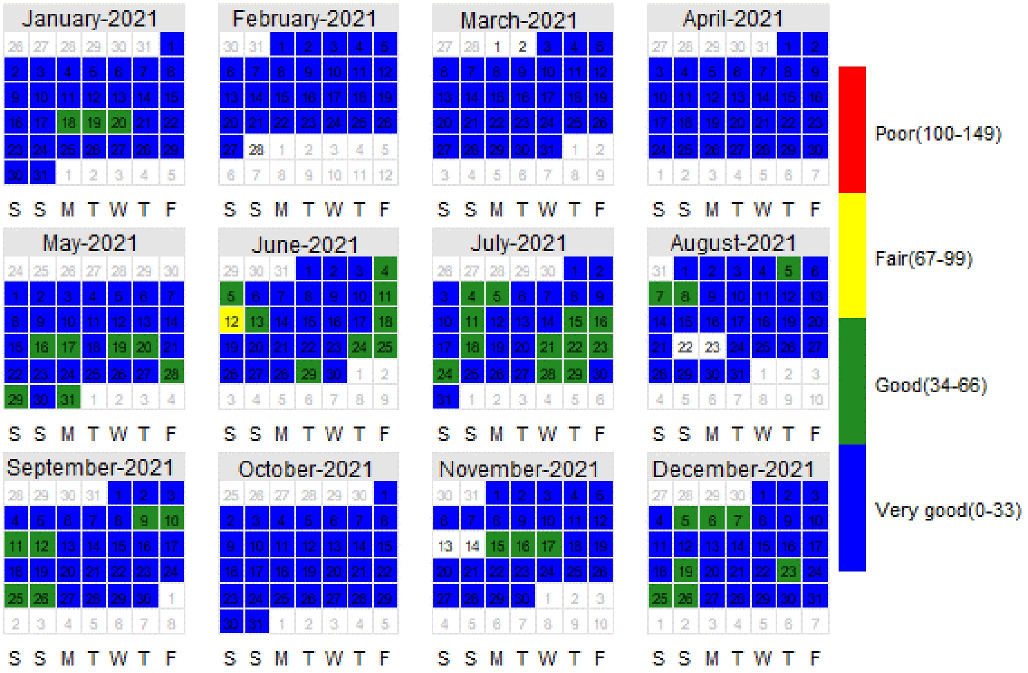

Figure K7. Calendar Plot for Glen Eden AQI values in 2021.

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