

Air Quality & Climate Change: Interconnected Environmental Issues

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Abbreviations / Glossary

Term	Meaning
Aerosol	Mixture of very small solid or liquid particles that can remain suspended in air from few minutes to many months depending on particle size and weight
Anthropogenic	Generated by human activities
BaP	Benzo-a-Pyrene
BC	Black Carbon
BTEX	Benzene, Toluene, Ethyl benzene and Xylene
BVOCs	Biogenic Volatile Organic Compounds
C2ES	Centre For Climate and Energy Solutions
CASANZ	Clean Air Society of Australia and New Zealand
CCN	Cloud Condensation Nuclei. CCN changes the cloud albedo (scattering radiation to the space)
CH ₄	Methane
CO	Carbon Monoxide (an air pollutant)
CO ₂	Carbon Dioxide
Coarse particles	Particulate matter sized between 2.5µm (PM _{2.5}) and 10µm (PM ₁₀)
DMS	Dimethyl Sulphate
ERF	Effective Radiation Forcing. ERF is the concept in climate science that describes change in the earth's energy balance caused by greenhouse gases, aerosol and land use pattern and is typically expressed in watts per square metre
Fine particles	Particles less than 2.5µm in size (PM _{2.5})
GHGs	Greenhouse Gases
HFCs	Hydrofluorocarbons
IPCC	Intergovernmental Panel on Climate Change
LAWA	Land Air Water Aotearoa. Platform to share environmental data and information in New Zealand
µm	Micrometre (one millionth of a metre)
MfE	Ministry for the Environment
N ₂ O	Nitrous Oxide
NESAQ	National Environmental Standard for Air Quality
NIWA	National Institute of Water and Atmospheric Research
NMVOCs	Non-Methane Volatile Organic Compounds
NO ₂	Nitrogen Dioxide
NO _x	Oxides of Nitrogen
NRC	Northland Regional Council
O ₃	Ozone
OH	Hydroxy radical

Term	Meaning
PAHs	Polycyclic Aromatic Hydrocarbons
PDP	Pattle Delamore Partners
PFCs	Perfluorocarbons
PM	Particulate Matter made up of various sizes
PM ₁₀	Particulate Matter less than 10µm in aerodynamic diameter
PM _{2.5}	A subset of PM ₁₀ , which is less than 2.5µm in aerodynamic diameter (also referred to as fine particulate)
RH	Relative Humidity
Sea salt	Particulate matter released to air through the action of wind and waves (also called marine aerosol)
SF ₆	Sulphur Hexafluoride
SOA	Secondary Organic Aerosol
SO _x	Oxides of Sulphur
UNIMO	United Nation's International Maritime Organisation
USEPA	United States Environmental Protection Agency
VOCs	Volatile Organic Compounds. Organic compounds that vaporise in room temperature.
WHO	World Health Organisation
Windblown dust	Particulate matter released from unsealed roads, construction sites, land use activities etc.

Executive Summary

Northland currently experiences generally good air quality, but this is expected to change as the climate continues to warm. Air quality and climate change are closely interconnected environmental challenges that influence one another through shared emission sources, atmospheric processes and changing weather conditions. While air quality is often managed as a local public health issue and climate change as a global environmental concern, both are driven by many of the same activities and respond to the same environmental forces. Understanding these connections is essential for effective environmental management in Northland.

This report examines how climate change is likely to influence future air quality in Northland and how air pollutants themselves contribute to climate change. The findings show that changing meteorological conditions are likely to increase some forms of air pollution even where emissions from certain sources decline. At the same time, air pollutants continue to influence the climate system by altering the Earth's energy balance and atmospheric chemistry.

Projected climate change in Northland includes rising temperatures, more frequent hot days, changing humidity patterns, increased drought conditions, reduced wind speeds and changes in rainfall. These shifts will influence how pollutants are emitted, transported, transformed and removed from the atmosphere. Warmer and more stable atmospheric conditions generally favour the accumulation and formation of air pollutants.

Future air quality is therefore expected to change in several ways. Particulate matter concentrations are likely to increase overall due to more frequent wildfires, greater dust generation during dry conditions and enhanced formation of secondary particles at higher temperatures. Ground-level ozone is also expected to increase, particularly during warm, sunny and low-wind conditions that promote chemical reactions between pollutants. Other climate-sensitive pollutants, including volatile organic compounds, black carbon and ammonia, may also rise under warmer and drier conditions. In contrast, some regulated pollutants, such as sulphur dioxide, nitrogen dioxide and carbon monoxide, may decline due to stricter regulation and cleaner technologies.

Air pollutants also influence the climate. Many gases and particles affect how heat is absorbed, reflected or trapped in the atmosphere. Some produce cooling effects, while others contribute to warming. Black carbon is particularly important because it absorbs sunlight and accelerates warming, especially when deposited on snow or ice.

Overall, the evidence indicates that maintaining Northland's current air quality will become more challenging as climatic conditions change. There remains uncertainty in the magnitude and timing of these changes, but the direction of change is consistent with international research and climate projections.

The report highlights the need for integrated management of air quality and climate change. Actions that reduce fossil fuel use, improve energy efficiency, support cleaner transport and strengthen land management can benefit both air quality and the climate. However, effective policy requires coordinated monitoring, improved emissions reporting, and inclusion of all climate-active pollutants in environmental assessments.

Addressing these interconnected challenges will require ongoing monitoring, improved modelling capability and integration of climate projections into air quality planning. A coordinated science, monitoring and policy response will be necessary to protect public health, ecosystems and long-term environmental resilience in Northland.

Key Findings

- Air quality and climate change are strongly interconnected and influenced by the same emission sources, atmospheric chemistry, and meteorological conditions.
- Climate change will significantly alter Northland's weather patterns, including higher temperatures, reduced wind speeds, and more frequent drought conditions.
- These atmospheric changes are likely to increase some forms of air pollution, particularly particulate matter, ammonia and ground-level ozone.
- Climate-driven factors such as wildfires, dust generation, and enhanced chemical reactions will play an increasing role in future air quality.
- Some regulated pollutants may decline due to technological advances and environmental regulation, but this may not offset increases in climate-sensitive pollutants.
- Air pollutants themselves influence climate through warming and cooling effects, with black carbon being a particularly strong warming agent.
- Current policy and reporting frameworks often treat air quality and climate change separately, despite their strong interdependence.
- Integrated monitoring, emissions reporting, and policy development are essential to manage both air quality and climate risks effectively.
- Measures that reduce fossil fuel use and improve energy and transport systems can deliver benefits for both public health and climate stability.

Introduction

We are surrounded by air. Clean air is essential for the health of humans and the environment. Breathing clean air is fundamental to our well-being and allows us to live healthy and active lives, while breathing polluted air can adversely affect human health. Many recreational, cultural and economic activities are directly related to the clear sky (MfE, 2022, MfE 2024). Health effects of air pollution and public concern regarding the quality of air we breathe has started to increase in recent decades as air pollution has become one of the leading environmental concerns in the world. In 2024, air pollution was identified as the second largest risk factor for early deaths globally, after high blood pressure (Health Effects Institute, 2024). If no action is taken to control air pollution, it is going to be the largest environmental cause of premature death worldwide by 2050 (Schneidemesser et al., 2015). The World Health Organization (WHO) estimates about seven million deaths annually from breathing polluted air (WHO, 2021).

Climate change refers to long lasting changes in the Earth's climate patterns, as a result of human activities such as burning fossil fuels, deforestation, and industrial processes. Emission from these activities increase the concentration of greenhouse gases (GHGs), such as carbon dioxide and methane, in the atmosphere, leading to warming the earth. Global warming results in a range of environmental impacts, including more frequent and severe weather events, rising sea levels, melting polar ice, and disruptions to ecosystems and biodiversity.

Air quality and climate change are serious environmental challenges of our time and for decades to come. Both impact on the earth's environment in different ways, but both are the result of emissions from anthropogenic and natural activities. In general, policy makers and scientists consider air quality and climate change as separate issues. The Resource Management Act 1991 did not mention climate change and GHGs when it was first introduced, even though air quality and climate change are deeply interconnected. Both issues are the result of air emissions from anthropogenic and natural activities, atmospheric properties and chemistry (Putland, et al 2023, Schneidemesser et al., 2015). In other words, the same sources emit both air pollutants and GHGs, for example, emissions from vehicles that contains particulate matter, carbon monoxide, nitrogen oxides and carbon dioxide. However, they impact on the surrounding environment in different ways.

Local air quality depends on contaminants discharged into the air. The fate of contaminants (particles and gases) released into the air depends on local meteorological parameters such as temperature, windspeed and wind direction, as they play a vital role in pollution formation, transportation, dispersion and chemical reactions between pollutants (Habeebullah et al., 2014). The local air quality in cities and towns is influenced by the following:

- the quantity of contaminants discharged to the air,
- atmospheric conditions that can trap, dilute, disperse, transport and remove those contaminants, and
- characteristics of the landscape.

The purpose of this report is to discuss interconnectivity between air quality and climate change, describe how conditions are changing in Northland, and identify implications for future environmental management. This includes the role and influence of climate and meteorology on air quality. It discusses sources of emissions and how emitted pollutants are going to be affected by climate change and, ultimately, how climate change is going to impact on local air quality. This report is based on a literature review, meteorological data obtained from NRC's air monitoring site at Robert Street, Whangārei and NRC's emission inventories.

Air Quality

Air quality describes the condition of the air we breathe and the presence of substances that may harm human health, the environment or the climate. When pollutants such as fine particles or gases are present in elevated amounts, they can pose risks to people, ecosystems and overall environmental wellbeing (MfE, 2009; NRC, 2026; Khanal & Naidu, 2022).

Air quality in Northland is generally good compared with many urban regions. This is largely due to prevailing south-westerly winds, a dispersed population, relatively low traffic density and limited heavy industry. These conditions help pollutants disperse more readily than in densely populated or enclosed urban environments.

However, air quality can deteriorate at certain times of the year. Concentrations of particulate matter (PM₁₀ and PM_{2.5}) occasionally approach or exceed the National Environmental Standards for Air Quality (NESAQ). Elevated particulate levels typically occur during cool, calm conditions when pollutants accumulate near ground level rather than dispersing. These episodes can affect both human health and environmental quality.

The main sources influencing air quality in Northland include:

- solid fuel burning for home heating
- backyard burning
- transport and industrial emissions
- dust from vehicles travelling on unsealed roads
- dust generated by earthworks and land disturbance
- agrichemical application

Further technical descriptions of individual air pollutants are provided in Appendix 2: **Common Air Pollutants**.

Climate Change

Climate change refers to long-term changes in the Earth's climate system, including shifts in temperature, rainfall patterns and weather conditions. Solar energy reaching the Earth is absorbed by the surface and re-emitted as heat. Certain gases in the atmosphere, known as greenhouse gases, trap part of this heat and warm the planet, which is known as the greenhouse effect (CASANZ, 2004).

The greenhouse effect is a natural and essential process that makes the Earth habitable. However, human activities, particularly the burning of fossil fuels and changes in land use have increased greenhouse gas concentrations in the atmosphere. This has intensified the greenhouse effect and accelerated warming beyond natural levels. As a result, climate change is now recognised as a major risk to human health, ecosystems and environmental stability (USEPA, 2025).

The Earth's climate has always changed over geological time, but current changes are occurring more rapidly than many natural historical variations. Scientific evidence indicates that climate conditions in the coming 50 to 100 years are likely to differ significantly from those experienced today (Bodeker et al., 2022). While the terms global warming and climate change are often used interchangeably, global warming refers specifically to the increase in average temperature, which in turn drives broader climate changes (Renowden, 2007).

Detailed descriptions of individual greenhouse gases are provided in Appendix 3: **Common Greenhouse Gases**.

Climate Change & Air Quality: Are they linked?

This chapter discusses the complex relationship between air quality and GHGs and will highlight both similarities and differences between these two environmental issues. As mentioned earlier, climate change and air quality are often talked about separately, even though they are interconnected. There are number of ways that air quality and climate changes are linked, including emissions; atmospheric properties; dispersal processes and chemistry; and mitigation measures (Schneidemesser et al., 2015). Similarly, there are differences between air quality and climate change, for instance, air pollutants are harmful to humans and the environment. They are localised and have a short lifespan in the atmosphere, whereas, GHGs contribute towards global warming and have a longer lifespan in the atmosphere (GeeksforGeeks, 2025). However, air pollutants and GHGs are responsible for problems to both human health and the natural environment and are linked to global warming.

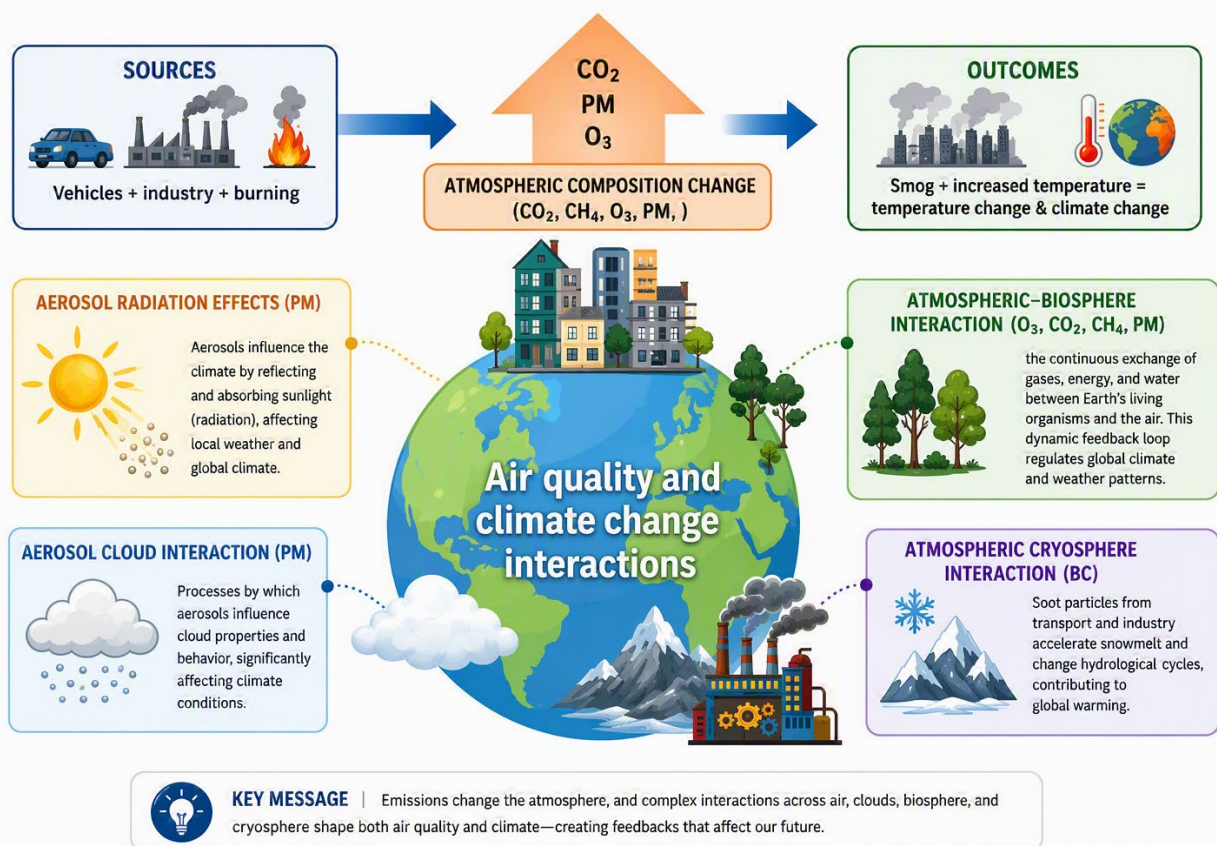


Figure 1: Climate change and air quality are interdependent, linked through shared emission sources, atmospheric processes, and combined environmental and health impacts.

Interaction between meteorology and air quality

Meteorological parameters such as windspeed, wind direction, temperature and humidity play vital roles in air pollutant formation, transportation, dispersion, dilution and reactions between air pollutants (Habeebullah et al., 2014). Therefore, air quality not only depends on emission sources but also on meteorological parameters.

Local winds

Local wind determines the extent to which air contaminants are dispersed. In general, strong winds can carry polluted air away from the emission source and improve local air quality. However, low winds allow pollutants to accumulate, leading to poor localised air quality. Wind direction determines where the polluted air travels from and helps to identify possible sources of air pollution at the monitoring site. Strong winds are responsible for vertical mixing in the atmosphere. On a windy day air pollutants are dispersed horizontally (downwind) and vertically (upper layers of the atmosphere) from the source of emission.

Atmospheric stability

Atmospheric stability is resistance of the atmosphere to vertical motion. It determines whether air parcels are going to rise, sink or stay in place when displaced. Atmospheric conditions play an important role in determining air quality. Air pollutant concentrations are lowest when emissions are mixed well with clean air (horizontally and vertically), and highest when mixing is restricted (Habeebullah et al., 2014).

The atmosphere has layers named stable, unstable and inversion. The stable layer is very still and restricts dilution of air pollutants, resulting in poor air quality. In the unstable layer pollutants are dispersed quickly. The presence and height of these layers is determined by atmospheric pressures and the ambient temperature. In the inversion layer a layer of stable warm air sits above layers of unstable air. This restricts the cooler polluted air below it from mixing, which results in very poor air quality. The inversion layer is usually seen in valleys and basins.

Other meteorological parameters

Other meteorological parameters that can affect air quality are cloud cover, solar radiation, ambient temperature, rainfall and humidity. Cloud cover, solar radiation and ambient temperature impact upon atmospheric stability and local winds. Humidity and rainfall are responsible for removing air pollutants out of the atmosphere (Jacob & Winner, 2009).

Temperature, humidity, solar radiation and cloud cover in general provide suitable conditions for the formation of secondary air pollutants such as ground-level ozone, secondary sulphates and nitrates. Particulate matter in the form of nitrates, polycyclic aromatic hydrocarbons (PAHs) and pesticides get converted to gases during high temperatures leading to decreased concentration of particulate matters. (Jacob & Winner, 2009). Soluble gases and particles are washed out from the air as they interact with cloud, fog, rain and snow in a process called wet deposition, one of the main processes for removing air contaminants from the atmosphere. However, concentrations of sulphates and nitrates (secondary pollutants) increase in contact with moisture.

Two sides of the same coin: GHGs and air pollutants

The main objective of this report is to investigate interconnection between climate change and air quality. In the following section we discuss whether the two issues are different or similar to each other.

Differences

The atmosphere is a complex system. There are several factors that play roles in climate change and air quality. The difference between air quality and GHGs lies in their different mechanisms and impact on the environment. Air quality is the presence of harmful contaminants in the air and is responsible for human health. On the other hand, GHGs are the presence of contaminants in the air which contribute towards global warming by trapping heat in the atmosphere.

GHGs such as carbon dioxide, methane, nitrous oxide and halocarbons are well mixed in the atmosphere and their concentrations are homogeneous due to their long lifespan in the atmosphere (e.g. decades to centuries). They contribute towards a continued warming effect on earth. However, air pollutants such as particulate matter, carbon monoxide, volatile organic compounds, oxides of nitrogen and sulphur, and Black Carbon are not well mixed in the atmosphere and their concentrations are not homogenous due to shorter lifespans in the atmosphere (e.g. minutes, hours, months). They significantly affect humans and the environment. Due to their shorter lifespan, the impact of air pollution is more localised. The difference between GHGs and air pollutants is presented in Table 1, referenced from GeekforGeeks (2025); NOAA Research (2024); and USEPA (2025).

Table 1: Difference between air pollutants and GHGs

Feature	Air Pollution	Greenhouse Gases
Definition	Presence of harmful substances in the air	Gases that trap heat in the Earth’s atmosphere
Main pollutants	PM, SO ₂ , NO ₂ , CO, PAHs, BC, O ₃ , VOCs, etc.	CO ₂ , N ₂ O, CH ₄ , SF ₆ , HFCs, etc.
Effects	Immediate human health and environmental damage	Global warming, climate change, long-term cumulative effects
Human health	Direct effects in lungs (respiratory) and heart	Long-term health effects
Visibility	Visible smog and haze	Invisible but felt through changing weather
Impact on the environment	Acid rain, smog formation, degradation of plants and ecosystems	Rising temperature, melting ice caps, sea-level rise, climate change
Time scale	Immediate and short-term effects	Long-term effects

Similarities

Air quality and GHGs are closely related and share several similarities, such as source, atmospheric processes, and mitigation measures. It is obvious that the same sources emit both GHGs and air pollutants. For example, emissions from driving a car include particulate matter, nitrogen dioxide, carbon monoxide, carbon dioxide, etc. When these contaminants are in the atmosphere they behave differently in terms of lifespan, effect on human health and climate change (Schneidemesser et al., 2015). The key similarities between these two environmental issues are presented in Table 2 (NOAA Research, 2024; USEPA, 2025).

Table 2: Similarities between air pollutants and GHGs

Feature	Description
Common source	Both impacted by anthropogenic and natural activities – burning fossil fuels, industrial processes, agriculture and volcanic emissions, forest fires and so on.
Human health	Both contribute to public health risks. • Poor air quality directly affects human health – causing respiratory problems, heart attacks, etc. • GHGs indirectly affect health by driving climate change such as heatwaves.
Shared pollutants	• Some air pollutants, such as Black Carbon and ozone, contribute to air quality as well as climate change. • Some air pollutants such as aerosols; sulphur dioxides have cooling effects.
Atmospheric mixing	• Once released both types of emissions mix freely in the atmosphere, affecting air quality and climate change simultaneously. • Atmosphere does not distinguish between GHGs and air pollutants, they interact each other's behaviour and effect.
Win-win	Solutions like switching to clean energy or reducing vehicle emission help improve both air quality and climate change outcomes.
Global concern	Both are urgent global challenges requiring urgent action.

Effect of Air Pollutants on Climate Change

Air pollutants are short-lived gases and can have both heating and cooling effects, depending on their radiative activity and the residence time in the atmosphere (in simpler terms, whether they absorb or reflect the sunlight). The heating or cooling effect of gaseous substances in the atmosphere depends on their effective radiation forcing or ERF, which is a concept in climate science that describes changes in the earth's energy balance caused by GHGs, aerosol and land use pattern, typically expressed in watts per square metre (Putland, et al 2023). An air pollutant with positive and negative ERF determines whether the pollutant causes warming or cooling effects on the earth's atmosphere (Putland, et al 2023).

Particulate Matter (PM)

Suspended fine solid or liquid particles in the atmosphere are called PM, also referred to as aerosols. PM have both natural and anthropogenic sources and can be emitted directly from sources or formed in the atmosphere (Schneidemesser et al., 2015). Particulate matters are defined as PM₁₀, PM_{2.5} (fine particles) and PM₁ (ultrafine particles) depending on their aerodynamic size in micrometre. As an air pollutant, PMs cause a variety of adverse effects on human health, including respiratory disease and cardiovascular disease and, at severe levels, PMs can lead to heart attack, stroke and premature death (MfE & Stats NZ, 2021). There is increasing evidence that finer, smaller particles (fine and ultrafine) are better indicators of health impacts across the population (Zoran, 2020; PCE, 2015; Schneidemesser et al., 2015). Particulate matters are not only harmful to human health, but also adversely affect ecosystems and cultural sites, and reduce visibility (Schneidemesser et al., 2015).

Particulate matter emitted from a direct source, such as industrial or vehicle emissions, are called primary particles. However, particles formed indirectly in the atmosphere, such as sulphates, are called secondary particles. Both types of particles have significant effects on climate change. PMs have both direct and indirect effects on climate change. Direct effect is by radiation i.e. absorbing or scattering radiation, and indirectly by aerosol cloud effects (Schneidemesser et al., 2015). The radiation effect of PM can contribute to both warming (i.e. Black Carbon absorbing radiation) and cooling (scattering radiation by sulphate and nitrate particles). Black Carbon absorbs sunlight and warms the atmosphere and when it lands on ice or snow it reduces albedo resulting in faster melting. The indirect effect is a capacity of larger aerosols to act as cloud condensation nuclei (CCN) which can change cloud albedo (that is scattering radiation to space) that shades the planet, resulting in a cooling effect. High concentrations of PM can reduce rainfall by altering the hydrological cycle (NASA, 2025).

The emission of aerosol particles and GHGs into the atmosphere has increased significantly since industrialisation. Increased aerosol concentrations have masked global warming to some extent; however, aerosol particles have a short life span (days to weeks) and their effect on climate is temporary, unlike GHGs as they stay in the atmosphere for decades to centuries (Schneidemesser et al., 2015).

Carbon Monoxide (CO)

Carbon monoxide is not a GHG like carbon dioxide or methane, but plays an important role in climate change, usually indirectly by altering atmospheric chemistry. Incomplete combustion is the primary source of carbon monoxide and burning fossil fuel and biomass are the major sources of carbon monoxide in the atmosphere (Schneidemesser et al., 2015; Boamponsem, 2022). Large

amounts of carbon monoxide also originate from the atmospheric oxidation of methane and non-methane volatile organic compounds (NMVOCs). High concentrations of carbon monoxide can be lethal as a result of asphyxiation (Beer, 2010).

NMVOCs and carbon monoxide indirectly contribute to a warming effect by increasing the life span of methane and producing tropospheric ozone. Degradation of methane in the atmosphere is due to the presence of OH (hydroxyl ions), but when carbon monoxide is present in the atmosphere it reacts with OH ions faster than methane and, therefore, methane remains in the atmosphere longer, which is a well-known GHG (IPCC, 2007). Similarly, carbon monoxide contributes towards photochemical reaction between oxides of nitrogen and VOCs in the presence of ultraviolet light to produce ground-level ozone (IPCC, 2007). Ozone is a short lived air pollutant and a GHG.

Carbon monoxide has a life span in the atmosphere of about one month, long enough to be transported long distances by wind, and enough time to oxidise and produce carbon dioxide, help photochemical reactions to produce ozone and capture hydroxyl ions and increase the life span of methane.

Nitrogen Oxides (NO_x)

The term nitrogen oxides describe a mixture of nitric oxide (NO) and nitrogen dioxide (NO₂). These gases are produced during combustion of fossil fuels and naturally during lightning. Soil and biomass burning also contribute to the formation of oxides of nitrogen. Emissions from diesel vehicles, powerplants, municipal waste incineration, aeroplanes and ships are the main sources of oxides of nitrogen (Schneidemesser et al., 2015). Most emissions from anthropogenic and natural sources emit nitric oxide, a colourless gas which is then oxidised to nitrogen dioxide in the atmosphere. Nitrogen dioxide is a pungent smelling acidic gas and is a main component of photochemical smog. Poorly ventilated houses with gas stoves, heaters or wood burners are significant sources of indoor nitrogen dioxide (Metcalf et al., 2025).

Nitrogen oxides have adverse health effects such as inflammation of the respiratory tract, respiratory issues such as asthma, heart disease and also contribute to increased hospital admissions and premature death (Schneidemesser et al., 2015). Oxides of nitrogen are not only significant air pollutants but also contribute to climate change directly and indirectly (IPCC, 2021).

Nitrogen oxides have a short life span from hours to days, which means their effect on the climate is short lived and localised. Even though nitrogen oxides are not GHGs, their influence on climate change is important to understand. Recent studies that evaluated the emission of nitrogen oxides from the 1850s to the 2000s found that NO_x had a cooling effect (Schneidemesser et al., 2015). However, this study does not include the effect of ozone on plants, which reduces their capacity to absorb carbon dioxide.

NO_x promote the formation of ozone, which has warming effects, but their interactions with methane by altering the concentration of hydroxyl ions and the formation of nitrate aerosols in the presence of ammonia have cooling effects.

On the other hand, nitrous oxide (N₂O), which is not included in the above paragraphs, is a potential GHG and has global warming potential around 300 times higher than CO₂ over 100 years (MfE, 2016a). Nitrous oxide is not an air pollutant.

Sulphur Dioxide (SO₂)

The main source of sulphur dioxide in the atmosphere is from the burning of fuel, mostly from industries, power plants, and shipping with minor contributions from biomass burning. Natural sources of sulphur dioxide are volcanic emissions and oxidation of dimethyl sulphide (DMS) from the ocean. SO₂ is an important air pollutant and responsible for affecting the respiratory system, lung function and eye irritation. It also causes coughing, asthma and chronic bronchitis (LAWA, 2024). When sulphur dioxide combines with water vapour in the atmosphere it forms sulphuric acid leading to acid rain (NRC, 2012). Sulphuric acid in the atmosphere leads to the formation of sulphate as an aerosol. Sulphate aerosols have adverse effects on ecosystems as they are acidic in nature.

Sulphate aerosols interact with incoming solar radiation through a scattering process, leading to a net cooling effect on the earth. However, this cooling effect is short lived as sulphate aerosols only have a life span of days to weeks. Sulphate aerosol particles can easily mix with other compounds in the atmosphere, grow their size through coagulation and activate cloud coagulation as the particles are hygroscopic in nature. Interaction between aerosols (not only sulphate) and clouds results in a cooling effect (Schneidemesser et al., 2015; IPCC, 2021).

Reducing emissions of sulphur dioxide in the atmosphere has a positive outcome on air quality and health-related issues, however, that can accidentally unmask the warming effects of GHGs. Recent studies have shown that the Atlantic Ocean is warming faster than expected because of disappearing clouds known as ship tracks (Voosen, 2023). It is suggested that one of the reasons of this warming effect is the regulation imposed by United Nation's International Maritime Organisation (UNIMO) to phase out high sulphur containing ship fuel by more than 80 percent to improve air quality and health (Voosen, 2023). As a result, crisscrossing clouds visible over the Atlantic Ocean are disappearing quickly leading to a warmer ocean.

Volcanic eruptions emit large amounts of SO₂ into the atmosphere, forming aerosols that can have cooling effects lasting between one and three years. For example, about 15 million tonnes of SO₂ was injected into the stratosphere when Mount Pinatubo in the Philippines erupted in 1991. Aerosols from that eruption reduced the global temperature by 0.6°C for about 15 months (NASA, 2001). This eruption is considered one of the most significant events in terms of climate impact, and serves as a real-world validation of climate models predicting aerosol-induced cooling effects on earth, Figure 2.



Figure 2. Eruption cloud of Mount Pinatubo, Philippines, June 1991, Photo by (Harlow, 1991).

Ozone (O₃)

Ozone is a secondary air pollutant, meaning it is not directly released by known sources but is formed in the atmosphere from the reaction between oxides of nitrogen and volatile organic compounds in the presence of sunlight. As the reaction to produce ozone occurs in the presence of sunlight, ozone concentration is higher in the spring and summer than in winter and autumn.

As an air pollutant, ground-level ozone (tropospheric) causes human health effects such as coughing, throat irritation and worsens asthma and lung diseases. Long-term exposure to ozone can lead to hospitalisation and premature death (LAWA, 2024). In addition to its effects on human health, ozone can also damage plants, disturb photosynthesis, reduce crop yields and impact forest health. On the other hand, stratospheric ozone is beneficial for human health and the environment as it absorbs harmful ultraviolet radiation from the sun.

Ozone is not only an air pollutant but also an active GHG due to its ability to absorb infrared radiation. Precursor compounds to ozone such as NMVOCs, CO and NO_x do not have direct influence in climate change but still affect the climate through a variety of indirect effects, not limited to their role in the formation of ozone. Ozone precursors except NO_x oxidised to CO₂, which is a most potent GHG (Schneidemesser et al., 2015).

The effects of ozone on climate change are not only limited to direct affects, but also indirect effects on climate change through adverse effects on vegetation, inhibiting the uptake of carbon dioxide. Ozone is a strong oxidising agent that enters plants through stomata on leaves and initiates a series of oxidation reactions that degrade chlorophyll and reduce photosynthesis. This process adversely reduces plant growth and capacity to uptake carbon dioxide. However, this effect varies from region to region as formation of ozone depends on availability of nitrogen oxides and volatile organic compounds (Unger, & Pan, 2012). It is believed that the interaction between ozone, aerosols and biochemical cycles may possibly be the most important climate impact of the short-lived air pollutants (Unger, & Pan, 2012).

Black Carbon (BC)

Black Carbon (soot) is a main component of fine particulate matter PM_{2.5}. BC particles are produced from incomplete combustion of carbon compounds such as fossil fuels. Bushfires, diesel engines, residential wood burning and industrial processes are major sources of BC. Even though BC is a component of PM_{2.5} it only contains carbon particles, whereas PM_{2.5} includes sulphates, nitrates, salts, BC and so on.

BC has similar health effects as PM_{2.5} such as respiratory symptoms and increased hospitalisation, cardiovascular problems and long-term exposure to high concentrations can lead to premature death (Kuschel et al. 2022). There is also evidence that exposure to PM_{2.5}, with a high BC component, leads to higher mortality rates than a PM_{2.5} mixture (sulphates, nitrates, etc.).

Unlike most aerosols, which scatter sunlight and have cooling effect on earth, BC efficiently absorbs sunlight and heats the atmosphere and is considered one of the most important light absorbers (Schneidemesser et al., 2015 & Bond, 2013). When BC particles settle on snow and ice, they reduce the amount of reflected sunlight leading to faster melting of glaciers and polar ice and ultimately contributing towards sea level rise (Bond, 2013). It is believed that BC is the second strongest contributor towards global warming after carbon dioxide ((Schneidemesser et al., 2015).

BC can change the precipitation pattern by interacting with cloud formation and reducing the reflectivity pattern of cloud and is an important driver for its impact on climate change and human

health effect. BC is short lived (days to weeks) but its impact on climate and health is much higher than expected by many policy makers and scientists. Therefore, reducing emissions of BC could benefit human health as well as reduce its impact on climate change.

Other air pollutants

Other air pollutants include polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), organic aerosol and NMVOCs. These pollutants are not well known to the public or listed in the National Environmental Standard for Air Quality (NESAQ) but are nasty air pollutants that originate from both natural and anthropogenic sources.

PAHs are a group of persistent organic pollutants, are usually present in particulate matter such as PM_{2.5} and have significant health effects. PAHs combined with PM_{2.5} can travel long distances. PAHs are linked to respiratory issues, mental health and ecological damage. Some PAHs are well known carcinogens such as benzo(a)pyrene (Cavanagh, 2009). PAHs are not GHGs, but they indirectly contribute to climate change. PAHs bound with particulate and BC can absorb sunlight and contribute towards warming. Polycyclic aromatic hydrocarbon compounds are made of carbon and hydrogen, and undergo photochemical oxidation and microbial degradation in air, soil and water. During this process PAHs break into smaller hydrocarbons and eventually produce carbon dioxide, a most important GHG (Cavanagh, 2009).

VOCs originate from both anthropogenic (vehicle exhaust, paints, coatings) and natural sources (emission from plants during photosynthesis). VOCs have direct effects on climate warming as they can trap heat themselves (Murrells, & Derwent, 2007). VOCs also indirectly contribute to climate change by forming ozone (a known GHG) by interacting with other air pollutants such as nitrogen dioxide (Schneidemesser et al., 2015). VOCs are responsible for smog formation that affects plant growth and reduces the ability of plants to capture carbon dioxide from the atmosphere. Photochemical smog reduces crop yield and damages ecosystems. Incineration of VOC is a common emission control practice to reduce emissions of VOC and improve the air quality of the surrounding areas, but unfortunately incineration of VOCs produces carbon dioxide (Murrells, & Derwent, 2007).

Effect of Climate Change on Air Quality

Good or poor air quality is dependent on meteorological parameters and, therefore, sensitive to climate change. There are many ways that climate change can affect air quality such as temperature, humidity, windspeed and direction (Habeebullah et al., 2014; Jacob & Winner, 2009). It is local meteorology that creates atmospheric conditions which determine good or poor air quality. The science behind this is complex, but in simple terms meteorological conditions such as windspeed helps to transport and disperse air pollutants. Similarly, temperature creates suitable conditions to interact between air pollutants to produce secondary air pollutants such as ozone. To understand effects of climate change on air quality, it is necessary to understand what the projected atmospheric conditions are due to climate change.

Projected changes to atmospheric conditions

To determine good or poor air quality we use hourly, daily and annual exposure to contaminants concentrations. It would be helpful to have projected atmospheric conditions to predict impact of climate change on air quality. The only projected information available for Northland is NIWA's projections undertaken in 2016 (Pearce, 2017). This report does not tell us how atmospheric stability will change or how frequent temperature inversion will occur. That makes it difficult to predict future air quality correctly.

The NIWA projections for Northland that are relevant to atmospheric conditions useful to predict future air quality, because of climate related changes, are:

- Northland is likely to warm significantly: annual hot days (>25°C) may increase from 25 days to 99 days by 2090;
- frost may decline from one frost every two years at present to one frost every 10 years by 2090;
- high solar radiation;
- increase in drought frequency;
- up to 10% less rainfall by 2040;
- rare, large extreme rainfall events are likely to increase; and
- decrease in windspeed.

International climate journals report that climate change will lead to fewer poor air quality days because of a decrease in winter stagnation events. Rainfall and humidity are expected to increase because of increased evaporation due to higher solar radiation (Jacob & Winner, 2009). Some other journals suggesting atmospheric conditions, such as heated upper troposphere, and temperature inversions are likely to occur frequently (Schneidemesser et al., 2015). Bodeker, et al., (2022) suggests an increase in temperature, a decrease in windspeed and more frequent north easterly winds in the summer months in New Zealand because of climate change.

There is no consistency in possible future atmospheric conditions as different models produce different projections. However, most journals and NIWA predict that temperature, humidity and solar radiation are going to increase. There is uncertainty on rainfall, windspeed and wind direction.

What NRC's meteorological data say

NRC started monitoring meteorological parameters such as temperature, windspeed, wind direction, humidity and so on in September 2010 from its air monitoring site situated at Robert Street, in the

Whangārei central business district. It is useful to collect meteorological data along with air pollutants, as air quality and meteorological parameters are closely linked.

IPCC (2021) and other climate researchers recommend using at least 30 years or more of monitoring data to define long-term climate change trends. Fifteen years of meteorological data from Whangārei is insufficient for long-term climate predictions but is a reasonable amount of data to check short-term climate variability that can provide valuable insights of the local meteorology.

We have used the de-seasonalised Theil-Sen technique with 95% confidence level for trend analysis of meteorological parameters using an OpenAir R package. Sen-Theil trend analysis is commonly used by councils in New Zealand for air quality reporting (Cadwell, 2019; Talbot & Crimmins, 2020). The trend analysis is divided into three separate time periods - the first for the whole monitoring period (September 2010 to August 2025); the second from 2011 to 2020 and the third between 2015 and 2024. The summary of trend analysis is shown in Table 3 below.

Table 3: Trend analysis of meteorological parameters in three separate scenarios

Parameter	Period	Change	Range	p-value	Significant?
Temperature	2010 - 2025	0.06 °C ↑	0.04 – 0.09 °C	<0.001	Yes
	2011 - 2020	0.10 °C ↑	0.06 – 0.13 °C	<0.001	Yes
	2015 - 2024	0.06 °C ↑	0.02 – 0.01 °C	<0.001	Yes
Relative Humidity	2010 – 2025	0.00% X	-0.09 – 0.08%	>0.0	No
	2011 – 2020	-0.31% ↓	-0.42 – -0.18%	<0.001	Yes
	2015 - 2025	0.24% ↑	0.11 – 0.36%	<0.001	Yes
Windspeed	2010 – 2025	-0.01 m/s ↓	-0.01 – 0.0 m/s	<0.05	Yes
	2011 – 2020	-0.01 m/s ↓	-0.01 – 0.0 m/s	<0.05	Yes
	2015 - 2025	-0.01 m/s ↓	-0.01 – 0.0 m/s	<0.1	No
Rainfall	2010 – 2025	0.00 mm X	0.00 – 0.00 mm	>0.0	No
	2011 – 2020	0.00 mm X	0.01 – 0.00 mm	>0.0	No
	2015 - 2025	0.00 mm X	0.00 – 0.01 mm	>0.0	No

↑ - upward trend

↓ - downward trend

X – no change

As mentioned in international journals, and by NIWA and IPCC, NRC's monitoring data show that the temperature in Whangārei is increasing in all scenarios as shown in Table 3. An increase in temperature by 0.06 °C per year is shown during scenario 1 and 3 and by 0.1 °C per year in scenario 2 and the increase in temperature is significant with $p = <0.001$ in all scenarios. This increase is higher than expected but is similar to that reported by Khanal & Naidu in 2022. Windspeed shows a decreasing trend in all scenarios as expected by Pearce (2017) and Bodeker et al., (2022). All scenarios show a 0.01m/s decrease in windspeed in Whangārei per year. Relative humidity shows a mixed trend. Increase and decrease in scenarios 2 and 3 respectively are significant with $p = <0.001$. However, over the full monitoring period no change in relative humidity was shown. As predicted by previous publications, windspeed showed a downward trend in all scenarios with moderate confidence ($p = <0.05$, 0.05 and 0.1 respectively). Rainfall did not show any trend. Table 3 only shows a summary of trend analysis; detailed graphs are given in Appendix1.

Climate change and emissions to air

Climate and meteorology impact on emissions to the air, both directly and indirectly, such as wind-blown dust emissions and temperature driven home heating requirements. This section discusses the main emission sources in Northland and how climate change is going to impact on these emission sources.

Home heating

Both climate and meteorology impact on the heating and cooling requirements of residential homes, businesses, schools, hospitals and industries. Northland's air quality is greatly impacted by emissions from home heating during the winter months. Northland's air monitoring records show high levels of PM₁₀ and PM_{2.5} often occur in cool and calm conditions. Even though Northland is often referred to as the winterless north, home heating is still one of the major sources of PM₁₀ and PM_{2.5} in our airsheds. Estimated PM₁₀ and PM_{2.5} emissions from home heating in Northland airsheds are shown in Table 4 below.

Table 4: Estimated PM₁₀ and PM_{2.5} emissions from home heating in Northland airsheds.

Airsheds	PM ₁₀		PM _{2.5}	
	Annual%	Winter day%	Annual%	Winter day%
Whangārei	45	71	54	78
Kaitiāia	15	35	19	40
Dargaville	46	65	50	67

Table 4 shows that domestic heating is one of the main sources of annual and winter day for both PM₁₀ and PM_{2.5}. In the Whangārei airshed domestic heating contributes 45% and 54% to the annual emissions of PM₁₀ and PM_{2.5} respectively. Domestic heating contributions increase to 71% and 78% of PM₁₀ and PM_{2.5} in winter day (PDP, 2021). Domestic home heating contributions to PM₁₀ (46% annual and 65% winter day) and PM_{2.5} (50% and 67%) in the Dargaville airshed are similar to the Whangārei airshed (Wilton and Zawar-Resa, 2023). However, domestic heating contributions to PM₁₀ and PM_{2.5} in the Kaitiāia airshed are significantly lower than both the Whangārei and Dargaville airsheds.

Wood burning releases large quantities of air pollutants into air, including particulate matter of mostly PM_{2.5}, carbon monoxide, carbon dioxide, oxides of sulphur and nitrogen. PAHs, VOCs, arsenic, and lead released from burning wood are usually present in particulate matter. Most wood burners are used in the evening and morning when atmospheric conditions are calm, cold and clear; the perfect conditions for air pollutants to accumulate and contaminant concentrations to rise.

Air pollutant emissions from home heating are expected to decrease in Northland with increasing temperatures, the introduction of low emission wood burners and the popularity of heat pumps. PDP (2021) reports that in 2018 fewer homes in Whangārei were using wood burners than they were in 2006. Climate change is going to reduce the use of wood burners in Northland with a projected increase in temperature and sunshine hours (Pearce, 2017). With changing seasonal patterns home heating frequency and duration is going to change. A decrease in frosty conditions is also expected due to climate change. Pearce (2017) assumed that the heating season will be shorter in most areas of Northland.

Motor vehicles

Emissions from transport or vehicles to air include tailpipe emissions of a range of air pollutants and particulate matter emissions due to wear and tear of brakes and tyres. This also includes contaminants from fuel evaporation during storage, distribution, refuelling, etc. The main air pollutants released from vehicles include carbon monoxide, oxides of nitrogen and sulphur, VOCs and particulate matter PM₁₀ and PM_{2.5}. Estimated PM₁₀ and PM_{2.5} emissions from motor vehicles in Northland's airsheds is presented in Table 5.

Table 5: Estimated PM₁₀ and PM_{2.5} emissions from motor vehicles in Northland airsheds.

Airsheds	PM ₁₀		PM _{2.5}	
	Annual%	Winter day%	Annual%	Winter day%
Whangārei	32	17	30	14
Kaitiāia	6	4	6	4
Dargaville	3	1	3	2

Annual and winter day PM₁₀ and PM_{2.5} emissions from vehicles presented in Table 5 shows that contributions from motor vehicle emissions to particulate matter decrease in winter in contrast to home heating emissions. Particulate matter emission from motor vehicles in Kaitiāia and Dargaville is significantly lower than that in the Whangārei airshed. Wilton and Zawar-Resa (2023) estimated that around two kilograms of PM₁₀ and PM_{2.5} are emitted from vehicles in the Dargaville airshed per day.

Motor vehicle emissions are gradually decreasing over time due to improved fuel quality and technology. As awareness towards climate change increases, it is a reasonable expectation that people will bike, walk and use public transport more often, resulting in lower emissions of air pollutants from motor vehicles. On the other hand, the number of motor vehicles will increase due to population growth, but newer technologies, improved fuel quality and an increase in electrical vehicle use is not going to add extra air pollutants from motor vehicles.

Increased temperature is going to have an effect on combustion and evaporative emissions, as warmer temperatures favour lower carbon monoxide, oxides of nitrogen and sulphur and particulate matter emissions (Habeebullah et al., 2014). With warmer temperatures, evaporative emissions such as VOCs could potentially increase. Drier weather conditions are going to favour road dust emissions, however, emissions from tyre and break wear and tear are not expected to alter with climate change.

Overall, it is expected that a warming climate will lead to lower motor vehicle tailpipe emissions, coupled with a change in commuting behaviour, but dust nuisance from roads is likely to increase due to drier conditions.

Industry

Industrial and commercial sources discharge a variety of air pollutants depending on industrial or commercial activities. Combustion, chemical processing and mechanical generation are the main emission sources of air pollutants, such as particulate matter, carbon monoxide, oxides of nitrogen and sulphur, VOCs, and PAHs. Industrial sites are also major sources of dust and odour nuisance. Estimated PM₁₀ and PM_{2.5} emissions from industries in Northland's three airsheds is presented in Table 6.

Table 6: Estimated PM₁₀ and PM_{2.5} emissions from industries in Northland airsheds.

Airsheds	PM ₁₀		PM _{2.5}	
	Annual%	Winter day%	Annual%	Winter day%
Whangārei	15	8	6	3
Kaitiāia	76	59	72	54
Dargaville	18	9	11	5

Table 6 shows that industrial emissions of PM₁₀ and PM_{2.5} in Dargaville and Whangārei airsheds are the third biggest source after home heating and vehicle emissions. However, industrial emissions are the largest contributor to annual and winter day PM₁₀ and PM_{2.5} readings in Kaitiāia (PDP, 2021; and Wilton and Zawar-Resa, 2023). Major particulate matter contributors in the Kaitiāia airshed are two

mills operated by Juken New Zealand, situated at the northern end of Kaitāia township. Industrial emission percentage goes down during winter as domestic heating activity increases.

Just as for vehicle emissions, industrial emissions in Northland are also decreasing over the years, because of the closure of industrial operations, upgrades in emission control systems, a switch to cleaner fuels and improved combustion related technologies (Khanal & Naidu 2022).

Climate change is going to have an influence on industrial and commercial emissions. Increasing temperatures are going to reduce heating requirements for industrial and commercial buildings (universities, schools, hospitals) while improved emission control systems and combustion engines will reduce air pollutants discharged to air. We expect VOCs and dust emissions to increase due to warmer and drier weather conditions. Emissions of VOC and increased temperature and sunshine hours will favour higher ozone production in the atmosphere (Schneidemesser et al., 2015).

Backyard burning

Burning and smoke nuisance complaints account for the majority of environmental incidents generated each year in Northland. Backyard burning of green waste or household materials release nasty air pollutants such as particulate matter, carbon monoxide, oxides of sulphur and nitrogen, VOCs, PAHs and BC. Backyard burning causes significant nuisance to neighbouring residents. Estimated PM₁₀ and PM_{2.5} emissions from backyard burning are presented in Table 7.

Table 7: Estimated PM₁₀ and PM_{2.5} emission from backyard burning in Northland airsheds.

Airsheds	PM ₁₀		PM _{2.5}	
	Annual%	Winter day%	Annual%	Winter day%
Whangārei	8	4	10	5
Kaitāia	3	2	3	2
Dargaville	33	25	36	26

Table 7 shows that backyard burning emissions of PM₁₀ and PM_{2.5} in the Dargaville airshed are the second biggest source after home heating. However, backyard burning is not a major contributor to annual and winter day PM₁₀ and PM_{2.5} in Whangārei and Kaitāia (PDP, 2021; and Wilton and Zawar-Resa, 2023).

The main impact on emissions from backyard burning due to climate change is difficult to predict. However, they are predicted to decrease as warmer, drier and windier conditions make it difficult to manage backyard burning as they could easily lead to uncontrolled fires. To minimise uncontrolled fire episodes, responsible authorities have to impose stricter rules on backyard burning and need to educate the public on the dangers of backyard burning. Promotion of alternative waste disposal methods and greater public awareness of climate change will help to reduce emissions of air pollutants from backyard burning.

Dust

Dust is a non-combustion component of particulate matter (mostly coarse particles). Dust is a nuisance issue such as soiling, visibility and reduced amenity, but it can carry contaminants that are harmful to human health and the environment (MfE, 2016). The major sources of dust in Northland are unsealed roads, earthworks, industrial and commercial yards, while quarries, bare land, ports, fertiliser application and aggregate stockpiles are other known sources of dust nuisance in our

region. Northland has over six thousand kilometres of unsealed roads, which accounts for around 61 percent of the total regional road length.

NRC has not prepared an emission inventory for dust for Northland airsheds and, therefore, we do not know how much dust is produced in Northland. However, NRC's unsealed road PM₁₀ monitoring showed an exceedance of the daily PM₁₀ National Environmental Standard for Air Quality (NESAQ) standard of 50 µg/m³ on several occasions (Khanal, 2020).

Climate change is expected to increase temperatures, sunshine hours, extreme weather conditions, and drought due to low rainfall, which are perfect conditions for dust generation. In these conditions dust particles easily become airborne, especially in areas where there is little or no vegetation present. Stronger winds will lift greater amount of dust into the air and transport it elsewhere. Overall, it is our opinion that dust events are likely to increase in Northland as a result of climate change.

Agricultural emissions

Agricultural practices in Northland that generate discharge to air include burning of vegetative waste, agrichemical and fertiliser applications, and livestock manure applications on land. The majority of these activities are nuisance related and release air pollutants. Application of manure and fertiliser releases ammonia that reacts with oxides of sulphur and nitrogen to form secondary particulate matter such as ammonium sulphate or ammonium nitrate. Warm temperatures with alkaline soil favour the release of ammonia into the atmosphere. Release of ammonia will also increase from intensive farming of animals (pig, poultry and dairy). Ammonia is associated with odour nuisance complaints to the council.

Agrichemical application to control spread of weeds, pest and insects and plant diseases releases nasty chemicals into the air. Application of agrichemicals that drift away from the intended area is expected to increase with high temperatures. Most of these chemicals are volatile in nature and vaporise in high temperatures. Meteorological conditions such as temperature, humidity, wind direction and windspeed influence spray-drift. Future use of agrichemicals is expected to increase due to the emergence of new pests and diseases because of warmer conditions. With greater chance of volatilisation of chemicals and changing wind patterns, this will result in larger areas being affected by spray-drift.

Vegetation

Emissions from vegetation include air pollutants discharged from wildfires, during photosynthesis and pollen. These pollutants contribute to the quality of the air we breathe and have effects on human health and the environment.

Wildfires can discharge large amounts of air pollutants to the air. These include particulate matter, carbon monoxide, oxides of nitrogen and sulphur, BC, PAHs, volatiles and heavy metals such as mercury and arsenic (Arriagada, et al. 2020). The impact on local air quality from wildfires is highest to neighbouring cities, but wildfire emissions can also affect air quality thousands of kilometres away. Australian bushfire smoke in the summer of 2019/2020 increased particulate matter concentrations in New Zealand air monitoring stations, including Northland air monitoring sites (Khanal, & Naidu, 2022).

During photosynthesis plants release biogenic VOCs such as isoprene and monoterpenes, which are highly reactive and only stay in the atmosphere for 3 to 5 hours. These compounds react with oxides

of nitrogen and produce secondary particulate matters (Arriagada, et al. 2020). Tree species like willows, poplars, oak, eucalyptus, pine and other conifer release isoprene, pinene, and monoterpenes (Khanal, 2003).

Vegetation release pollen and spores into the air. Pollens are bigger than PM_{10} but can impact on human health. Pollen can break into smaller particles in the atmosphere and cause asthma symptoms and other allergic reactions.

Climate change is going to influence emissions from vegetation. Increased temperatures, drought, low soil moisture and humidity affect vegetation moisture level and increases rate of combustion and spread of fire. Wind direction and speed is going to determine extent of fire. Strong winds help to spread fires quicker than it can be controlled. Therefore, we expect wildfires to continue to occur more frequently and is going to be more intense. The amount of air pollutant emissions will continue to increase (Arriagada, et al. 2020).

Climate change will have strong influence on biogenic VOCs and pollen emissions. The pollen season is expected to get longer than presently, which is usually between Spring (end of August) and early Autumn (March).

Other emissions

Other air pollutants likely to be affected by climate change include the generation of bioaerosols like fungal spores, bacteria, mould and viruses as well as emissions from waste management, landfill and contaminated sites. Landfill gases such as methane and carbon dioxides are GHGs, but there are other air pollutants such as odour associated with composting of organic matter. Emissions from waste management sites also include odour causing gases such as VOCs and sulphides.

Effect of climate change on air pollutants

Air quality strongly depends on meteorology. Therefore, air quality is sensitive to climate change. Previous sections discussed how climate change is going to affect major air emission sources in Northland. In this section we discuss how climate change is going to impact individual air pollutants and future air quality in our region. The focus of this section is on air pollutants that are of concern now (particulate matter) and those likely to increase in concentration due to climate change (ozone, VOCs) based on projected changes on atmospheric conditions.

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

Particulate matter (PM) monitoring results for Northland confirm compliance with the NESAQ. In general, particulate matter concentrations are lower in summer and higher in winter, indicating the contributions from home heating sources during winter months.

Factors influencing PM concentrations such as increases in temperature, humidity, drought and decrease in windspeed (stagnation) favour growth in particulate matter concentrations. The effect of climate change is going to increase wildfires episodes, that will increase fine particulate matter ($PM_{2.5}$), BC and secondary aerosols such as organic carbon. Schneidemesser et al. (2015) reports up to a 40 percent increase in organic carbon particulates in the western United States, 90 percent of that contributed from wildfires. Emissions from more frequent and intense wildfires can travel long distances from origin and will degrade air quality in bigger areas. High temperature and sunshine

hours will increase the formation of secondary PM, such as sulphates and nitrates, with projected increases in humidity leading to more foggy days in Northland.

Several studies investigated the influence of climate change on future wildfire risk and areas burned rather than the impact on air quality. But we understand that wildfires are going to increase in emissions of air pollutants to the atmosphere as wildfire season is going to extend between spring and autumn due to warmer temperatures (Schneidemesser et al., 2015).

Currently Northland is experiencing lower concentrations of PM in summer. The projected climate change is likely going to result in higher concentrations of PM₁₀ in summer from expected dust storms and dust emission from unsealed roads. Dust impact is localised, but with suitable wind direction and speed, finer particles of dust can travel long distances. Marine aerosol PM concentrations are going to increase in coastal areas and predicted low windspeed can lead to accumulation of PM₁₀ due to decreased dispersion of PM.

On the other hand, climate change can lead to lower PM concentrations (especially PM_{2.5}) as warmer temperatures are likely to reduce emissions from heating sources in residential and commercial buildings. It is expected PM_{2.5} emissions from industries and motor vehicles will decline due to the use of newer and efficient technologies. Some studies and models are suggesting a decrease in PM concentrations due to increased temperatures. The particulate component of nitrates and VOCs will shift from PM to gas because of higher temperature and sunshine hours (Jacob & Winner, 2009). Stricter discharge to air regulations and cleaner technologies can offset some of the increase in PM concentrations, especially in summer months.

It is expected that pollen concentrations will increase. High pollen concentrations will not impact on our monitored PM concentration as pollen particles are larger than PM₁₀, but they will impact on human health. Pollen season is going to be extended.

It is difficult to correctly predict the impact of climate change on PM because we do not know many variables other than the increase in temperature. How often extreme dust storms, wildfires and marine aerosol events will occur or if weather conditions will be more stable is unknown. However, it is our opinion that even though there will be decreases in winter PM concentrations or daily concentrations, annual concentrations of PM are going to increase due to an increase in dust storms and wildfires in the summer months.

Ozone (O₃)

There is no ground-level ozone monitoring conducted in Northland. Ozone is not a primary air pollutant. It is formed by photochemical reactions between carbon monoxide, oxides of nitrogen and VOCs in the presence of sunlight. It is our understanding that the concentrations of oxides of nitrogen and VOC in Northland is not sufficient for photochemical reactions to occur for ozone to form in Northland at present.

Ground-level ozone concentration is going to increase due to climate change. There are a variety of reasons to support this statement, such as an increase in temperature, humidity, sunshine hours and natural emissions of VOCs. These conditions are favourable for photochemical reactions to occur. A number of international journals have projected an increase in ground-level ozone in the future (Jacob & Winner, 2009; Schneidemesser et al., 2015; Arriagada, et al. 2020). Schneidemesser et al. (2015) mentioned that there will be an increased exchange between troposphere and stratosphere, which will affect future ozone concentration.

The expected increase in humidity due to an increase in water vapour as a result of increased temperatures is expected to decrease ozone lifetime and lower ground-level ozone in remote areas and less polluted regions, particularly over the oceans. However, increased VOCs, oxides of nitrogen and favourable meteorology will ultimately increase the concentration of ozone in the atmosphere (Schneidemesser et al., 2015 and Jacob & Winner, 2009).

PAHs

PAHs are semi-volatile in nature and can be present as particles and gases in air. They are generally produced by combustion of organic materials and main sources of PAHs in Northland are emissions from vehicles, wood burners, and industries. PAHs are known carcinogens to humans and the priority contaminant in New Zealand's Ambient Air Quality Guidelines (Cavanagh, 2009).

From the projected meteorological parameter changes it is expected that the concentration of PAHs in the atmosphere will potentially increase in summer as wildfires are likely to be frequent and intense. A study in central Canada found that concentrations of PAHs in the areas affected by smoke from wildfires were 17 times higher than areas unaffected by smoke (Wentworth, et al; 2018).

Higher temperatures are going to enhance the volatilisation of PAHs from soil and water into the atmosphere, which will increase airborne concentrations of PAHs. Photochemical reactions due to increased sunshine hours and temperature can lead to the formation of nitrated, oxygenated and alkylated PAHs, which are more toxic than the parent PAHs.

In winter we expect PAH emissions from home heating, vehicles and industries to be lower because of reduced heating requirements and improved technology and fuel quality. These reductions will, in part, be offset by potential increases from wildfires. Overall, PAH concentrations in the future will increase.

VOCs

Volatile organic compounds such as benzenes, ethyl benzene, toluene, xylene (BTEX) are known toxins to humans and can cause neurological impairment. VOCs are emitted to the atmosphere from motor vehicles, bulk storage sites, petrol stations, workshops, spray painters and dry cleaners. Biogenic VOCs are emitted by plants during photosynthesis.

Emissions of biogenic VOCs and other VOCs are strongly dependent on temperature, sunlight and composition of surrounding air, vegetation type and the leaf area. Several models and studies have suggested that with climate change future concentrations of VOCs are going to be affected and are going to increase ((Schneidemesser et al., 2015). It is predicted that climate change is going to increase isoprene emissions by 30 to 80 percent by the year 2100 (Schneidemesser et al., 2015). Higher concentrations of isoprene are going to increase concentrations of ozone and particulate matter.

Some international journals are reporting that deforestation by human activities and their replacement with crops may decrease emissions of biogenic VOCs. On the other hand, there is also a trend to replace agricultural land with plantations of woody species (such as pine in New Zealand or palm plantations elsewhere) that is going to increase emissions of biogenic VOCs (Schneidemesser et al., 2015 and Jacob & Winner, 2009).

Other

We did not find reliable literature on the effects of climate change on other air pollutants such as nitrogen dioxide, sulphur dioxide and carbon monoxide. Cleaner energy, improved technologies and strict air quality regulations are expected to decrease concentrations of sulphur dioxide, but concentrations of carbon monoxide and nitrogen dioxide are expected to increase due to high energy demand as a result of increased temperatures. Higher concentrations of carbon monoxide and nitrogen dioxide will increase the formation of more ozone in the atmosphere.

Higher temperature and lower windspeed can lead to an increase in nuisance effects such as odour, smoke and dust. Warmer weather will enhance production of odorous air pollutants from intensive farming. Smoke nuisance will increase due to wildfire activities. An increase in pollen related allergies because of climate change is also expected.

The effect of climate change on air pollutants explained in the above paragraphs is summarised in Table 8 with expected trends, confidence levels and key drivers.

Table 8: Summary of climate change impact on air pollutants.

Pollutant	Expected trend	Confidence level	Key drivers	Reference
O ₃	↑ Increase in ground level ozone, during heatwaves and stagnation events.	High	Higher temperature, increased sunny days, high VOC and NO _x emissions	NOAA, 2023
PM _{2.5}	↑ Increase due to wildfires, drought, and secondary aerosol formation	High	Wildfires, reduced precipitation and increased stagnation	NOAA, 2023
PM ₁₀	↑ Increase in arid regions due to deforestation and dust storms	Medium	Land degradation, drought, wind erosion	IPCC, 2023
NO ₂	↑↓ Variable: may decrease with mitigation but increase locally due to heat driven demand	Medium	Traffic emissions, energy use, temperature driven chemical reactions	USEPA, 2025
SO ₂	↓ Decrease due to cleaner fuels and air quality regulations but episodic increase possible such as volcanic eruptions	High	Fuel use, industrial emissions, ship emissions volcanic activities.	USEPA, 2025
CO	↓ Overall decrease expected but wildfires and biomass burning can cause spikes	Medium	Combustion sources, wildfires	USEPA, 2025
VOCs	↑ Increase in biogenic VOCs due to vegetation change and temperature rise	Medium	Plant emission, temperature, urban heat effects	Enciso-Diaz et al. 2025
Lead	↓ Decrease, due to phaseout from fuels, industrial controls, paints etc.	High	Regulatory control, reduced industrial emission	USEPA, 2025
Mercury	↑ Increase release from wildfires, thawing of permafrost, soil	High	Wildfire, coal burning, warming oceans enhances microbial activity	Esquivel-Elizondo, et, al. 2025
Ammonia	↑ Increase due to high temperature increases volatilisation of fertiliser, manure, change in agricultural practice	High	Livestock waste, fertiliser use, drought conditions, changed farming practice.	Esquivel-Elizondo, et, al. 2025
PAHs	↑ Increase due to wildfires and volatilisation from ground and water due to increase in temperature	High	Wildfires, high temperature, photochemical reaction due to long sunshine hours	NOAA, 2023

How do we address the complex relationship between air quality and climate change? By linking science and policy

Even though there is a strong link between air quality and climate change, scientists and policy makers fail to work together. Scientists and policy makers need to collaborate to integrate air quality and climate change strategies promoting clean energy, which ultimately results in clean air and better human and environmental health outcomes.

Scientists need to develop technologies that are efficient and capable of reducing emissions from energy generation, transportation and agricultural activities. Better computer models with improved air quality and climate data collection capability to track emissions and translate that knowledge to policy makers. Policy makers need to design regulations that simultaneously reduce GHG emissions and improve air quality. Smart regulation is required to build climate resilient infrastructure, which will support vulnerable communities. Regulations must promote renewable energy sources. It should also align with international climate and air quality goals (MfE, 2024).

Sometimes a policy designed to improve air quality can conflict with climate change aspirations and vice versa. For example, a policy that encourages diesel car use to reduce carbon dioxide emissions (climate change considerations) can lead to harmful effects of oxides of nitrogen and particulate matter emissions (air quality challenges). Similarly, a policy that is designed to reduce particulate matter emissions leads to warming effects (Schneidemesser et al., 2015). Therefore, integrated policies are necessary to balance these trade-offs. The interdependence between air quality and climate change is demonstrated in this report. We need to have combined policy decisions that equally weigh both air quality and climate change aspirations.

In many cases, climate change and air quality issues are caused by the same source of anthropogenic emissions, e.g. carbon dioxide, sulphur dioxide, oxides of nitrogen and BC released from shipping. Carbon dioxide is a long-lived gas and remains well mixed in the atmosphere causing warming effects, while sulphur dioxide, BC and oxides of nitrogen are short lived and cause harm to human health and the environment. Therefore, it is possible to implement policies that can reduce GHG emissions and improve air quality simultaneously, leading to win-win outcomes. However, certain climate reduction policies can lead to win-lose scenarios, when policy targeting one issue leads to exacerbating the other (Putland, et al 2023, Schneidemesser et al., 2015). Examples of commonly proposed and adopted air quality and climate change policies, mitigation measures and the synergies between them are shown in Figure 3.

Air pollutants, such as sulphur dioxide and particulate matter, are harmful to human health and the environment. They also have climate cooling effects due to the formation of aerosols by absorbing radiation and aerosol-cloud interactions (Putland, et al 2023). Energy efficiency, renewable energy, nuclear power, electric vehicles and carbon capture and storage are win-win scenarios. However, uncontrolled coal and oil fossil fuel usage in stationary and mobile sources are lose-lose scenarios. The relationship between air quality and climate change demands the need for integrated environmental policies. The delicate balance between improving air quality and managing climate change impacts requires a thorough understanding of environmental effects of various mitigation policies.

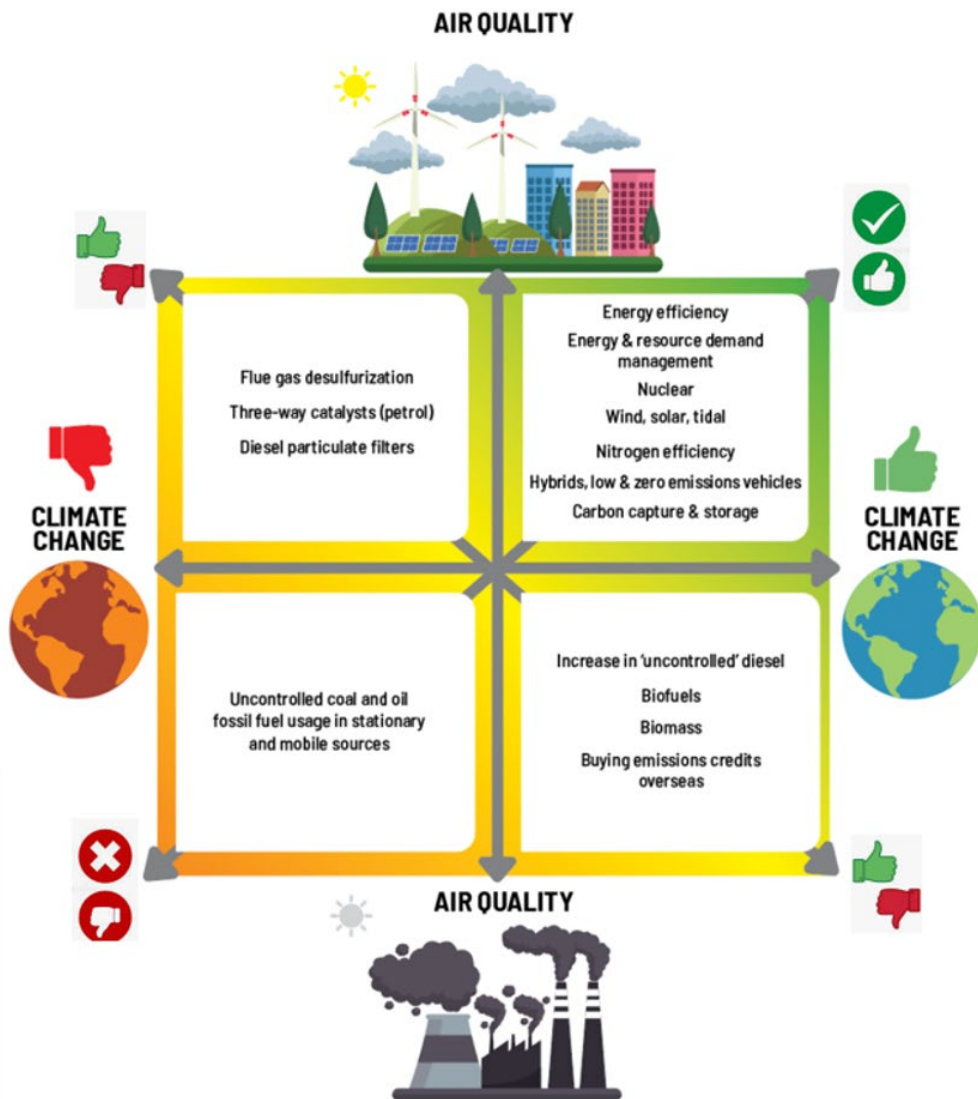


Figure 3: Climate change and air quality policy and technology mitigation measures showing synergies and trade-offs (adopted from Putland, et al., 2023; Schneidmesser et al., 2015).

Air pollutant and greenhouse gas reporting

Greenhouse gas reporting covers six gases that have global warming potentials - carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride (MfE, 2016a). Green house emission is reported as CO₂ equivalents (CO₂-e) based on “global warming potential” (GWP) of various GHGs compared to CO₂ over 100 years (Putland, et al 2023, MfE, 2016a).

The current greenhouse inventories focus is on well-mixed long life span GHGs, but this does not include short lived air pollutants. This results in an incomplete estimation of GHG inventories as air pollutants with cooling or warming potential are not included in the calculations. We understand it may not be practical within the current reporting regime, but it is possible with better coordination between scientists and environmental policy makers. To fully understand climate change implications on new actions plans to minimise effects of climate change, it is necessary to include complex interactions between climate and air in the atmosphere.

Conclusions

Northland's air quality is currently good overall, but it is likely to change as the climate continues to warm. Projected meteorological shifts, including higher temperatures, increased humidity and sunshine hours, and reductions in rainfall and wind speed, are expected to influence how pollutants form, disperse and persist in the atmosphere. These changes are likely to increase concentrations of some pollutants, particularly secondary particulate matter, ozone, black carbon, ammonia, volatile organic compounds and polycyclic aromatic hydrocarbons. At the same time, concentrations of some priority pollutants, such as oxides of nitrogen, sulphur dioxide and carbon monoxide, may decline due to regulatory controls and technological improvements.

Seasonal air quality patterns are also expected to change. Historically, Northland has experienced better air quality in summer and poorer conditions in winter. Climate change is likely to alter this pattern. Warmer winters may reduce emissions from domestic wood burning and improve winter air quality. However, summer air quality is expected to deteriorate due to increased photochemical activity, higher secondary pollutant formation, and greater nuisance effects such as dust, odour and wildfire smoke. While Northland is expected to continue to meet daily National Environmental Standards for Air Quality, elevated annual concentrations and emerging summer pollution pressures may become increasingly important. Managing ozone in particular is likely to become a growing challenge for air quality management.

There remains uncertainty in the magnitude and timing of these changes. However, the direction of change is consistent across climate projections and international research, indicating increasing pressure on air quality systems over time. This highlights the importance of early monitoring and adaptive management.

The strong and complex interactions between climate change and air quality mean that they can no longer be managed as separate environmental issues. Climate change will increasingly shape pollution patterns, and air pollution control measures can influence climate outcomes. Policies that reduce emissions from transport, energy and industry can deliver substantial co benefits, improving both air quality and climate resilience. However, poorly aligned policies risk creating unintended trade-offs.

Future planning in Northland will need to explicitly account for changing climatic conditions. This includes incorporating climate projections into air quality management frameworks, strengthening monitoring networks to detect emerging trends, and supporting adaptive strategies that protect public health, particularly for vulnerable communities.

Overall, the evidence indicates that maintaining Northland's currently good air quality will require proactive and integrated management as environmental conditions change. A coordinated approach that combines monitoring, planning, regulation and community action will be essential to safeguard environmental quality, public health and regional resilience over the coming decades.

Recommendations

This report has been prepared with limited locally specific information on projected meteorological changes associated with climate change. Much of the analysis relies on international or national scale projections, which may not fully represent conditions in Northland or New Zealand.

Strengthening locally relevant evidence is essential to support informed decision-making, effective air quality management and proactive adaptation planning. To improve confidence in future air quality predictions and strengthen regional preparedness, the following actions are recommended:

- develop regionally specific meteorological projections for Northland, including expected changes in the frequency and duration of stable atmospheric conditions, temperature inversions, fog events, heatwaves and winter frosts, to support improved prediction of pollution dispersion and seasonal air quality patterns;
- strengthen and regularly update emissions inventories for Northland to better quantify major pollution sources and assess how emissions may change under future climate, population growth and land use scenarios;
- develop and implement a regional air quality modelling framework that incorporates projected meteorological conditions and emissions scenarios to assess future pollutant concentrations, identify emerging risks and evaluate future compliance with air quality standards and guidelines;
- incorporate projected land use and land cover change into air quality planning to better assess future biogenic VOC emissions, wildfire risk and dust generation from exposed land;
- quantify current and projected ammonia emissions in Northland to improve understanding of secondary particulate formation and potential impacts on air quality and ecosystems;
- evaluate how home heating emissions may change under warmer winter conditions, including potential shifts in fuel use and seasonal emission patterns;
- strengthen monitoring and assessment of pollen and bioaerosol concentrations to better understand climate-driven changes in air quality and public health risks;
- quantify dust emissions across Northland, including contributions from unsealed roads, land disturbance and drought-related soil exposure, to support targeted management and mitigation measures;
- strengthen monitoring and modelling of ozone formation and precursor emissions to support future compliance assessment and management planning; and
- develop a comprehensive regional greenhouse gas and air pollutant inventory to support integrated climate and air quality management and identify opportunities for emission reduction co benefits.

Implementing these actions will improve Northland's ability to anticipate, monitor and manage emerging air quality risks associated with climate change, supporting informed planning, regulatory decision-making and long-term protection of public health and environmental quality.

Reference

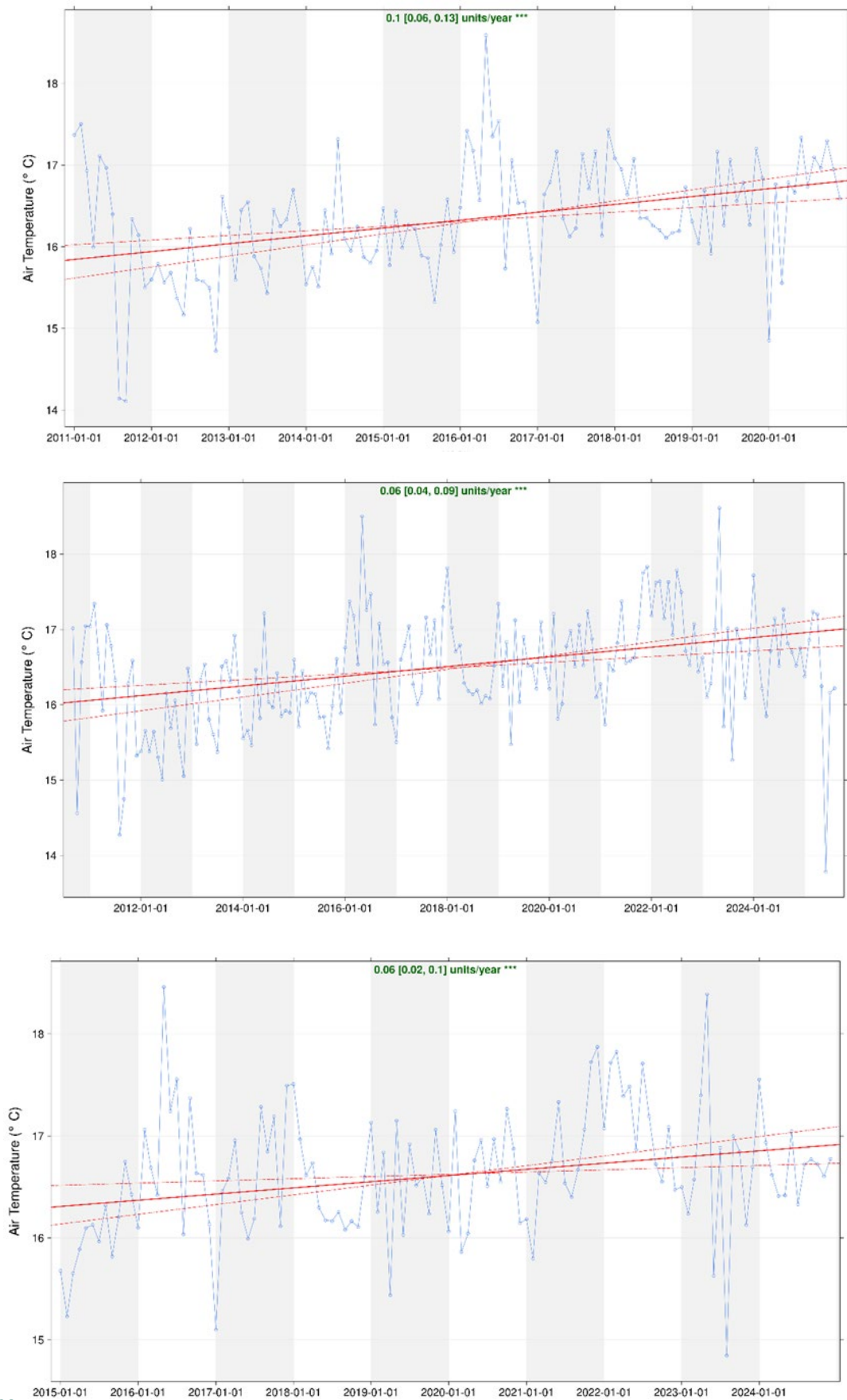
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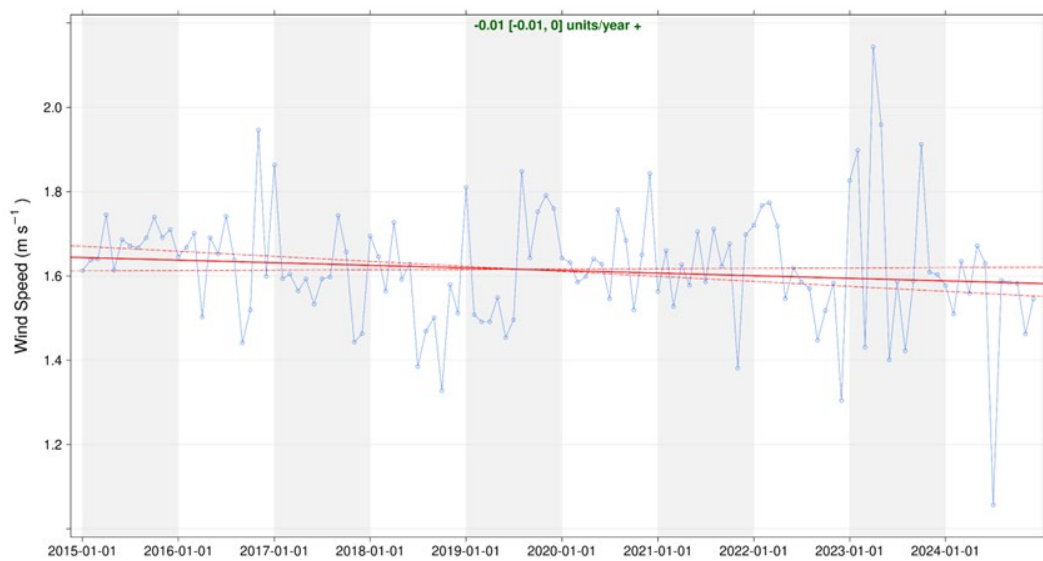
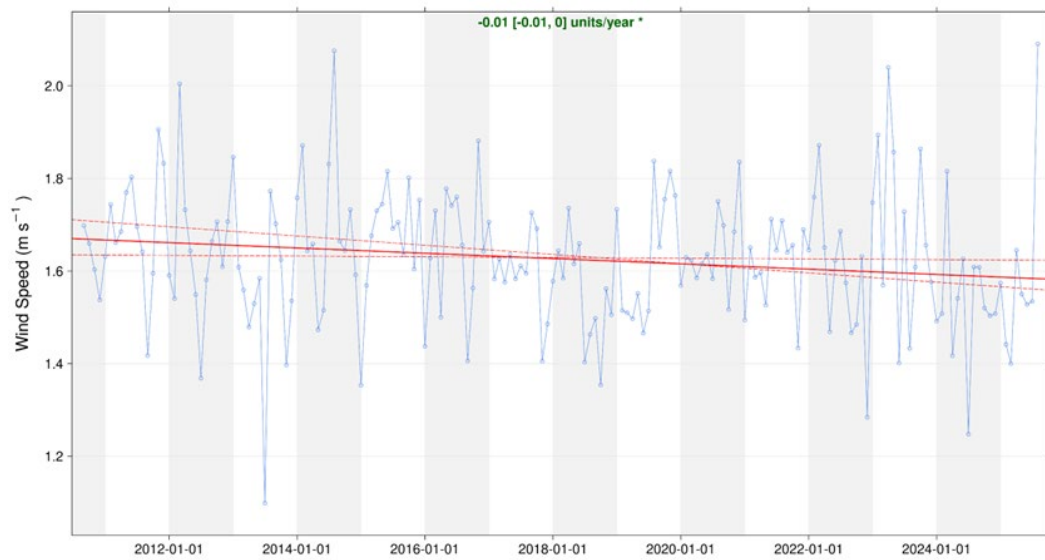
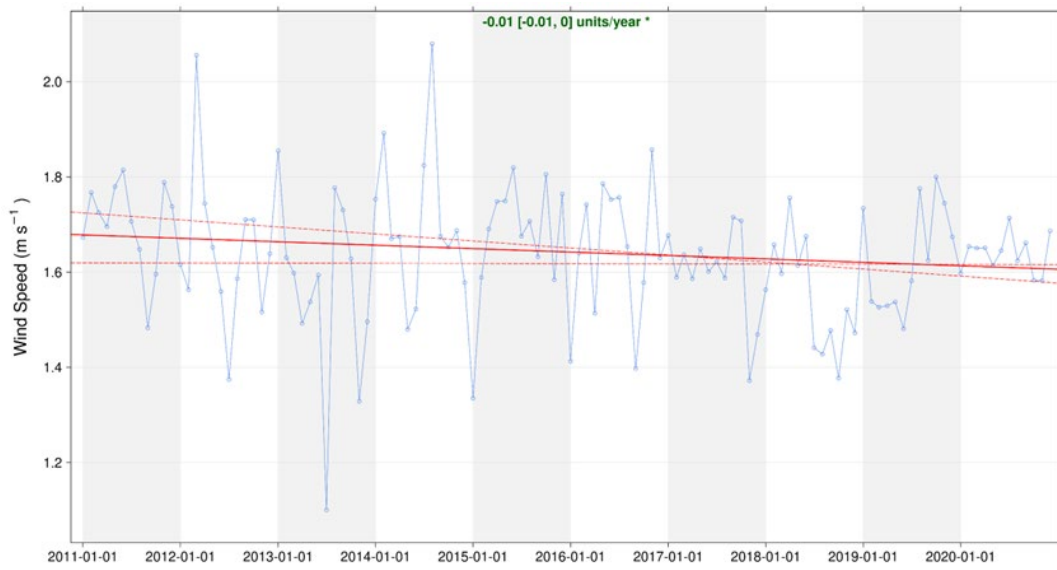
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Appendix: 1

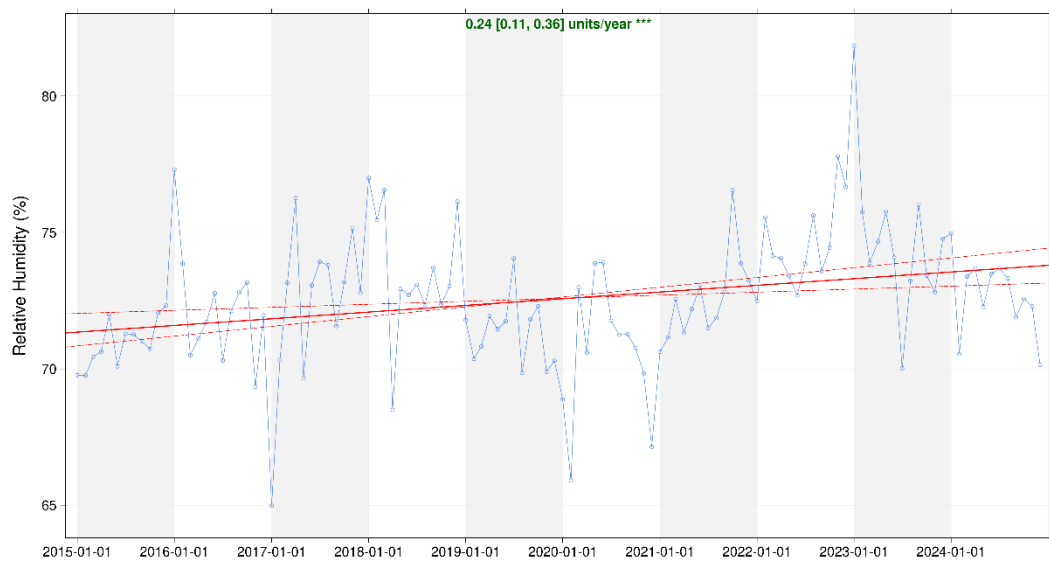
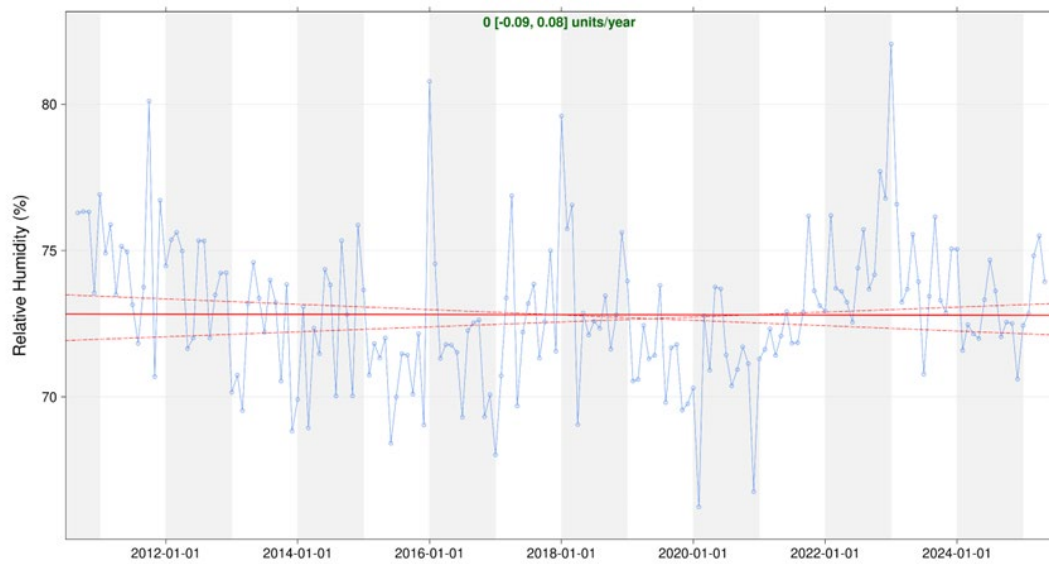
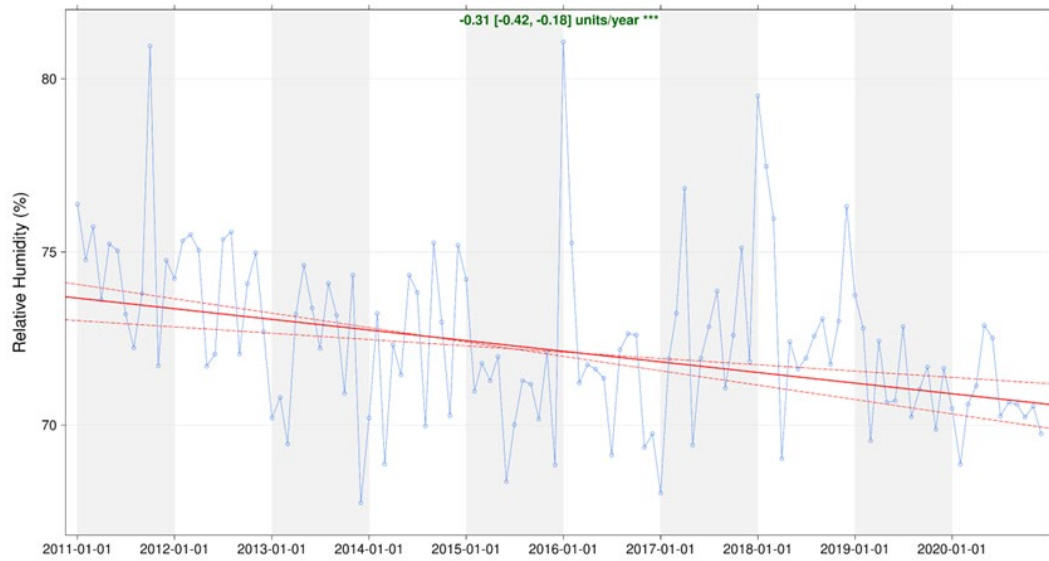
Temperature Trends



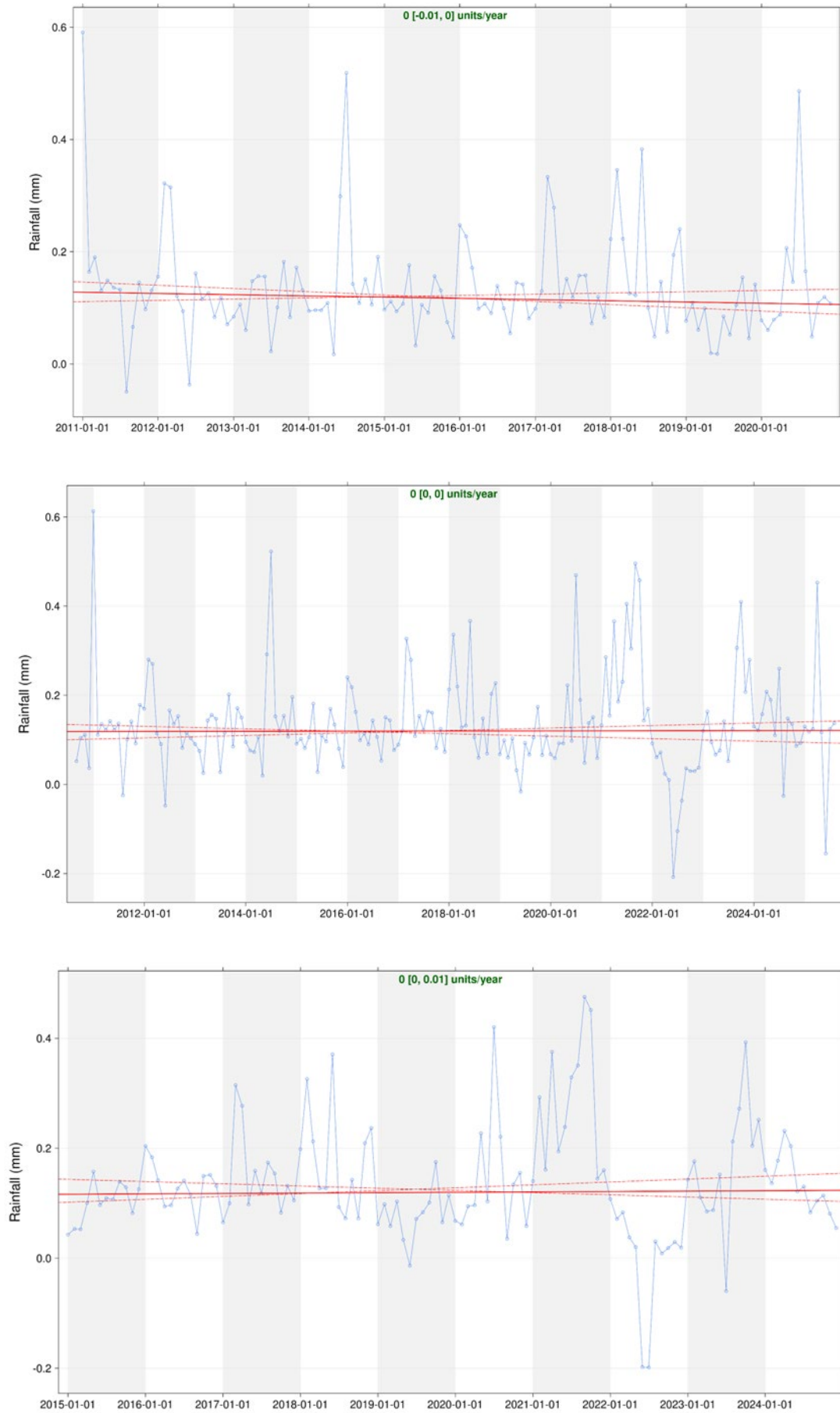
Windspeed Trends



Relative Humidity Trends



Rainfall Trends



Appendix: 2

This appendix provides detailed descriptions of major air pollutants, their sources, behaviour in the atmosphere and potential health and environmental effects.

Common air pollutants

Particulate Matter (PM)

Particulate matter is a collective term used to describe very small solid or liquid particles such as dust, fumes, smoke and mist or fog (Khanal, 2025 and MfE & Stats NZ, 2021). There are two types of particles; those discharged directly from a source (primary particles), or those formed in the atmosphere by chemical reactions (secondary particles) (Seinfeld & Pandis, 2006). Particulates originate from both human activities (automobile exhaust, solid fuel burning) and natural sources (forest fires, windblown dust, volcanic eruption, sea salt) (NRC 2015, Khanal 2025).

Particles are classed by size based on their potential for human health effects. PM₁₀ refers to particulate matter with an aerodynamic diameter of less than 10 microns. PM_{2.5} is a subset of PM₁₀ and refers to particulate matter less than 2.5 microns. Smaller particles are mostly sourced from combustion and remain in the atmosphere for longer periods of time (days to weeks) than coarse particles (minutes to hours). Mechanical processes including surface abrasion, crushing and grinding produces coarse particles.

Carbon Monoxide (CO)

Carbon monoxide is a stable, colourless, tasteless and odourless gas produced during incomplete combustion of materials containing carbon, such as fuel from cars, burning wood, coal, and vegetation. Carbon monoxide is also produced by natural processes (e.g. volcanic eruption) (LAWA, 2024). Places where vehicle emissions accumulate, such as traffic jams, tunnels and car parks are locations of potentially high concentrations of carbon monoxide (NRC 2012).

Nitrogen Dioxide (NO₂)

Nitrogen dioxide is formed in the air by the oxidation of nitric oxide (NO), produced during the combustion process by the combination of nitrogen and oxygen (LAWA, 2024). Nitric oxide absorbs blue light and produces a reddish-brown-coloured haze. This gas is also produced naturally during decomposition of vegetative matter, but major sources are the combustion processes of fossil fuels. Nitrogen dioxide is responsible for the formation of smog and acid rain.

Sulphur Dioxide (SO₂)

Sulphur dioxide is a strong pungent smelling colourless gas emitted from the combustion of fossil fuels (e.g. industrial processes, shipping) (LAWA, 2024). Natural sources include volcanic emission, geothermal activity, and marine organisms. Sulphur dioxide reacts with moisture in the atmosphere to produce sulphuric acid aerosols (NRC, 2012).

Ground-level Ozone (O₃)

Ozone is not directly emitted into the air from a source but formed by photochemical reactions between oxides of nitrogen and volatile organic compounds in the presence of sunlight (LAWA, 2024). Ozone is also produced by the reaction between carbon monoxide, methane and oxides of nitrogen (USEPA, 2020). Sources of reactants to produce ozone are motor vehicle emissions and industrial processes.

Polycyclic Aromatic Hydrocarbons (PAHs)

PAHs belongs to a large group of organic compounds containing carbon and hydrogen with at least two combined aromatic rings. These compounds are produced during incomplete combustion of organic materials (Cavanagh, 2009). Forest fire is a major source of PAHs in the atmosphere (Oluwabamise et. al. 2020). Bigger PAHs are usually present in particulate matter and smaller PAHs can be present either in particulate matter or in a gaseous state.

Volatile Organic Compounds (VOCs)

These are carbon compounds that vaporise (change to gas) at room temperature. Common sources are vehicle exhaust and housekeeping and maintenance products such as paint and coatings. Natural sources include emissions from vegetation during photosynthesis and bushfires. VOCs are responsible for producing ozone in the atmosphere.

Appendix: 3

This appendix describes the primary greenhouse gases, their sources, atmospheric behaviour and relative warming potential.

Common Greenhouse Gases

GHGs are gases in the atmosphere that absorb heat energy radiated from the earth's surface and raise the surface temperature of the earth. Emissions from industrial processes and changes in land use significantly contribute to the volume of GHGs in the atmosphere. There are six main GHGs, as agreed during the Kyoto Protocol adopted in 1997 and entered into force in 2005 (MfE, 2016a). Different GHGs last in the atmosphere for different lengths of time and also absorb different amounts of heat.

Carbon Dioxide (CO₂)

Carbon dioxide is a colourless and odourless gas produced by natural processes (e.g. volcanic eruption, respiration, decomposition). Anthropogenic sources of CO₂ include burning fossil fuels and deforestation, as well as industrial processes. CO₂ plays a vital role in the carbon cycle and photosynthesis but is a major contributor to climate change (C2ES, 2025). Half of the anthropogenic CO₂ emitted to the atmosphere is absorbed by oceans, but this is making oceans acidic (Climate Change & Nature, 2025).

Methane (CH₄)

Methane is a colourless and odourless gas produced naturally (e.g. wetlands, ocean floors). Anthropogenic sources of methane are emissions from live stocks during digestion, rice plantations, landfills and fossil fuel use and extraction. Methane is lighter than air and burns cleanly, producing water and CO₂. Methane decays in the atmosphere within 10 to 15 years but is 25 times more powerful in absorbing heat in the atmosphere than CO₂ (MfE, 2016a).

Nitrous Oxide (N₂O)

Nitrous oxide is commonly known as laughing gas. It is colourless and used for recreational and therapeutic purposes such as pain relief and is also used as a food additive (MfE, 2024). N₂O is a powerful GHG that is 300 times more potent than CO₂ over a 100-year period (MfE, 2016a). The major sources of N₂O are agricultural activities such as the use of nitrogen-based fertilisers, industrial processes, fossil fuel combustion and wastewater treatment. It is a stable gas and stays in the atmosphere for more than 100 years. N₂O is also responsible for ozone layer depletion in the stratosphere (Climate Change & Nature 2025).

Hydrofluorocarbons (HFCs)

HFCs are synthetic compounds made of hydrogen, fluorine and carbon. They were introduced in the late 20th century to replace chlorofluorocarbons (CFCs) to protect the stratospheric ozone. HFCs were found to be useful to protect the ozone layer but are thousands of times more powerful GHGs than CO₂ (Climate Change & Nature 2025). HFCs have an atmospheric lifetime of between 10 and 15 years and are mainly used in refrigeration and air conditioning.

Sulphur Hexafluoride (SF₆)

Sulphur hexafluoride is also a man-made compound. It is a colourless, odourless, non-toxic and non-flammable highly stable gas that is heavier than air. This gas is mainly used in electric switchgear for insulation, medical imaging, semiconductor manufacturing and double-glazing windows (Climate Change & Nature 2025). The global warming potential of SF₆ is thousands of times higher than CO₂.

Perfluorocarbons (PFCs)

PFCs are synthetic compounds made with carbon and fluorine. The major sources of PFCs are aluminium production, semiconductor manufacturing and industrial processes. This group of compounds are the most persistent and potent GHGs (Climate Change & Nature, 2025).

Other GHGs

Other GHGs which are not listed in the Kyoto Protocol are cloud and water vapour, ozone, aerosol and Black Carbon. These gases can have both cooling and warming effects in the atmosphere.

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