Sustainable Communities and Waste

National Environmental Science Program

How will a changing climate and emissions reduction measures impact sources of air pollution and secondary pollutant formation?

A literature review

May 2023

Kathryn Emmerson

UNSW SYDNEY

CSIRO

MONASH University

Curtin University

UNIVERSITY of TASMANIA

Citation

Emmerson, Kathryn. How will a changing climate and emissions reduction measures impact sources of air pollution and secondary pollutant formation?
A literature review. Australia: CSIRO; 2023. csiro:EP2023-1847.
https://doi.org/10.25919/6c1c-4h18.

Version 1.1 – May 2023. Prepared for the Australian Government Department of Climate Change, Energy, the Environment and Water.

Acknowledgements

The Sustainable Communities and Waste Hub acknowledges all Aboriginal and Torres Strait Islander Traditional Custodians of Country and recognises their continuing connection to land, sea, culture, and community. We pay our respects to Elders past, present, and emerging.

This project is supported with funding from the Australian Government's National Environmental Science Program.

Document ID: EP2023-1847

Report on Sustainable Communities and Waste Hub's Air Quality air quality and climate change project (IP4.02.02)

Dr Kathryn M. Emmerson, CSIRO.

May 2023

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Motivation for this study

How will a changing climate and emissions reduction measures impact sources of air pollution and secondary pollutant formation?

The goal of this project is to identify the activities necessary to design a set of future modelling experiments based on a range of projected climate scenarios. These experiments will provide a lens on how altered we can expect air quality to be under future emission scenarios in Australia.

We will specifically review the literature across:

1. Studies in Australia and internationally that have modelled changes in air pollution sources and secondary pollutant formation **under warmer climate scenarios** with a particular emphasis on understanding the changes to atmospheric chemistry that may occur.
2. Studies in Australia and internationally that have modelled changes in air pollution sources and secondary pollutant formation **under emission reduction scenarios** with a particular emphasis on understanding the changes to atmospheric chemistry that may occur.
3. Studies in Australia and internationally that have **estimated health impacts** of air pollution under warmer climate scenarios and emission reduction scenarios.

We will also review the potential emission reduction actions likely to be undertaken by Australia.

Executive summary

The Australian federal government, states and territories have all committed to net zero carbon emissions by 2050 and have different plans to achieve this. Commonalities in these plans embrace new clean technologies for energy production and transport, and all commit to increasing tree planting for carbon sequestration. The plans to achieve net zero will impact the sources and strengths of emissions to the atmosphere that will change air quality in both positive and negative ways. Climate change itself will impact on air quality, in terms of increasing the speed of most chemical reactions and increasing emissions of natural gases and particles. These natural emissions will cause a new background level in pollution in Australia which need to be understood before we study the additional impacts that anthropogenic emissions will cause in 2050. Ongoing droughts will cause higher concentrations of dust in the atmosphere, and additional carbon sequestration plantings will increase the biogenic VOC emissions. Modelling of air quality across a range of predicted climate outcomes for 2050 will provide a lens on what future levels of air pollution could look like in Australia.

1 Introduction

In 2015 the Paris Climate agreement laid out plans to limit global warming to below 2°C by 2100 via cutting anthropogenic emissions of carbon dioxide (CO_2). However, climate change is already occurring (Cresswell et al., 2021), causing rising sea levels, more frequent and severe weather events, increased risk of drought and wildfire, and the loss of biodiversity. These impacts have significant social and economic consequences, particularly for vulnerable communities who often bear the brunt of climate induced disasters.

Much has been written how anthropogenic emissions, (e.g. CO_2, CH_4 and aerosols) cause climate change (IPCC, 2021), but there are relatively very few studies that have predicted the impacts of climate change on air quality, particularly on a regional level. A Google search of the terms “air quality, Australia, 2050” yields only government reports outlining plans to net zero and three scientific papers.

If humanity does nothing, climate change and atmospheric chemistry will impact on each other, entering into a feedback loop described by Jacob and Winner (2009) in Figure 1. Both processes can cause perturbations to air quality.

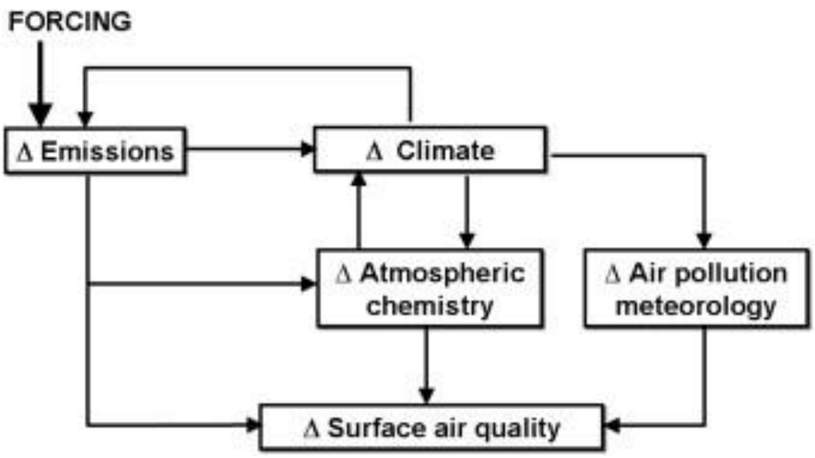

Figure 1 Taken from Jacob and Winner (2009). Effect of climate change on surface air quality placed in the broader context of chemistry-climate interactions. Change is forced by a perturbation to anthropogenic emissions resulting from socio-economic factors external to the chemistry-climate system. This forcing triggers interactive changes (Δ) within the chemistry-climate system resulting in perturbation to surface air quality.

Impacts on air quality can be separated as those occurring due to a warming climate, and those occurring due to emissions increases and reductions. Due to the non-linear behaviour of the atmosphere and the chemistry occurring within it, reducing emissions can have both a positive and negative impact on air quality (von Schneidemesser and Monks, 2013). These will be reviewed and discussed within this report.

2 Warmer climate scenarios

Temperature has a significant impact on atmospheric chemistry, as it affects the rates of many chemical reactions that occur in the atmosphere. Generally, chemical reactions occur more quickly at higher temperatures and more slowly at lower temperatures. This is because higher temperatures increase the energy of molecules, making them more likely to collide and react with one another. As a result of this, changes in temperature can have significant impacts on the concentrations of chemicals in the atmosphere. For example, warmer temperatures can accelerate the breakdown of pollutants such as long chain hydrocarbons. On the other hand, colder temperatures can slow the rate of reaction and also the volatility of compounds, allowing these pollutants to persist in the atmosphere as particle species for longer periods of time.

Temperature can also impact atmospheric chemistry in more complex ways, such as by altering atmospheric circulation patterns, which can impact the transport and distribution of pollutants in the atmosphere. The strength and direction of wind patterns can change which impacts the transport and dilution of pollutants away from their source locations. Increased stagnation of the atmosphere is one problem that would reduce the pollution dilution capability of the air.

In 2009, Guy Brasseur wrote a review piece for the World Meteorological Organisation bulletin in which he laid out the predicted changes to atmospheric composition under a changing climate. The changes have been observed in global models that took part in the Intergovernmental Panel on Climate Change studies (IPCC, 2007) and are still relevant today. The following list is copied from Brasseur (2009):

- Changes in atmospheric temperature affect the rates at which chemical reactions take place;
- Changes in atmospheric humidity affect the chemical production and destruction of chemical species and, specifically, the loss rate of tropospheric ozone;
- Changes in the frequency and intensity of lightning affects the atmospheric production of nitric oxide with direct impact on the ozone budget in the upper troposphere;
- Changes in atmospheric cloudiness affect the atmospheric composition by modifying the penetration of solar radiation and, hence, the photochemical activity in the atmosphere; aqueous and heterogeneous chemistry associated with the presence of clouds is also modified;
- Changes in the frequency and intensity of precipitation resulting from climate change affect the rate at which soluble species are scavenged and therefore removed from the atmosphere;
- Changes in surface temperature and precipitation affect the emission and deposition of chemical compounds and the surface deposition by vegetation and soil;

- Changes in ocean temperature affect the atmosphere-ocean exchanges of compounds such as dimethyl sulphide, which are a source of sulphate aerosols;
- Changes in the frequency and intensity of prolonged stagnant air conditions affect the dispersion of pollutants and enhance the frequency and intensity of pollution events with severe consequence for human health;
- Changes in the general circulation of the atmosphere affect the long-range transport of pollutants from continent to continent;
- Changes in convective activity lead to changes in vertical transport in the chemical composition of the upper troposphere;
- Changes in stratosphere-troposphere exchange affect the abundance of chemical species, including ozone, in the upper troposphere;
- Changes in surface wind intensity over the continent modify the mobilization of dust particles in arid regions and, therefore, the aerosol burden in the troposphere;
- Changes in surface wind intensity over the ocean modify the exchanges of trace gases at the ocean-atmosphere interface, and affect the emission of sea-salt particles to the atmospheric boundary layer.

Brasseur's work (2009) suggests that the impacts of climate change on current emissions levels need to be understood before we can tease out the impacts of anthropogenic emission reductions.

Jacob and Winner (2009) estimated the sensitivity of ozone and PM to changes in meteorological parameters brought about by climate change. Of the parameters listed in the table below, conditions leading to stagnant air will have the worst impact on air quality. Higher temperatures will strongly increase ozone but decrease PM.

Table 1 Taken from Jacob and Winner (2009). Dependence of surface air quality on meteorological variables[a]

Variable	Ozone	PM
Temperature	++	−
Regional stagnation	++	++
Wind speed	−	−
Mixing depth	=	− −
Humidity	=	+
Cloud cover	−	−
Precipitation	=	− −

a

Sensitivities of surface ozone and PM concentrations in polluted regions as obtained from the model perturbation studies reviewed in Section 4. Results are summarized as consistently positive (++), generally positive (+), weak or variable (=), generally negative (−), and consistently negative (− −) See text for discussion, including comparison to observed correlations (Section 3).

The UK's Air Quality Expert Group articulated the potential impacts of climate change on the UK's air quality in a 2007 report (Air Quality Expert Group (AQEG), 2007) as follows:

- Decrease in stagnant conditions that cause pollution in winter (e.g., it will be windier).
- Increase in summertime smog due to higher temperatures (faster chemistry), lower cloud cover (increased photolysis) and increase in vegetation emissions (biogenic emissions).
- Decrease in the atmospheric lifetime of CH_4 and O_3 due to increased oxidant conditions.
- Increase in water vapour concentrations, leading to changes on O_3 production.
- Increase in the exchange of O_3 from the stratosphere to the troposphere.
- Reduced surface for pollutant deposition from vegetation destruction.

A warmer climate will change weather patterns in each region differently and will impact the atmospheric chemistry of that region. However, studies with a global focus do not have the resolution to identify processes/problems at a local scale. It is important to undertake studies specific to the Australian context.

2.1 Natural emissions in a warmer climate: focus on Australia

The temperature in Australia has already increased by 1.47°C since records began in 1910, and this trend is expected to continue (Bureau of Meteorology and CSIRO, 2022). The impacts of climate change will be felt the hardest by our Indigenous populations, who are least well positioned to cope with the impacts (HEAL Network & CRE-STRIDE, 2021).

The “Climate change in Australia” website (https://www.climatechangeinaustralia.gov.au/en/changing-climate/national-climate-statement/) list the following expected changes to the atmosphere to occur in the coming decades:

- Australia is projected to continue to get hotter into the future, with more extremely hot days and fewer extremely cool days.
- The average temperature of each future year is now expected to be warmer than any year prior to the commencement of human-caused climate change. This is scientifically referred to as climate change 'emergence '.
- Ongoing climate variability means each year will not necessarily be hotter than the last, but the underlying probabilities are changing. This leads to less chance of cool years and a greater chance of repeatedly breaking Australia’s record annual average temperature (e.g. record set in 2005 was subsequently broken in 2013 and then again in 2019).
- While the previous decade was warmer than any other decade in the 20th century, it is likely to be the coolest decade for the 21st century.
- A longer fire season for the south and east and an increase in the number of days experiencing dangerous fire weather is projected.
- Australia's cool season rainfall is projected to decrease across many regions of the south and east, likely leading to more time spent in drought.
- As the climate warms, heavy rainfall is expected to become more intense throughout Australia.
- The amount of climate change expected in the next decade is similar under all plausible global emissions scenarios. However, by the mid-21st century, higher ongoing emissions of greenhouse gases will lead to greater warming and associated impacts, while lower emissions will lead to less warming and fewer impacts.

The Australian climate projections work above does not consider changes in air stagnancy mentioned by Brasseur (2009) and AQEG (2007), which will impact the transport and dilution of air pollutants. Changes to wind speeds in 2050 should be one of the parameters to focus on in the modelling study.

There are several natural sources of air pollutants that are predicted to increase in a warming climate: Fire, biogenic volatile organic compounds (VOCs) and dust (Figure 2). This will lead to an increase in the levels of particulate matter in the atmosphere, and understanding particle sources and formation processes is a priority for

Australian research (Cope et al., 2014; Emmerson et al., 2014; Dean and Green, 2018).

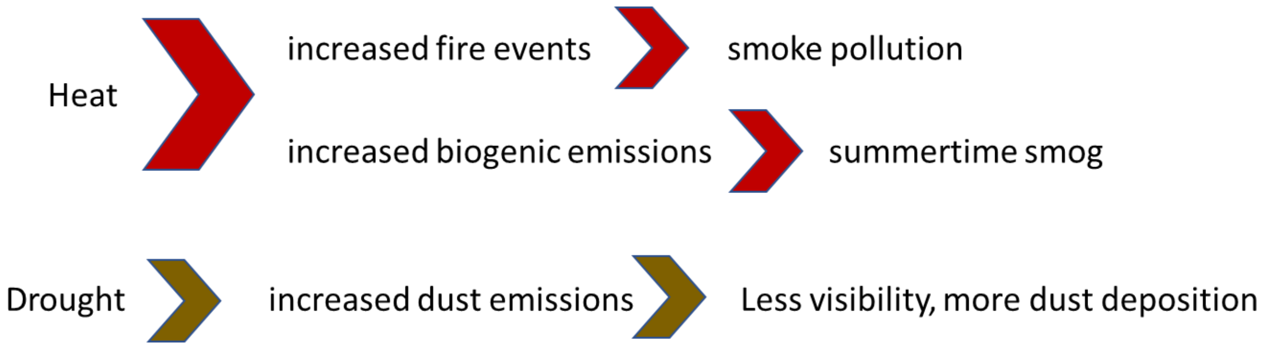

Figure 2 schematic to highlight how climate change will impact natural emissions and thus air quality.

2.1.1 Fire

Heatwaves, dry conditions, gusty winds and lightning lead to bushfires. Over the last 90 years there has been an upward trend in the area burned each year in Australia, attributed to climate change (Canadell et al., 2021). The United Nations predicts that the number of fires globally will increase due to climate change by 30% by 2050 (United Nations Environmental Program, 2022). Severe wildfire conditions are predicted to increase in Australia as the climate changes, which will bring increased smoke conditions to more people, more frequently.

Smoke from the Australian black summer bushfires of 2019/2020 led to concentrations of $PM_{2.5}$ in excess of 900 mg/m^3 (as a 24 hour average) being measured across a number of consecutive days in the south-east of Australia (Emmerson and Keywood, 2021) and was the cause of more than 400 excess deaths (Borchers Arriagada et al., 2020).

2.1.2 Biogenic Volatile Organic Compounds

Of all VOCs emitted to the atmosphere, around 75% come from natural sources in Australia (National Pollutant Inventory, 2020). Vegetation emits biogenic VOCs in response to heat, light and other plant stressors such as herbivory and water availability (Sharkey et al., 2008). In the presence of NOx and other oxidants, biogenic VOCs contribute to the formation of ozone and secondary organic aerosol which are both strong components of summertime smogs.

As the temperature rises, emissions of isoprene and monoterpenes (the largest groups of biogenic VOCs) will increase. Global emissions of biogenic VOCs are in the region ~1000 Tg C per year (Guenther et al., 2012), with *Eucalyptus* species amongst some of the highest emitters in the world (Benjamin et al., 1996). *Eucalyptus* are native to Australia, and thus the temperate forests in the south are a global hotspot for biogenic VOC emissions (Emmerson et al., 2018).

Climate change will also impact biogenic VOC emissions in other ways. It will change the distribution and composition of vegetation, which can indirectly impact biogenic VOC emissions. For example, as temperatures rise, some tree species may shift their geographical range and spread, altering the emissions profile of a region. This shifting of vegetation may also impact the distribution of allergenic pollens, moulds and fungi, causing human health concerns in terms of asthma and hayfever (Beggs, 2021).

Using surface temperature projections for Australia in 2050, Emmerson et al (2020) designed an experiment focussing on how higher temperatures in Sydney increased the VOC emissions from nearby vegetation and how these impacted on the atmospheric chemistry. The study used eight models in the Coupled Model Intercomparison Project 5 (CMIP5), under the worst climate projection from the representative concentration pathways whereby the radiative forcing in 2100 reaches 8.5 Wm^{-2}. The study found changes in summertime hourly ozone concentrations up to 20 ppb in Sydney. An additional 20 ppb of ozone is approximately 1/5th of the hourly ozone air quality limit and suggests keeping concentrations underneath the limit will be a challenge in future. However, this study did not consider the changes in chemical reaction rates due to higher temperatures, as only surface temperature data was available.

Vegetation emissions also respond to higher atmospheric CO_2, with experimental data from the Eucalyptus Free Air CO_2 Experiment (EucFACE) at the Hawkesbury Institute in North western Sydney showing reduced isoprene, but increased monoterpenes in a 550 ppm CO_2 atmosphere (Jiang et al., 2020). Concentrations of CO_2 are expected to reach 550 ppm by 2050 (data from Kennaook/Cape Grim measures 415 ppm in September 2022 https://www.csiro.au/en/research/natural-environment/atmosphere/latest-greenhouse-gas-data). Applying the elevated CO_2 mitigation to isoprene in the Emmerson et al (2020) study only reduced the peak hourly ozone concentrations by 4 ppb.

Implications for urban greening

We need to properly understand the impact of increased vegetation emissions in a warmer climate, as the increase to the background pollution in summertime smog could be substantial. The problem should be managed by reducing anthropogenic emissions of nitrogen oxides, to curb the ozone and particle pollution in cities. Choice of tree species that emit low levels of biogenic VOCs when planting or planning new urban developments can also be part of this strategy (Paton-Walsh et al., 2019). However, because trees use biogenic VOCs to protect against heatwaves, the trees must be drought- and heat-tolerant too.

2.1.3 Dust

Soil loss occurs due to wind and water erosion (Van Pelt et al., 2017), and depends upon vegetation cover and type, soil type, wind speed and soil moisture; variables significantly affected during drought years (Moore and Ghahramani, 2013). Consequently, in years of low rainfall the shear strength required to detach soil particles from the soil surface is decreased. As temperatures rise and precipitation patterns shift, some regions may become drier and more prone to desertification. This can lead to increased dust emissions from exposed soil, particularly in areas with little vegetation cover (Emmerson et al., 2023). Changes in atmospheric circulation patterns could lead to stronger winds, which can exacerbate dust emissions by increasing the amount of soil that is lifted into the atmosphere. The amount of groundcover is also impacted in strong drought years, leading to increased soil loss and high airborne dust concentrations for local communities. These communities are often located in the most remote regions of Australia, who may experience the most socioeconomic disadvantage in the population. Therefore a study of what air pollution remote communities may experience under climate change is important.

3 Emission reduction scenarios

Most global government action is focussed towards reducing emissions of carbon to the atmosphere to curb man-made climate change and keep the global temperature increase to below 2°C. Australia is committed to emission reduction measures that will help combat climate change.

3.1 Carbon dioxide reduction strategies

Reducing CO_2 emissions is essential to mitigate the impacts of climate change. This requires significant changes in how energy is used and produced, as well as management of land, food and waste. Common CO_2 emission reduction measures being considered globally include:

- Renewable Energy: The transition from fossil fuels to renewable energy sources, such as wind, solar and hydropower. Reducing the amount of fossil fuels burned for electricity production will also lead to a reduction in emissions of nitrous oxides (NOx) and particulate matter (PM).
- Alternative energy sources such as hydrogen: Use of hydrogen as a fuel will produce only water as an emission to the atmosphere. Hydrogen can be produced by splitting water (H_2O) at high temperatures, or by splitting ammonia (NH_3), both of which require energy to do so. It is expected that leaks of NH_3 to the atmosphere could occur in practice, due to storage and transport processes. This could lead to higher secondary aerosol production.
- Energy Efficiency: Improving energy efficiency in buildings, industry, and transportation can significantly reduce CO_2 emissions. This includes energy-efficient building design, use of efficient appliances and lighting, and investment in public transportation and electric vehicles. More efficient buildings, appliances, and vehicles require less energy and therefore emit fewer pollutants. Whilst electric vehicles will significantly reduce emissions of NOx and PM from the tailpipe, there will still be tyre and break dust produced.
- Carbon Capture and Storage (CCS): Capturing CO_2 emissions from power plants and industrial processes and locking them away permanently. New technology is also considering capturing CO_2 directly from ambient air. Monoethanolamine (MEA) is a highly effective solvent for capturing CO_2 in these processes, which can be released to the air as an unintended consequence (Emmerson et al., 2013). Further research needs to be conducted on the environmental impacts of carbon capture.
- Carbon Taxes and Emissions Trading: Implementing carbon taxes or an emissions trading scheme to incentivise businesses to reduce their CO_2 emissions.
- Forest Conservation and Reforestation: Forests absorb CO_2 from the atmosphere and store it in trees and soil. Protecting and restoring forests, as well as planting new trees, can help to offset CO_2 emissions from other sources. Trees emit biogenic volatile organic compounds (VOCs) that lead to ozone and secondary organic aerosol (SOA) formation.

- Circular Economy: A circular economy model can help reduce waste, increase resource efficiency, and minimize emissions. This can include measures such as recycling and reducing the use of single-use products.

These emission reduction measures will impact the sources, types and strengths of anthropogenic emissions to the air and thus change the levels of air pollution and secondary pollutant formation in our cities. Von Schneidemesser and Monks (2013) discuss how some of these technologies that will remove carbon dioxide from the atmosphere will impacts on air quality, and how not all of the technologies will result in better air quality (Figure 3).

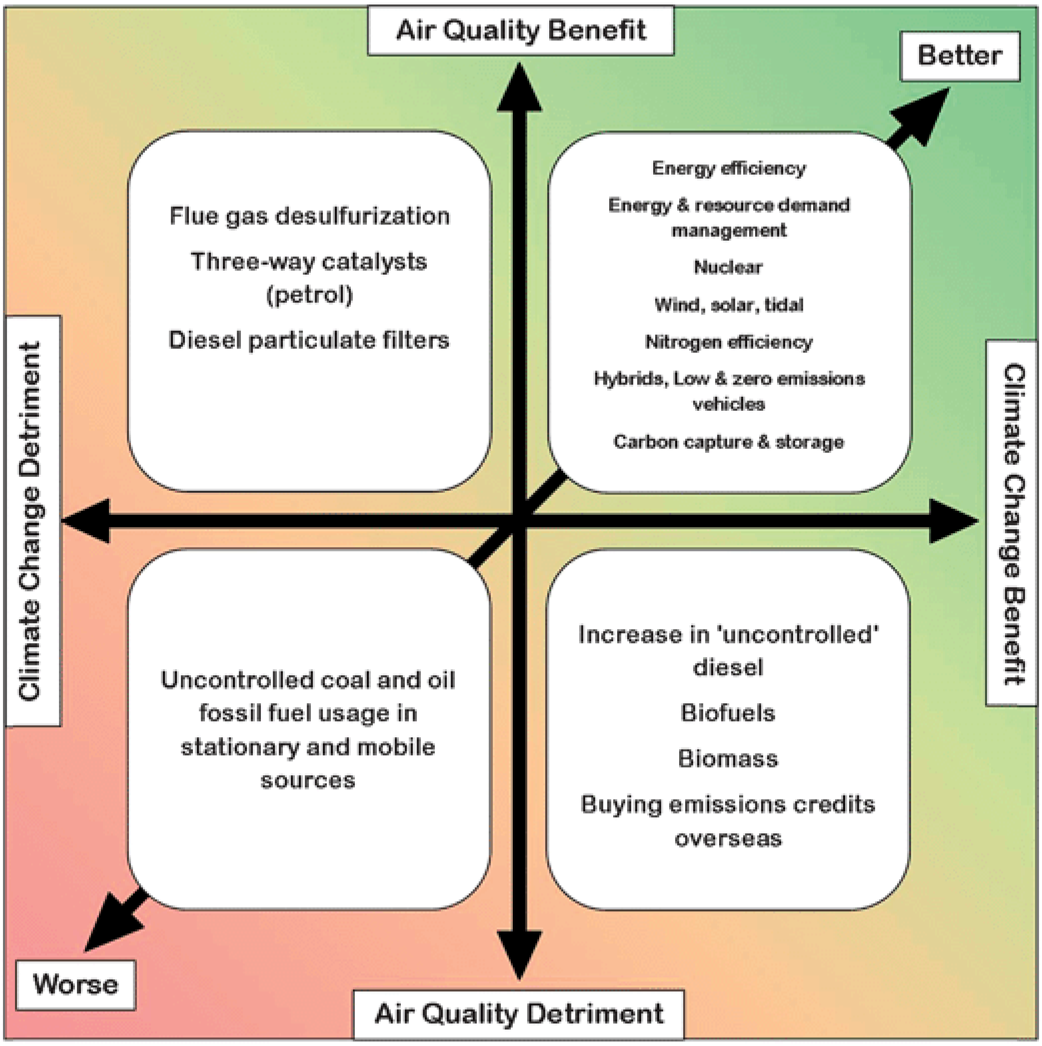

Figure 3 Taken from von Schneidemesser and Monks (2013): Synergies and trade-offs from policies and technologies to address climate change (CC) and air quality (AQ).

Policies that have ultimately are a benefit to the climate but have a detrimental impact on air quality feature in the bottom right of Figure 3. They pertain to carrying on burning fuel, here ‘biofuel’ or ‘biomass’, as a means of energy production. Burning any fuel creates smoke (increased airborne particle concentrations), however the biomass route can avoid 50% of the CO_2 emissions (Patrizio et al., 2021). The figure also mentions purchasing carbon credits from overseas which amounts to no climate/air quality action being taken by the purchasing country. Policy actions that benefit air quality but adversely impact the climate are shown in the top left of Figure 3 and include desulfurisation. Sulfate aerosol has a cooling effect on the climate, so removing sulfur gas as a pollutant from the atmosphere will increase the level of warming.

Care also needs to be taken that any energy required to produce low carbon technologies does not come from a fossil fuel source. Unintended air pollution consequences of transitioning to new technologies include clearing land for renewable power generation such as solar or wind turbines can lead to increased dust and other particulate matter emissions in surrounding areas. The manufacturing process could also lead to further mining and transportation of raw materials, which have knock-on impacts for local communities.

The UK Met Office in conjunction with the University of Leeds have developed the climate (co)benefits portal to help policymakers see the potential benefits after taking various courses of climate mitigation action. https://priestleycentre.shinyapps.io/climatecobenefitsportal/. The impacts on air quality are mentioned through the urban greening pathways.

A review of (mainly American) peer reviewed journal papers highlighting the co-benefits of reducing carbon emissions on air quality found common themes on which policy action could focus for the biggest benefits (Gallagher and Holloway, 2020). These findings were:

- A reduction in fossil fuels reduced air pollution on the worst polluted days and corresponded to reduced NOx, SO_2 and primary $PM_{2.5}$ emissions. However, the percentage of air quality benefits were not as large as the percentage fossil fuel reduction (i.e. not linear);
- Renewable energy options offer the highest health and economic benefits on regions relying on coal;
- Use of electric vehicles reduced air pollution on peak pollution days but could increase ozone in cities due to the lack of titration with vehicular emitted NOx. This shows the non-linear response of the atmosphere to changes in emissions.

3.2 Non-linear response of the atmospheric chemistry system

The non-linear response of the atmospheric quality system to reduced emissions is explained by how the atmosphere disperses and transports the pollutants, non-linearities in chemical processing and how quickly wet and dry processes can act to remove the pollutants from the atmosphere. These non-linearities can most easily be studied via modelling that can show difference over spatial and temporal timescales. Vandyck et al (2018) shows how the response of various pollutants varies by region (Figure 4) according to CO_2 reduction measures. As the CO_2 reduction increases, the response in sulfur dioxide is more strongly linear than nitrogen oxides, and there is almost no clear response from black carbon, organic carbon and carbon monoxide levels. The countries/regions with the larger responses are more reliant on fossil fuels and will gain the most from abatement strategies.

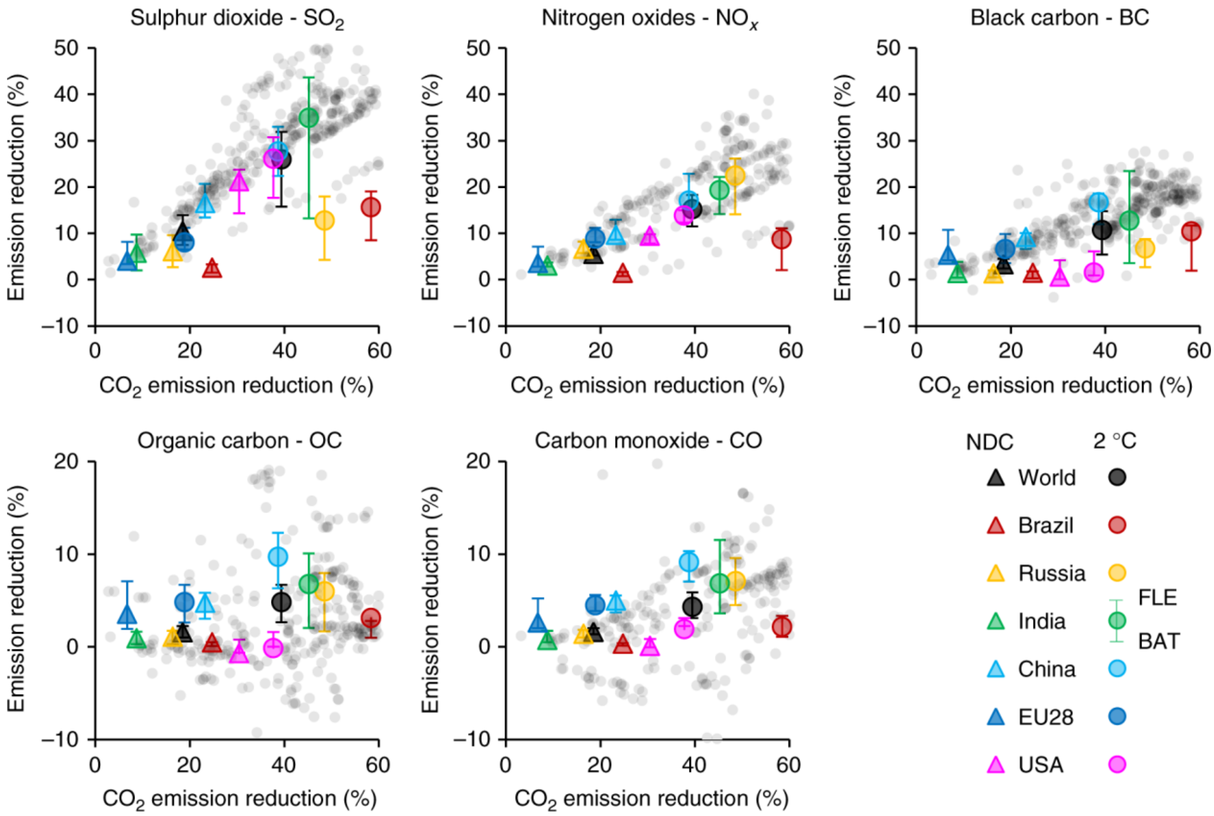

Figure 4 Taken from Vandyck et al (2018). Co-movement of emissions of CO2 and air pollutants per region due to climate change mitigation policies. Emission reductions are expressed as percentage difference from the respective Reference climate scenario emissions cumulative over 2015–2050. Symbols represent the results for the Stringent Legislation air quality scenario, while the whiskers indicate the results for the Fixed Legislation (FLE) and Best Available Technologies (BAT) air quality scenarios. Grey dots show global results obtained from IPCC AR5 WGIII. NDC = Nationally Determined Contributions.

Doherty et al. (2022) present a useful assessment of uncertainties in climate projections and air quality modelling. There are several main sources of uncertainty that arise from: (a) future changes in emissions related to human activity, (b) models responding differently to climate change and/or emission changes, (c) natural variability in the climate system. The formation of nitrate aerosol is mentioned specifically as a process lacking from most earth system models, but is of importance to air quality studies.

The Aerosol and Chemistry Model Intercomparison Project, AerChemMIP studied the ensemble of global earth system model responses to a range of input scenarios (Collins et al., 2017). As the study was conducted on a global grid, the horizontal resolution is necessarily coarse and cannot resolve individual cities. Most of the focus of this model intercomparison project is geared towards assessment of anthropogenic emissions on radiative forcing, rather than the impacts/feedbacks of climate change on air quality.

A reduction in NOx emissions (eg by transitioning to electric vehicles) has long been hailed as a solution to improving urban air quality. In the US, NOx emissions have been falling steadily, but concentrations of NO_2 have since plateaued. Karl et al (2023) examined what could be happening to the NO->NO_2->O_3 cycle under these reduced NOx conditions, finding that concentrations of ozone were increasing, not decreasing as expected. Higher ozone leads to more efficient NO to NO_2 conversion. Karl et al (2023) also calculated that the ozone deposition flux onto urban vegetation was negligible, plants instead were taking up atmospheric NO and NO_2 as a source of nitrogen. They postulated that if the overall NOx concentration decreased by a factor of 2 in future it would increase the AOT40 (the accumulated amount of ozone over the threshold value of 40 ppb) in urban vegetation by 67%. This will be detrimental to plant health as ozone deposition damages leaves and inhibits photosynthesis.

3.2.1 Covid induced reductions in emissions in Australia

The 2021 State of the Environment report highlighted several Australian studies that looked into the impacts on air quality from the stay at home orders to reduce the transmission of coronavirus (Emmerson and Keywood, 2021). Emissions reductions from the lockdowns were looked upon as a real experiment that provided a lens on what future emission reductions could do to improve air quality. Globally, the results were mixed: huge improvements in air quality and visibility were observed in countries in south east Asia undergoing strict lockdowns (Bauwens et al., 2020), but in southern Australia where the first lockdowns occurred over the winter months, wood heater emissions increased (Choi et al., 2022).

Reductions in traffic measured in Adelaide were 40% during the peak of the lockdowns, causing a similar decrease in carbon monoxide emissions. Traffic in Melbourne also decreased by ~30%, and resulted in a decrease in nitrogen dioxide concentrations of 24 ppb in the city (Choi et al., 2022). In Sydney, traffic reductions of up to 44% led to decreases in CO and NO_2 concentrations of 13% and 18% respectively (Duc et al., 2021). Meteorological conditions can hamper direct correlations of traffic reductions with improvements in air quality due to dilution and transport effects (Gkatzelis et al., 2021). A reduction in NO_2 should lead to decreased ozone, however Ryan et al (2021) observed increases in ozone (+20%) and particulate matter (+24%) in Sydney after detrending these data for meteorological effects.

3.3 Australian Government policy

The federal and state governments have set different emission reduction targets.

The federal government has a staged reduction target of 43% by 2030 and net zero emissions by 2050 (Australian Government Department of Industry, Science, Energy and Resources, 2021).

Some states aim to go further than this: In New South Wales the approach targets a 75% emission reduction by 2030 and net zero by 2050, but are forecast to achieve a 35% reduction on 2005 levels by 2030 (NSW DPIE, 2020). Victoria aims for a 50% emissions reduction by 2030 and net zero by 2050 (Independent Expert Panel on Interim Emissions Reduction Targets for Victoria, 2019). The ACT has a 65% to 75% emissions reduction target by 2030, 90% by 2040 and net zero by 2045 (ACT Government, 2019), Queensland intends to have 50% of all energy from renewable sources by 2030 and net zero by 2050 (Queensland Climate Action, 2023), South Australia intends to have a 100% renewable energy target by 2030 and net zero by 2050 (South Australian Government, 2022), whilst Western Australia and the Northern Territory plan to reach net zero by 2050 (Western Australian Government., 2020; Northern Territory Government, 2020). Tasmania's large forested regions mean that the state can offset all its carbon emissions and achieve net zero by 2030 (The Tasmanian Government, 2021).

In the NSW plan to have net zero carbon emissions by 2050 (NSW DPIE, 2020), they propose to focus the energy production towards renewables such as rooftop solar, encourage uptake of electric vehicles (and provision of public charging infrastructure), push for energy efficient appliances, and encourage new technologies to reduce emissions from industry and agriculture. Such new technologies could include hydrogen as a fuel, as long as the hydrogen is produced without the use of fossil fuels. New South Wales has also committed to increasing the land area of their national parks, to encourage uptake of carbon by vegetation.

None of the state and territory plans lay out what the expected mix of transport will be by 2050. The NSW Clean air plan to 2030 uses terms such as 'incentives' for uptake of 'zero and low tailpipe emissions vehicles' (NSW DPIE, 2021), but metrics on how successful these incentives will be won't be known until 2030. Potentially fossil fuel powered vehicles could be difficult to eradicate, particularly in remote Australia.

The Emission Reduction Fund (ERF, https://www.cleanenergyregulator.gov.au/ERF) is a plan under which the Australian government will purchase carbon credits in exchange for activities that will remove CO_2 from the atmosphere. Such activities span carbon capture and storage, energy efficiency in industry, reducing emissions from landfill, waste treatment and the agricultural sector (soil management, additives to dairy herd feed, better efficiency in fertiliser use), fire management and re-vegetation projects. In terms of revegetation, the planting projects must be of mixed tree species and be maintained for at least 25 years.

As of February 2023, the ERF has issued over 124 million carbon credits, broken down into the following categories:

Table 2. Carbon credits issued by the Australian emissions reduction fund (to February 2023).

	Carbon credits issued	%
Agriculture	1,683,604	1.36
Carbon capture	0	0
Energy efficiency	2,241,252	1.81
Industrial fugitives	1,588,153	1.28
Savannah burning	11,392,764	9.18
Transport	113,909	0.09
Vegetation	69,013,719	55.58
Waste	38,127,986	30.71
Total	**124,161,387**	**100**

Source: (https://www.cleanenergyregulator.gov.au/ERF/project-and-contracts-registers/project-register)

More than 55% of all carbon credits in Australia have been issued for tree planting activities (vegetation), which impacts on biogenic emissions to the atmosphere. There are no current projects that involve or use carbon capture technology yet in Australia. However, there is the option for projects to revoke their arrangement with the ERF and return the carbon credits. Of the 1448 projects registered, 254 have revoked and returned credits, some due to land use changes that remove vegetation, or changes in business operations that result in carbon no longer being sequestered.

It is clear that increasing vegetation is a key part of most state and territories plans to achieve net zero by 2050. Understanding the impact on biogenic emissions will be key to understanding how the air quality in our cities will change in future.

3.4 USA and UK policy

The Biden government has committed to reduce greenhouse gas emissions by 50-52% on 2005 levels by 2030 (Kerry, 2021). The aim is to be net zero carbon emitters by 2050. This will be undertaken via investing in clean electricity producing technology, facilitating carbon capture and storage and supporting building upgrades to increase energy efficiency. Emissions from vehicles will be reduced through support for renewable fuels and investment into public transport.

The UK also aims to achieve net zero emissions by 2050 (HM Government, 2021).

4 Estimated health impacts

The Organisation for Economic Co-operation and Development (OECD) states that outdoor air pollution will be the highest cause of deaths from environmental factors globally by 2050 (OECD, 2012). Lelieveld et al (2015) put a figure of 6.6 million deaths world-wide in 2050 caused by air pollution unless emissions were curbed drastically, including those governments traditionally find hard to curb – emissions from wood heaters and agriculture.

4.1 Australia

Physick et al. (2014) estimated the impact on mortality in Sydney in the 2050s from the changes in ozone concentrations as compared to 1996-2005 levels. They used an A2 emissions scenario which assumes high population growth (IPCC, 2000). Increases in the 1-hour ozone concentrations were found in all regions except at the coasts, and were caused by decreases in the NOx concentrations (titration), increases in VOC emissions and an increase in the number of hot days. The ozone increase was predicted to cause the additional deaths of up to 65 people in Sydney.

Dean and Green (2018) presented a comprehensive review of health impacts from global climate modelling studies that mentioned Australia specifically. They found four studies. Using the same A2 emissions scenario as Physick et al. (2014), one study also found an increase in ozone in Australia (West et al., 2013), whilst three others using a more moderate emissions scenario found no increase in ozone associated deaths at all (Selin et al., 2009; Fang et al., 2013; Silva et al., 2016). The Fang et al (2013) study also suggested that particulate matter would increase due to dust and sulfate aerosol, causing a 5% increase in all-cause mortality. However, climate change induced increases in $PM_{2.5}$ would lose 6000 years of life per year over the 21st century.

4.2 China

Hong et al (2019) investigated how more frequent extreme events brought about by climate change would result in poorer air quality, impacting the health burden costs. Such extreme events include extreme heat waves and atmospheric conditions leading to persistent stagnant air. Using Representative Concentration Pathway 4.5 (RCP4.5) they calculated that approximately 85% of China’s population would be adversely impacted by air pollution by 2050 via increases to ozone and fine particulate matter concentrations. These increases are expected to result in the deaths of up to 12,100 more people each year. The problems are set to be exacerbated by an increasingly ageing population.

4.3 Poland

Zysk et al (2020) report potential health costs of 35,000 deaths and 2.4 billion Euros in 2050 if decarbonisation measures are not enforced in Poland. Three scenarios were considered where vehicular, household and power generation emissions were either moderately or highly (both centralised and decentralised) cut. The centralisation aspect to the study referred to whether power was generated at a singular location, or locally by householders and businesses. The base year used was 2015, on which the 2050 comparison was made. The largest $PM_{2.5}$ reductions up to 5 mg/m^3 were achieved by 2050 using the high emissions cut (centralised) scenario, which cut power and household emissions of $PM_{2.5}$, SO_2, NOx and CO_2 by between 79 and 99%.

4.4 South Asia

Using the two worst projected climate outcomes of the Representative Concentration Pathway emission scenarios (RCP6.0 and RCP8.5, which use emissions leading to a world with 6 and 8.5 W/m^2 radiative forcing by 2100), Kumar et al. (2018) paint a bleak picture of air quality and health outcomes for people in South Asia, leading to shortened life spans. In some parts of South Asia (Nepal, Bangladesh and the Indo-Gangetic Plain) $PM_{2.5}$ concentrations are predicted to exceed the World Health Organisation air quality guidelines on an almost daily basis.

4.5 United Kingdom

A report into the public health implications of air quality in 2050 found the most socioeconomically challenged people were still exposed to the worst air pollution, particularly from NO_2 (Williams et al., 2018). One of the emissions options investigated was through the increased use of biomass for power generation, which achieved the UK’s commitments to reducing carbon emissions under their Climate Change Act, but led to the worst outcome for health because of the additional $PM_{2.5}$ emitted.

5 Conclusions

Impacts of climate change on air quality is not a linear process and is highly variable between regions. Studies with a global focus do not have the resolution to identify processes/problems at a local scale, so it is important to undertake studies of this nature for Australia.

Previous work has investigated impacts on air quality in 2050 resulting from a warmer climate alone (eg Brasseur 2009), and from emission reductions alone. There are relatively few that have used projected climate outcomes for 2050 along with emission reduction measures to study a more realistic impact on air quality, and only two in Australia (Physick et al. 2014 and Emmerson et al. 2020), both of which only focussed on Sydney.

Targeted, high spatial and temporal resolution modelling studies are required to tease out impacts from the competing processes of climate change and emissions reductions on air quality in Australia. An important first step is to study the new level of natural emissions to the atmosphere resulting from droughts and higher temperatures. Natural emissions are important as many plans for net zero include tree planting as a focus, with Tasmania suggesting that all their carbon emissions can be offset using trees by 2030. Higher airborne dust concentrations from ongoing droughts will impact remote communities and need to be understood.

Anthropogenic emissions in 2050 will look very different to present day emissions, with a raft of clean energy production and transport options planned. Whilst it is expected that lower anthropogenic emissions of NOx and particulate matter will improve air quality, the non-linearities in the atmospheric chemistry system could mean that pollutants like ozone may increase. A modelling study will help to assess ozone levels in our cities by 2050.

As a final component of this project, it is important to liaise with other SCaW researchers with health and epidemiology expertise to ensure the best use can be made of the future RP3 modelling outputs. We anticipate that this will result in predictions of the likely morbidity/mortality outcomes from the changes in air pollution experienced under a warmer climate and with emission reduction policies in place.

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