COP-AQ

UK-China collaboration to optimise net-zero policy options for air quality and health

Final Report

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COP-AQ

The UK-China Collaboration to Optimise Net Zero Policy options for Air Quality and Health

Final Report

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Summary

Clean Air policies in the UK and China have substantially improved air quality in recent years. However, reaching the new WHO guidelines on air pollution exposure to protect health remains a major challenge in both countries. Ambitious climate policies have already delivered significant co-benefits to air quality in the past. Future net zero or carbon neutrality policies may offer opportunities to contribute to improved air quality towards meeting the WHO guidelines. However, some climate policies have potentially negative impacts on air quality.

An immediate policy challenge is to develop the underpinning science to formulate policies to maximise the co-benefits of net zero and carbon neutrality measures on air quality and health, and to minimize their disbenefits.

Leveraging existing world-leading UK-China strengths in air quality, climate, health and data sciences, the overall aim of COP-AQ (funded via the Global Research and Innovation Programme, GRIP) has been to develop a joint research agenda to determine how net zero / carbon neutrality policy options can be optimised to maximise co-benefits for air quality and health and to enhance cross-disciplinary capacity to deliver such an agenda.

Through proof-of-concept case studies, an International Workshop on Net Zero and Air Quality, and a Scoping Workshop, COP-AQ has delivered:

- A portfolio of collaborative pilot research studies to assess research approaches and consequent impacts on key challenges in maximising co-benefits of net zero policies for air quality and health;
- A joint research agenda for an ambitious UK-China research and innovation programme to optimise net zero policy options for air quality and health, integrating emission projections and atmospheric process studies with health and economic evaluations, based on novel three-dimensional observational platforms and hybrid data science and modelling approaches.

Through networking, cross-border knowledge exchanges, and training, COP-AQ has also contributed to enhance cross-disciplinary research capacity for addressing the challenge of optimising net zero policies for air quality and health. COP-AQ also extended the UK's science leadership internationally through working with overseas partners to tackle global challenges such as climate change and air quality.

Acknowledgements

This work is supported by NERC (2021GRIP02COP-AQ) under BEIS GRIP programme. We would like to thank Caroline Culshaw, Heather Birch, and Edoardo Fioradalisi from NERC and Manhui Kou, Hongyan Liang and Sophie Durrans from UKRI-China Office for their support in all the project activities. We appreciate the support from our formal project partners including Kebin He, Huan Liu, Qiang Zhang, Zhu Liu, Wenjia Cai, Shu Tao, Xuejun Wang, Junfeng Liu, Guofeng Shen, Tong Zhu, Lin Zhang, Keding Lu, Huizhong Shen, Tzung May Fu, Steve Turnock, Fiona O’Connor, Jie Li, Peiqun Zhang, Pinghua Xie, Pingqing Fu, Qili Dai, Shengrui Tong, and Huijian Dong. We also thank all colleagues who are not formal project partners for their support including in the workshops and training activities. Finally, we thank the hundreds of participants who attended the workshops and contributed to the discussions.

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Chapter 1 : Introduction

1.1 Rationale and project background

Air pollution causes 7 million premature deaths per year globally. In addition to the human health burden, air pollution exerts significant direct and indirect economic costs (including affecting ecosystems and vegetation, reducing crop yields globally), around 5% percent of world GDP/year (Fuller et al., 2022). The key air pollutants responsible for these impacts are fine particles ($PM_{2.5}$), nitrogen dioxide (NO_2) and ozone (O_3).

Clean air actions and technological change have substantially reduced air pollution emissions in recent years in China (Zhang et al., 2019) and the UK (DEFRA, 2021). This brings significant benefits to human health and the economy (Geng et al., 2021; Zhang et al., 2019). However, even current $PM_{2.5}$ levels in the UK, which are several times lower than those in China, pose a serious health risk, contributing to 40,000 premature deaths per year (Royal College of Physicians, 2016). Annual average $PM_{2.5}$, NO_2 and 8-hour daily maximum O_3 levels in both the UK and China are still much higher than the updated WHO global Air Quality Guidelines (AQG) to protect human health, which are 5, 10 and 100 $\mu g\ m^{-3}$, respectively. While not binding, these are influential syntheses of evidence that must be considered in setting future air quality objectives and long-term targets for countries.

The highly ambitious WHO air quality guidelines, and interim targets, pose a huge challenge: Existing clean air actions will almost certainly be insufficient for pollution levels in the UK and China to comply with the AQGs. However, a key opportunity arises from emerging Net Zero (NZ, in the UK) or Carbon Neutrality (CN, in China) policies that aim to tackle the increasing impacts of climate change, as many NZ/CN policies, especially those which relate to fossil fuel combustion, will deliver significant air quality and health co-benefits (AQEG, 2020) in addition to reducing greenhouse gases (GHGs). There is clear evidence that past climate actions have delivered significant benefits to air quality. For example, Wang et al. (2022) argued that against the business-as-usual scenario, the synergistic effect of climate change and air pollution mitigation contributed to a 15% reduction in the annual mean $PM_{2.5}$ concentration in China, resulting in the prevention of 0.29 million (95% CI: 0.28-0.30) $PM_{2.5}$-attributable excess deaths during 2015.

However, different NZ/CN measures will have different impacts (e.g. scale, pollutant species) on air quality, which lead to significant uncertainties in quantifying the air quality mediated benefits to health (Figure 1.1). Furthermore, not all climate actions will bring benefits to air quality. For example, the transition to electric vehicles (EVs) has the potential to worsen urban ozone exposure (at least in the short term), as demonstrated during the COVID-19 lockdown (Shi and Song et al., 2021); even though the transition reduces NO_2 and $PM_{2.5}$; biofuel plantations and afforestation have the potential to increase biogenic volatile organic compound (BVOC) emissions, which can worsen regional ozone and secondary organic aerosol pollution (Fitzky et al., 2019); tighter building insulation has the potential to worsen indoor air quality; and carbon capture and storage has the potential to release amines which can contribute to new particle formation (NPF) (AQEG, 2020).

Currently, air pollution drives significant environmental health inequality, with the worst air quality exposure tending to be associated with the least advantaged communities (Ferguson et al., 2021; Fecht et al., 2015). NZ/CN-driven air quality changes may worsen or ameliorate this both on a national scale (for example, the balance between shifts in emissions in urban centres vs more rural impacts from power generation changes) and internationally (AQEG, 2020; Royal Society, 2021), where the differing air pollution challenges between nations will be affected differently by NZ/CN shifts, depending upon current approaches to power generation, agricultural practices etc.

In summary, most NZ/CN policies have brought and will continue to bring major benefits for air quality and public health, but a quantitative understanding on the magnitude (and even direction), spatial scale and population focus of the changes is lacking. This understanding is needed to optimise NZ/CN options to maximize the co-benefits to air quality, health and health equity, and support a trajectory towards WHO AQGs. However, the first challenge is to identify the research priorities so that future research in this area can be focused.

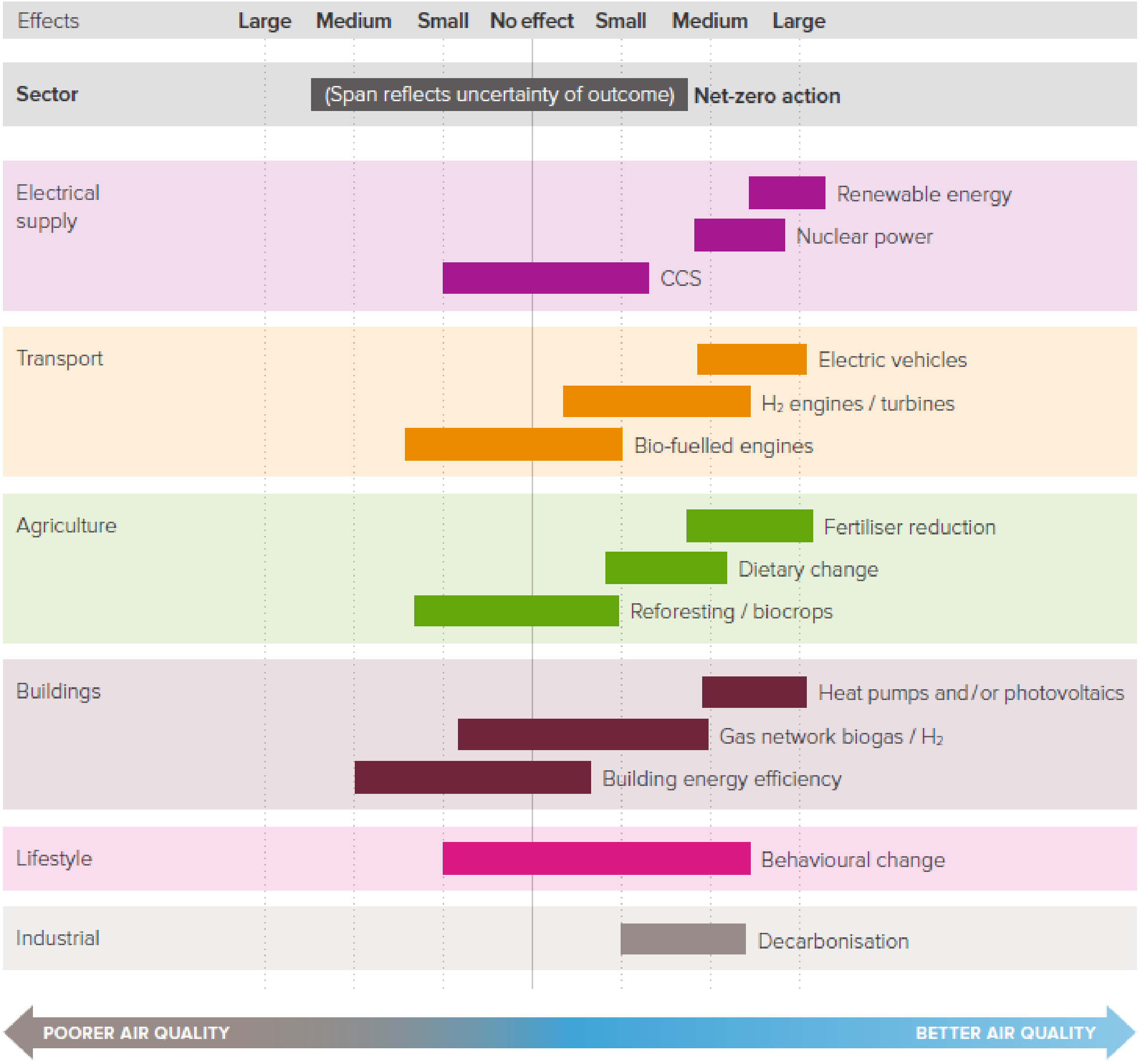

Figure 1.1: Qualitative summary of possible effects of NZ measures on air quality. Note the perceived uncertainties are qualitative (Royal Society, 2021).

The COP-AQ project was set up to address this challenge. The overall aim of COP-AQ is to identify the research priorities to optimise NZ/CN options to maximise co-benefits for air quality and health. Specific objectives are:

1) To understand the research needs to deliver future air pollutant emission projections based on plausible pathways to NZ/CN, to model future air quality, and to evaluate health benefits/impacts;
2) To determine the optimum observation and data science framework needed to evidence the air quality and health benefits of NZ/CN options and to identify potential negative consequences;
3) To develop methodologies to optimise NZ/CN co-benefits for health equity, considering variations across space and time compared with population vulnerability;
4) To advance UK-China partnerships and interdisciplinary capacity in delivering the underpinning science to deliver win-win solutions for NZ/CN and air quality.

COP-AQ has 19 investigators from the UK and 23 partners from China. COP-AQ builds upon the successful collaboration between UK and Chinese researchers within the "Atmospheric Pollution and Human Health in a Chinese Megacity (APHH-China)" NERC programme (Shi et al., 2021) but incorporates significant expertise from the wider community, particularly on climate change and CN. From November 2021 to March 2022, the COP-AQ team with support from the wider community has:

- Carried out 9 case studies;
- Organized the first International Workshop on Net Zero and Air Quality;
- Organized a Scoping Workshop;
- Delivered training to early career researchers and developed resources for the community.

This report will first outline the results of the case studies, followed by a summery of the talks given during the International Workshop on Net Zero and Air Quality and capacity building activites and finally list the resources available. The proposed research agenda has been submitted to funder for review and thus will not be made publicly available.

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Chapter 2 : Proof-of-concept case studies

2.1 Introduction

After the COP-AQ project was funded, a call for Case Study (CS) proposals was announced to the UK APHH-China community. A total of 11 proposals were submitted, from which 7 were selected by a panel of Phase I lead PIs to be developed based on their potential to deliver the call objectives and taking into account the different approaches and UK's research strength. To cover all the call objectives, two additional CS proposals were then solicited. Overall, the topics covered (Table 2.1) reflect challenges common to both the UK and to China. The following CS reports outline the aim, methods, and key results including the identified future research priorities.

Table 2.1: The challenges that each CS addressed.

	CS1	CS2	CS3	CS4	CS5	CS6	CS7	CS8	CS9
Sources and emissions	🟩	🟩	🟩			🟩	🟩	🟩	🟩
NZ/CN impacts on air quality		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Heath effects and equity		🟩	🟩				🟩	🟩	🟩
Economic impacts								🟩	🟩

2.2 Case studies

CS1: Combining air pollutant and CO_2 measurements with high resolution models for integrated air pollution and CO_2 emissions assessment in cities

Rod Jones, Lekan Popoola (University of Cambridge), Huan Liu (Tsinghua University), David Carruthers, Amy Stidworthy, George McCosh, and Daniel Conolly (Cambridge Environmental Research Consultants, CERC).

Aim

- To demonstrate the use of air quality and GHG monitoring networks, coupled with street level resolution models and data assimilation to optimise and verify air pollution and carbon dioxide (CO_2) emission inventories to inform emissions mitigation strategies, arising for example from NZ policies;
- To assess the potential of the technique to cities more widely, including in China.

Background

Concentrations of air quality pollutants are measured in cities using reference monitors and low cost sensors, and other techniques including diffusion tubes, satellites and Lidar. More recently concentrations of GHGs (CO_2 and methane, CH_4) are being measured in some cities both in the UK and in China.

Detailed emission inventories for both air quality pollutants and GHGs have been compiled for some cities. Where emission inventories have not already been compiled, activity data for different source sectors and emission factors are being used to develop inventories.

High resolution air quality models such as the ADMS-Urban model already used in both UK and China, can be used together with emissions inventories to calculate concentrations in the air of air quality pollutant and GHGs. Together with measurements of concentrations the ADMS model can be used with an inversion model to optimise/verify emission inventories at very high spatial resolution (Carruthers et al., 2019).

Methods

Two pre-existing low cost air quality and GHG networks were used to provide inputs to this study supplemented as detailed below with reference standard instruments. The Breathe-London (Pilot) project (London, 2018-2021) involved ~100 AQMesh instruments each measuring CO_2, NO, NO_2, PM and in some cases O_3. These had the same broad geographical coverage as the reference networks, but were not co-located. The QUANT/COP26 project (Glasgow, 2021-2022) involved 15 AQMesh instruments each measuring CO_2, carbon monoxide (CO), nitric oxide (NO), NO_2, particulate matter (PM) and O_3, and were co-located with reference sites (PM and nitrogen oxides, NO_x) and in 2 cases with reference standard CO_2 instruments. More details about the ADMS and inversion techniques are given in Carruthers et al. (2019).

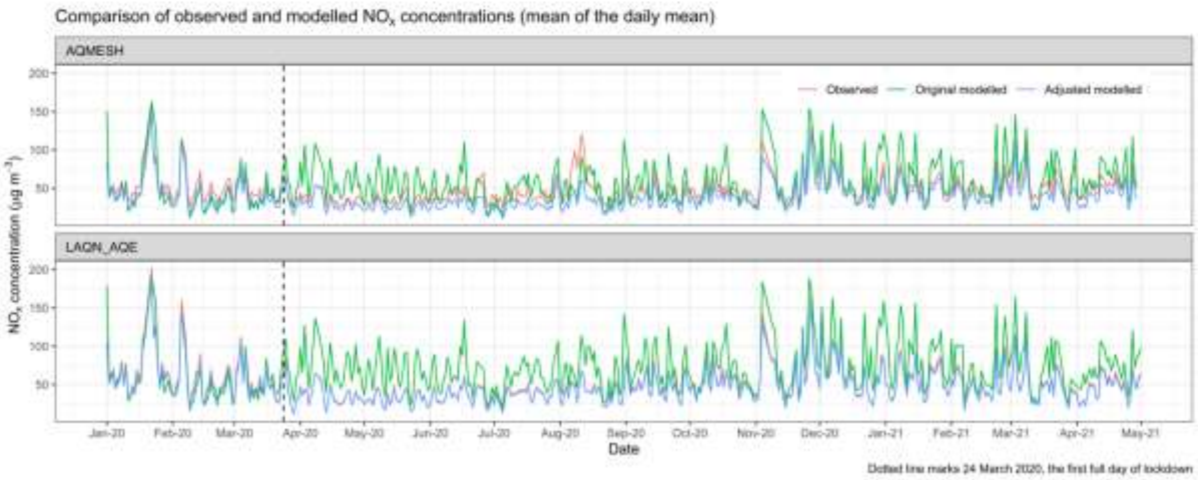


Figure 2.1: Comparison of observed and modelled NO_x concentrations at 199 monitoring sites in London from 1 January 2020 until 30 April 2021. The graph shows observed (red), original modelled (green) and adjusted modelled (blue) values. The plotted values are the means over all stations of the daily means at each station; the values at AQMesh sites and reference sites (LAQN and AQE networks) are shown in the upper and lower plots respectively; the vertical dotted line marks the first full day of the COVID-19 lockdown in London

Results

London and Glasgow

For London, concentrations of NO_x at the 199 monitoring sites were modelled using the ADMS-Urban model for the period from 1 January 2020 to 31 April 2021 using Business as usual (BAU) emissions based on the London Atmospheric Emissions Inventory (LAEI). These were combined with measured data (82 AQMesh sensors and 117 reference-grade monitors from the LAQN and AQE networks) using an inversion scheme to determine adjusted modelled concentrations using a consistent dataset of adjusted emissions. Illustrative results show (**Error! Reference source not found.**) that the first COVID-19 lockdown caused a large and immediate drop in measured NO_x levels compared with the BAU case, which is captured well by the adjusted modelled concentrations for both low cost and reference networks. The agreement is better for the LAQN-AQE networks as they are assumed in the inversion procedure to have lower measurement uncertainty than the AQMesh.

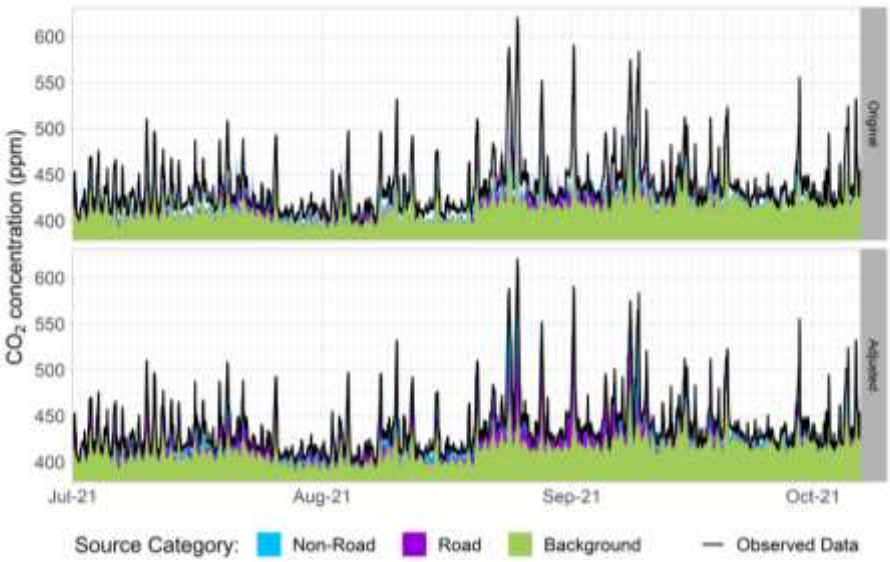


Figure 2.2: Time series graphs of hourly mean CO2 concentration at a single Glasgow roadside monitoring site. The upper plot shows the original results; the lower plot shows the inversion-adjusted results. The coloured regions represent the amount of modelled CO2 due to road (magenta), non-road (blue) and non-Glasgow (green) sources; the black line shows the observed level and is the same on both plots.

For Glasgow we focus on CO$_2$. Here concentrations of CO$_2$ were modelled using ADMS-Urban and combined with measurements from 15 AQMesh sensors and 2 Li-Cor monitors using the inversion scheme to optimise the modelled values based on a consistent dataset of revised emissions. **Error! Reference source not found.**.2 shows how, at a single roadside site, the inversion scheme increases the contribution from local sources in order to match modelled and measured levels. The inversion improves the agreement between modelled and measured CO$_2$ at all sites, in terms of both the hourly and the period mean (**Error! Not a valid bookmark self-reference.**), improving the R value from 0.6-0.7 to 0.96-0.98, and reducing the root-mean-square error (RMSE, ppm) from 15.8-21.8 to 4.2-5.9.

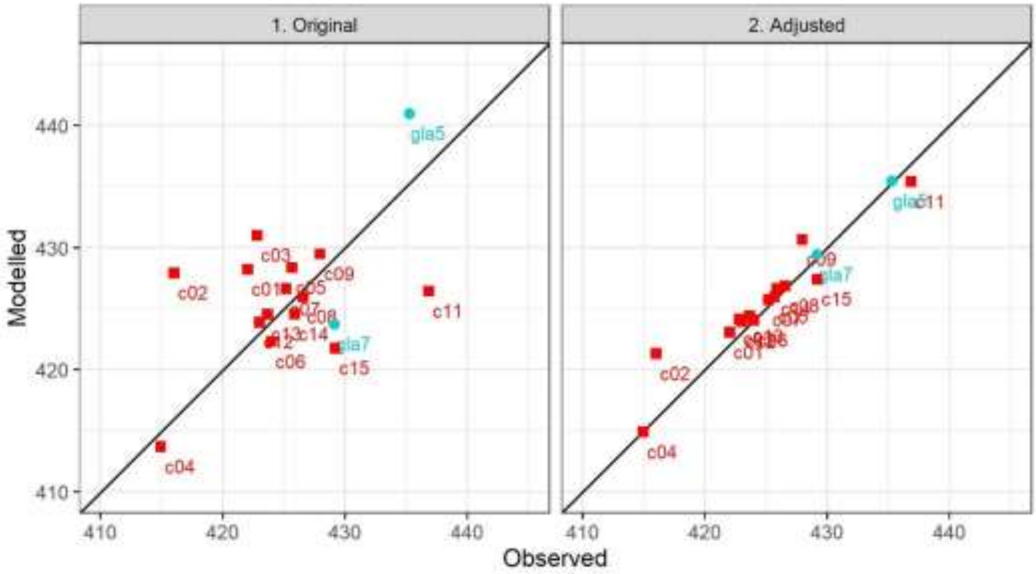


Figure 2.3: Comparison of CO2 (ppm) before inversion (original) and after the inversion (adjusted) with measurements. The scatter plot compares mean modelled and measured CO2 (ppm) for AQMesh (red) and reference-grade Li-Cor (blue) monitors. The table gives the correlation (R) and RMSE for the hourly data.

Finally, Figure 2.4 shows a map of modelled CO_2 emission rates following assimilation of the network measurements.

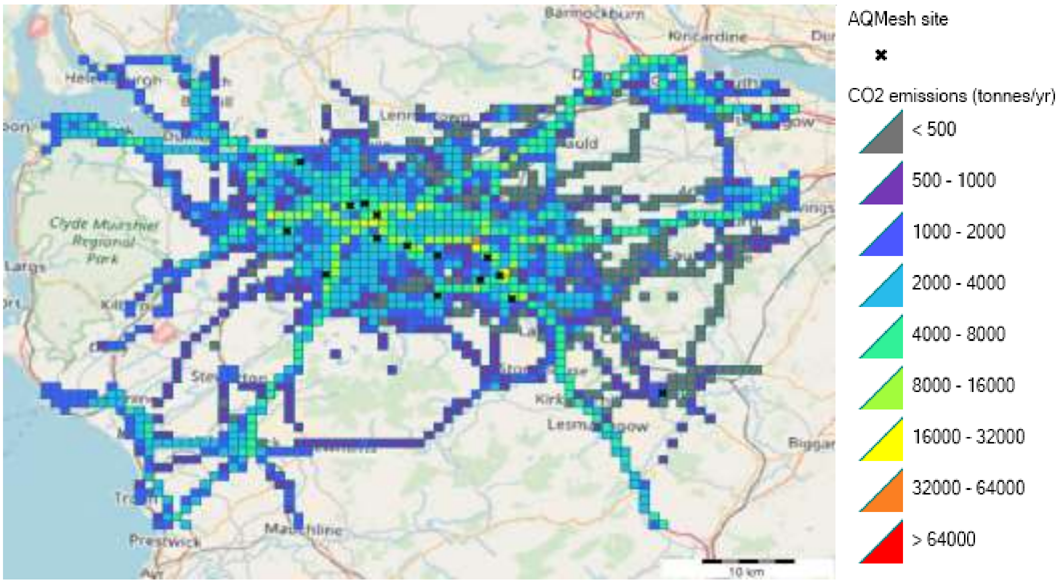


Figure 2.4: Map of gridded road inversion-adjusted CO_2 emission rates over the Glasgow region.

Overall, these two case studies demonstrate clearly the utility of assimilation of air quality and GHG data for emission inventory optimisation.

China Context

At present, China has 1,436 urban air quality measurement stations in 338 cities for monitoring sulfur dioxide (SO_2), NO_2, particles less than 10 µm in diameter (PM_{10}), $PM_{2.5}$, CO, and O_3. There are 31 national monitoring stations in municipalities and capitals cities for monitoring CO_2, CH_4, and nitrous oxide (N_2O). Those stations were considered as well maintained with routine quality assurance / quality control. However, considering such a large area and significant variation on emission sources, the number of the monitoring station is still clearly not sufficient for constraining the national emissions budget. Targets for GHGs include localized GHG emission data for critical industries, application of inversion techniques for carbon emissions in urban areas and integrated detection of regional GHG emissions and ecosystem carbon sinks. A range of measurement techniques are encouraged including low cost sensors and remote sensing by UAV and mobile systems.

Emission changes arising from carbon neutral policies need to be quantified. These are usually estimated based on the variations of energy consumption and fuel types, such as using the Global Change Assessment Model (GCAM). The atmospheric impact is further evaluated according to the Chemical Transport Models and then their health effects quantified using a relative risk model. However, current studies mostly focus on impacts at global or national scales, while the differences in responses to carbon neutral policies across regions are not considered. Therefore, based on the development of the emission inventory and observation technologies on the urban scale, assessing the impact of carbon neutral policies in urban areas will be highly relevant to policymakers. These studies will in turn contribute to the development of Monitoring, Reporting and Verification Systems (MRVs) for different source sectors which are an important element of the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement.

Future research priorities

- To develop strategies to enhance monitoring of both air quality and GHGs in the UK and China by combining reference monitors, sensors, satellite data, lidar data (requiring automated calibration (sensors) and estimation of measurement uncertainty);

- To further develop and share the inversion modelling techniques to use full range of available measurements simultaneously;
- To implement and test the inversion methods in different urban environments including in UK and China with different characteristics and different air pollution and GHG measurement networks to improve understanding of both local and regional emissions.

CS2: Scoping study on the biggest sources of uncertainties in evaluating the impact of specific net zero / carbon neutrality actions on air quality and health

Dominick Spracklen (University of Leeds)

Aim

- To identify the sources of uncertainties in evaluating the impact of NZ/CN action on air quality and health;
- To identify future policy and research priorities.

Background

Particulate air quality is improving in China and the UK and is projected to improve further under current air quality legislation. Despite projected reductions in $PM_{2.5}$ exposure, China's ageing population and the associated increased susceptibility to air pollution, means that the disease burden may increase between now and 2050. Future reductions in health burden will require substantial emission reductions, delivered through stringent air quality policies or ambitious climate mitigation measures. There is an urgent need to understand how air quality and NZ/CN policies can deliver the maximum reductions in air pollutant exposure and optimise benefits for health. But first of all, we need to understand the uncertainty on future air quality under different emission scenarios, particularly from specific sectors, from which we can identify and prioritise research needs.

Methods

We used a novel framework using an emulation simulator to quantify the air quality impacts of a wide range of emission scenarios based on different CN pathways in China. This is based on a statistical emulator of the WRF-Chem regional chemistry climate model that enables rapid predictions of $PM_{2.5}$ and ozone concentrations. We further developed the framework to allow us to simulate the health impacts associated with these air quality changes. A full description of the approach is described in Conibear et al. (2022c). We used this framework to predict the air quality and chronic health impacts across China from a) hypothetical changes in emissions (based on 2015 data) to assess and understand sensitivities, b) historical changes in emission sectors over 2010–2020, c) future emission scenarios under different NZ/CN actions from 2020-2050. This approach also allows us to identify the emission sectors responsible for pollution exposure and health burden under different projections.

Results

We examined how different emission sectors contributed to changes in $PM_{2.5}$ exposure over 2010 to 2020 across China. We found that national average $PM_{2.5}$ exposure peaked in 2012 at 52.8 $\mu g\ m^{-3}$ (Fig. 2.5b), with contributions primarily from industrial (31%) and residential (22%) emissions (Figure 2.5d). $PM_{2.5}$ exposure reduced by 36% in 2020 due mostly from lower industrial (by 58%) and residential (by 29%) emissions (Figure 2.5). Reductions in $PM_{2.5}$ reduced the disease burden by 9% over this period (Fig. 2.5g). Overall our work demonstrates that reductions in emissions from the industrial and residential sectors have dominated reductions over the 2010-2020 period. Full details of this work is given in Conibear et al. (2022b).

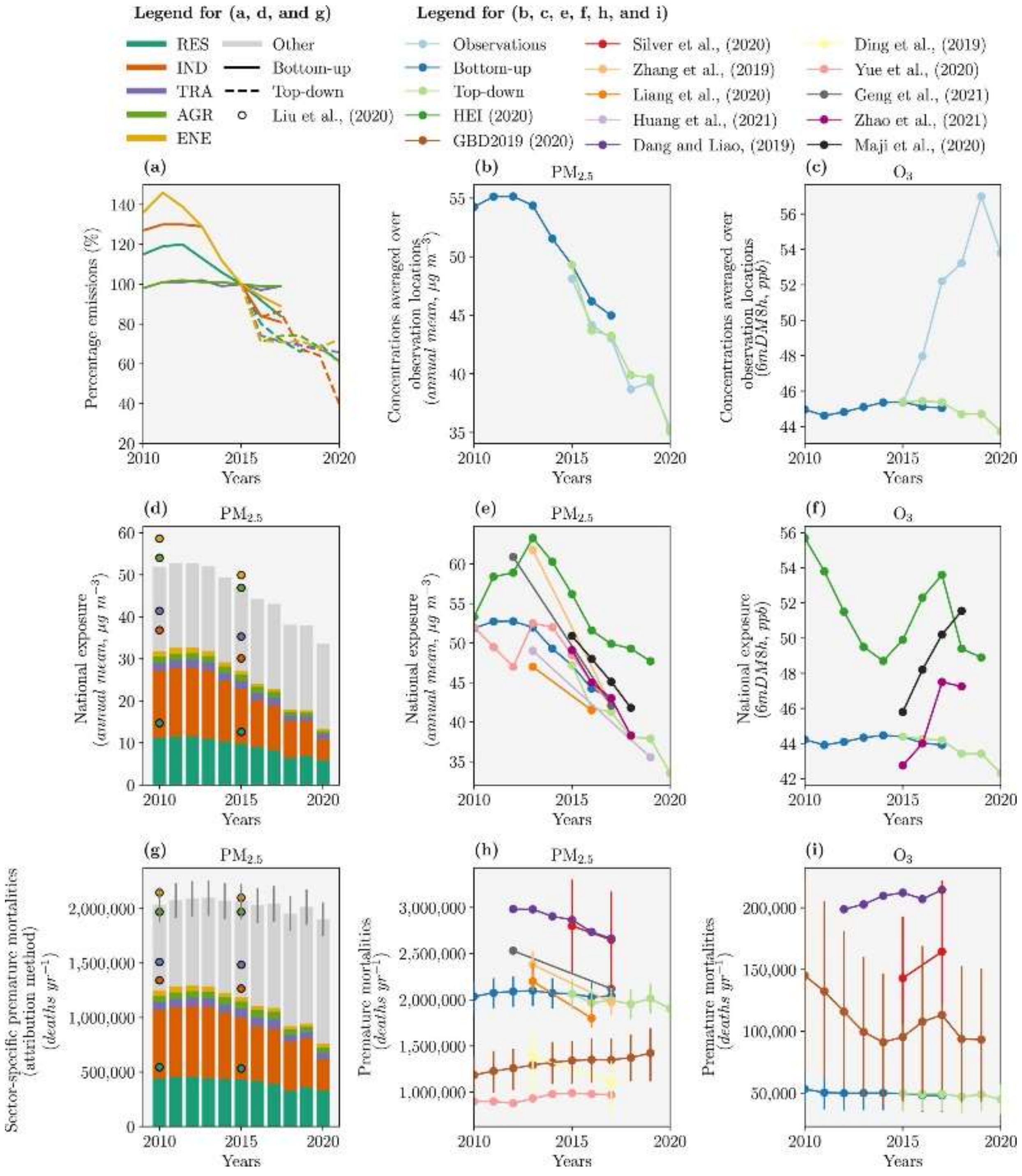


Figure 2.5: Changes in emissions, air quality, and health impacts in China over 2010-2020. (a) mean emission changes relative to 2015, (b) mean $PM_{2.5}$ concentrations at observation locations, (c) mean ozone (O_3, maximum 6-monthly-mean daily-maximum 8-hour, 6mDM8h) concentrations at observation locations, (d) sectoral contributions to $PM_{2.5}$ exposure, (e) national $PM_{2.5}$ exposure, (f) national O_3 exposure, (g) sector-specific premature mortalities (MORT) from $PM_{2.5}$ exposure using the attribution method, (h) annual MORT from $PM_{2.5}$ exposure, and (i) annual MORT from O_3 exposure. Sectors are residential (RES), industrial (IND), land transport (TRA), agricultural (AGR), and power generation (ENE) emissions.

Next we assessed the impacts of different emission scenarios on projected $PM_{2.5}$ exposure and disease burden over 2020 to 2050 and examined the contribution of different emission sectors to projected changes. We compared future scenarios combining baseline activity projections with current legislation air pollution storyline (BASE-CLE), baseline activity projection with maximum feasible reduction (MFR) air pollution storyline (BASE-MFR), and sustainable development activity projection with MFR air pollution storyline (SDS-MFR).

We found that $PM_{2.5}$ exposure declines in all scenarios across China over 2020–2050, with reductions of 15% under current air quality legislation, 36% when exploiting the full potential of air pollutant emission reduction technologies, and 39% when that technical mitigation potential is combined with emission controls for climate mitigation (Figure 2.6a).

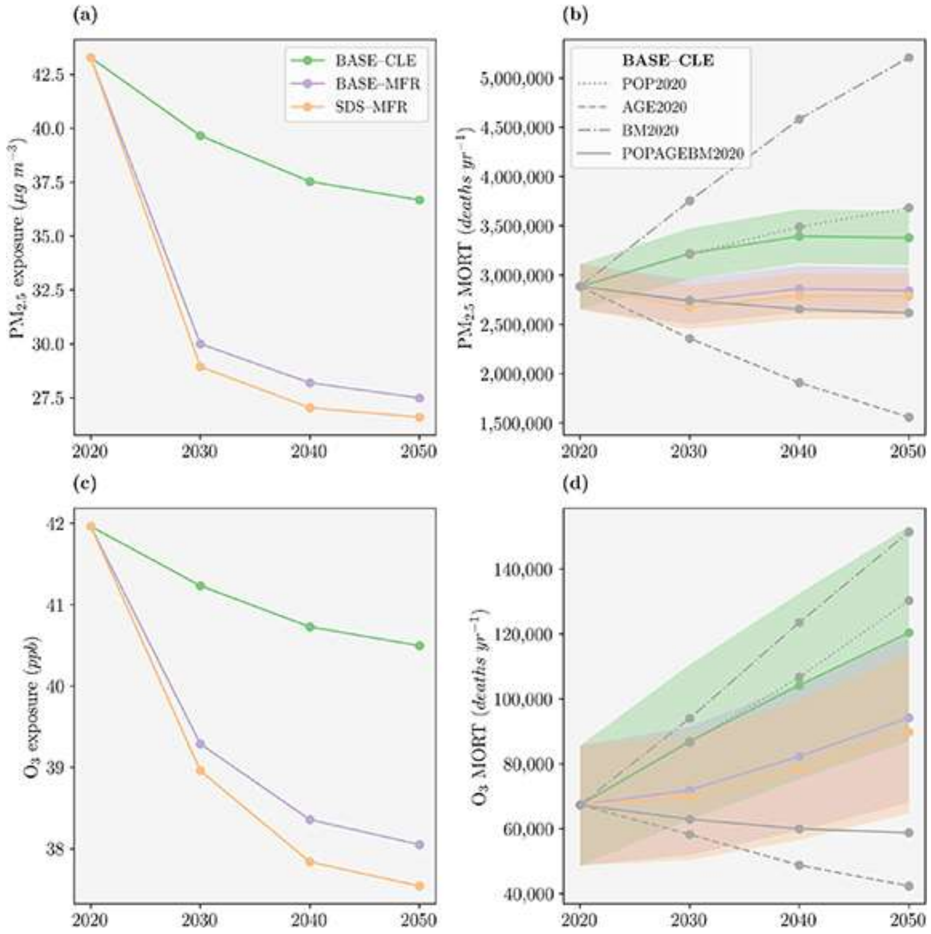


Figure 2.6: The impacts of future emission scenarios on air quality and human health in China from 2020 to 2050. Scenarios are the baseline activity projection with current legislation air pollution storyline (BASE-CLE), baseline activity projection with maximum feasible reduction (MFR) air pollution storyline (BASE-MFR), and sustainable development activity projection with MFR air pollution storyline (SDS-MFR). Results are for (a) $PM_{2.5}$ exposure, (b) annual premature mortalities (MORT) from $PM_{2.5}$ exposure, (c) maximum maximum 6-monthly-mean daily-maximum 8 h (6mDM8h) ozone (O_3) exposure, and (d) annual MORT from O_3 exposure. Sensitivity health impacts are shown for the BASE-CLE for 2050 using 2020 data for population count individually (POP2020), population age groupings individually (AGE2020), baseline mortality rates individually (BM2020), and all three of these variables combined (POPAGEBM2020).

We examined how different emission sectors contributed to projected changes in $PM_{2.5}$ exposure. Annual mean $PM_{2.5}$ exposure and the associated disease burden were most sensitive to changes in industrial and residential emissions (Figure 2.7).

We investigated how changes in $PM_{2.5}$ exposure, population, demographics and baseline health contributes to projected changes in disease burden. Population ageing means that the $PM_{2.5}$ disease burden under current air quality legislation increases by 17% in 2050 relative to 2020 despite substantial reductions in $PM_{2.5}$ exposure under this scenario. The disease burden is only reduced by 3% under maximum feasible emission reduction and climate mitigation (Figure 2.6). Full details of this work can be found in Conibear et al. (2022a).

Overall, our work demonstrates that changes to industrial and residential emissions have dominated changes in $PM_{2.5}$ exposure over the last decade and are likely to dominate changes over the next few decades. We show that population ageing over the 2020-2050 period means that large reductions in $PM_{2.5}$ exposure are required to achieve reductions in health burden highlighting the need to identify win-win options between air quality and climate mitigation.

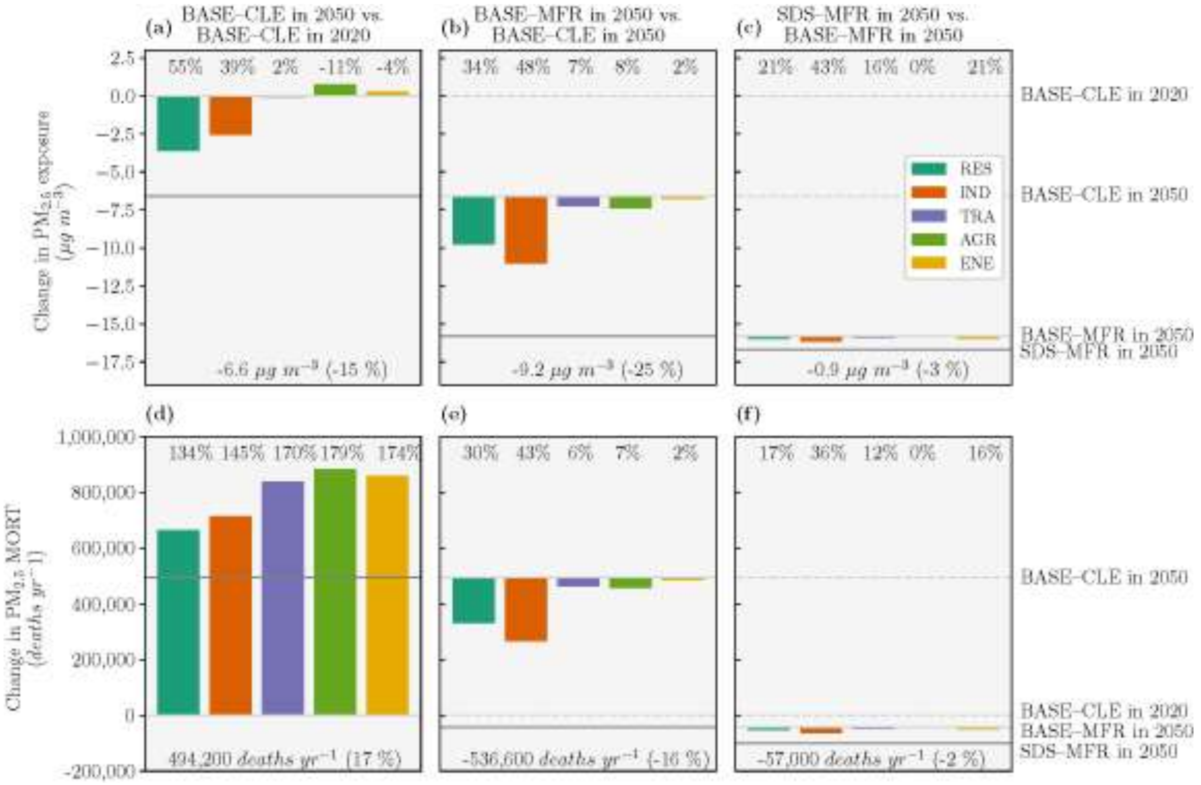


Figure 2.7: The relative impacts of individual sector changes on (a)-(c) annual-mean $PM_{2.5}$ exposure and (d)-(f) associated premature mortalities (MORT) from future emission scenarios in China. Scenarios are (a) and (d) the baseline activity projection with current legislation air pollution storyline (BASE-CLE) in 2050 compared to 2020, (b) and (e) the baseline activity projection with maximum feasible reduction (MFR) air pollution storyline (BASE-MFR) in 2050 compared to BASE-CLE in 2050, and (c) and (f) the sustainable development activity projection with MFR air pollution storyline (SDS-MFR) in 2050 compared to BASE-MFR in 2050. The overall impact per scenario is shown by the horizontal lines and bottom estimates. The sector-specific impacts per scenario are shown by the top percentages.

Future research priorities

- To assess sub-sector attributions as well as the air quality impacts of specific interventions and technological solutions;
- To apply the approach developed here to assess air quality impacts in the UK as well as other regions where emissions are changing rapidly such as Asia and Africa;
- To further develop our framework to understand how air quality and climate change (e.g. heat waves) impacts combine and how societal changes such as population ageing and urbanisation will alter the health impacts.

CS3: Consequence of net zero policies for population attainment of 2021 WHO interim targets and progress toward air quality guideline levels

Jian Zhong, James Hodgson, William Bloss (University of Birmingham)

Aim

- To assess the air quality co-benefits of predicted NO_2 and $PM_{2.5}$ levels under plausible NZ policies in the West Midlands;
- To explore the scope for NZ measures to reduce environmental health inequalities;
- To identify future research priorities.

Background

Many air pollutants and GHGs have common sources most obviously through the combustion of fossil fuels. Quantifying these NZ and air quality co-benefits, and tensions, is important to quantify the wider local health benefits that will accrue. There is also the possibility to apply NZ policy options in a way that reduces air-quality-mediated environmental health inequalities between communities.

Methods

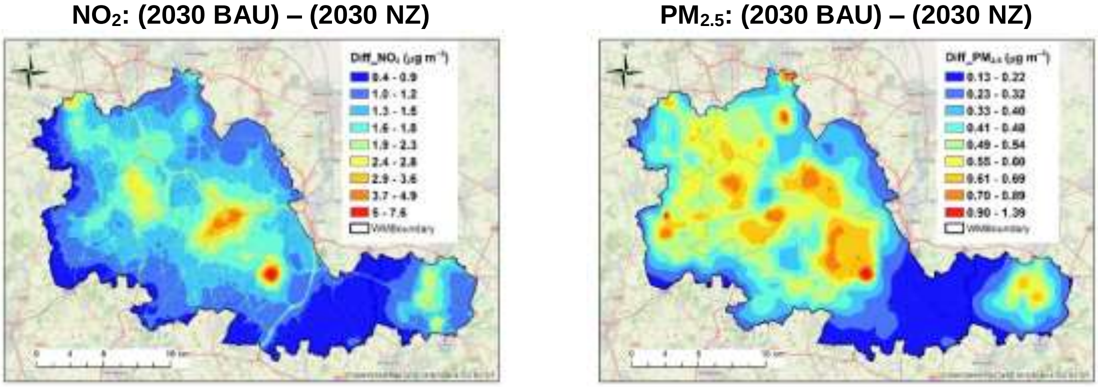
We applied the high resolution ADMS-based local air quality model for the West Midlands, developed in collaboration with CERC (Zhong et al., 2021). The model has been validated against NO_2 and $PM_{2.5}$ data from regional background stations and local roadside sites. Model outputs were used at their native street scale resolution, and averaged to ward level for comparison with WHO guidelines. Four emission scenarios were constructed (Table 2.2).

Table 2.2: Emission scenarios used in CS3.

Scenario	Emissions Assumptions
2021	Baseline (no Covid effects considered)
2030 BAU	Anticipated emissions changes in line with NECD commitments / 2019 Clean Air Strategy
2030 NZ	Emission reductions estimated for the UK NZ strategy, estimated with reference to CO_2 changes (as appropriate to sector/activity); CO_2 emission changes as evaluated by the CCC (2022).
2030 EV	Transport sector only changes in line with the above – corresponds to 24% car; 9% HGV; 25% bus/coach = EV)

Results

Figure 2.8 shows predicted reductions in NO_2 and $PM_{2.5}$ due to NZ policies (relative to 2030 BAU) in the West Midlands. Reductions of annual mean NO_2 of 5-7 μg m^{-3} and annual mean $PM_{2.5}$ of 0.9-1.4 μg m^{-3} could be achieved. The implications of the above NZ scenarios on attainment of the WHO guidelines for air pollution, and other targets were assessed, as summarised in the tables below. For $PM_{2.5}$, 28 wards have mean concentrations above 10 μg m^{-3} in 2030, representing some 15% of the region's population. This falls to zero under the NZ strategy, but only reduces slightly under the EV-only scenario. This means that transport shifts to electric vehicles, alone, do not significantly reduce PM levels in the West Midlands. All wards fail to comply with the WHO guideline for $PM_{2.5}$ of 5 μg m^{-3} under all scenarios (Table 2.3). For NO_2, under 2030 BAU conditions, mean pollutant concentrations across all wards meet the first two WHO Interim Targets for NO_2 (40 and 30 μg m^{-3}), but 3 wards fail to meet IT3 (20 μg m^{-3}) and 189 wards fail to meet the guideline level (10 μg m^{-3}) (Table 2.4). Under the NZ scenario, all wards meet the IT levels, but 174 (out of 192) fail to meet the guideline level.


NO_2: (2030 BAU) – (2030 NZ)

$PM_{2.5}$: (2030 BAU) – (2030 NZ)

Figure 2.8: Predicted reductions in NO_2 and $PM_{2.5}$ due to NZ policies, relative to 2030 BAU, in the West Midlands.

Impacts on environmental health inequality were further assessed by evaluating the relationship between ward-level NO_2 and $PM_{2.5}$ concentrations, and the ONS Index of Multiple Deprivation (IMD) decile, under baseline and 2030 NZ scenarios. The results showed a slight reduction in the relationship between IMD and both $PM_{2.5}$ and NO_2, with both the gradient and absolute difference in concentration between the most and least deprived wards reducing under 2030 NZ, relative to the 2021 baseline scenario (change from 4.1 to 3.62 $\mu g\ m^{-3}$ for NO_2; 1.42 to 1.17 $\mu g\ m^{-3}$ for $PM_{2.5}$) (Tables 2.3 and 2.4).

In summary, NZ policies will significantly improve air quality in the West Midlands, particularly for NO_2, through fleet electrification. The improvements for $PM_{2.5}$ are more modest if the NZ changes are restricted to transport electrification alone: reductions in emissions across all sectors (power, industrial, manufacturing, domestic) is required to realise the benefits. NZ changes as proposed will slightly reduce environmental health inequality, narrowing the air pollutant concentration gap between the most and least deprived wards.

Table 2.3: Impact of different emission scenarios on $PM_{2.5}$ concentrations.

Scenario	**No. Wards** where mean $PM_{2.5}$ > **10** $\mu g\ m^{-3}$ **	(c) **% Population** [total 2.9m] in wards where mean $PM_{2.5}$ > **10** $\mu g\ m^{-3}$ **	**No. Wards** where mean $PM_{2.5}$ > WHO AQG (**5** $\mu g\ m^{-3}$) **
2021	104	57.2	192
2030 BAU	28	15.9	192
2030 NZ	0	0	192
2030 EV	26	14.7	192

Table 2.4: Impact of different emission scenarios on NO_2 concentrations.

Scenario	**No. Wards** where mean NO_2 > **40** (IT 1)	**No. Wards** where mean NO_2 > **30** (IT 2)	**No. Wards** where mean NO_2 > **20** (IT 3)	**No. Wards** where mean NO_2 > **10** (AQG)
2021	0	0	78	192
2030 BAU	0	0	3	189
2030 NZ	0	0	0	174
2030 EV	0	0	2	187

Future research priorities

- To develop methodology to estimate the relationship between air pollutant and carbon emissions (both model and measurement, i.e. empirically based);
- To develop coherent emissions (activity) data, regionally and nationally, under anticipated NZ policy scenarios, consistent with NAEI approaches;
- To identify which emission sectors should be prioritised for NZ changes, to maximise the health benefits and inequality reduction, alongside carbon reductions;
- To determine where NZ changes will first be apparent in measured air pollutant levels, to demonstrate the local health gains.

CS4: Estimating future new particle formation under different emission scenarios

James Brean, Alex Rowell, Zongbo Shi and Roy M Harrison (University of Birmingham).

Aim

- To evaluate the formation and growth rates of new particles under plausible scenarios;
- To identify future research priorities in understanding NPF and growth in the future.

Background

NPF is an important atmospheric process wherein gas phase molecules cluster together and grow to form new aerosol particles. These aerosol particles have the potential to contribute greatly to $PM_{2.5}$ mass loadings (Kulmala et al., 2021, 2022; Guo et al., 2014), thereby contributing to regional air pollution, and the nanoparticles produced by NPF processes are a health risk in their own right. NPF is a photochemically driven secondary source of aerosol particles that is highly sensitive to the concentrations of both gas phase precursors such us SO_2, non-methane volatile organic compounds (NMVOCs), NO_x, ammonia (NH_3), and amines, and pre-existing particle surface area. In the urban environment, particle formation from sulphuric acid (H_2SO_4) and amines has been shown to be the dominant mechanism (Yao et al., 2018; Cai et al., 2021; Brean et al., 2020; Deng et al., 2020), while condensation of sulphuric acid and oxygenated organic molecules (OOMs) can largely explain the observed particle growth (Yao et al., 2018; Brean et al., 2020; Qiao et al., 2021). Understanding how NZ/CN policies may change the formation and growth of new particles is key to predict future air quality and health impacts.

Methods

In order to investigate future changes to NPF, we developed a script which simulates basic photochemistry, clustering of sulphuric acid and amines to form new particles, and growth due to coagulation and condensation of sulphuric acid, amines, and OOMs. The script reproduces gas-phase concentrations of H_2SO_4 and OOMs, and resultant formation and growth rates in summertime Beijing accurately. The pre-existing particle population is taken from data measured in Beijing in the summertime (Shi et al., 2019). We use future predictions for the effect of NZ policy on the emissions of SO_2, NMVOCs, NO_x, NH_3, and amines from the Dynamic Projection for Emission in China (DPEC) model (Tong et al., 2020) to investigate the possible future changes to NPF in China (Beijing) under a range of different climate constraints, socio-economic drivers and air pollution control measures for the years 2040 and 2060. We present three possible future scenarios:

1) Baseline follows the SSP4 narrative which envisions slower economic growth and a fast-increasing population. Climate constraints are minimal under RCP6.0 conditions and air pollution controls remain at 2015 levels;
2) Current-goals presumes China will achieve its National Determined Contribution (NDC) pledges by 2030. It follows the SSP2 narrative which envisions slow economic progress. Climate constraints are moderate under RCP4.5 conditions and air pollution controls adopt current and upcoming policy to 2030;
3) Ambitious-pollution-Neutral-goals represents China’s commitment to achieve CN by 2060. It follows the SSP1 scenario which envisions a gradual shift towards a more sustainable society. Climate constraints are more ambitious under China’s carbon neutral goals and air pollution controls adopt the best available end-of-pipe technologies.

Results

We found that the projected changes to SO_2 emissions are key in changing future NPF. Particle formation rates are highly dependent on H_2SO_4 concentrations, with different scenarios producing either a doubling, or near total reduction in sulphuric acid-amine particle formation rates (Fig. 2.9a). Particle growth rates are projected to change little in all but the most ambitious scenarios, where a >60% reduction in growth rates is seen (Fig. 2.9b). This is due to the changes in NMVOC concentrations (as an OOM source) are offset by our predicted changes to particle surface area (as an OOM sink). This substantial change to particle formation rates results in vastly differing particle number concentrations (Fig. 2.9c).

We further showed that these future emission reductions will come with the co-benefit of reductions to NPF-derived particle mass (Fig. 2.9d) from 15 µg m^{-3} to 9 µg m^{-3} under *current goals*, and to 4 µg m^{-3} under the *ambitious goals* scenario. Further increases in a “business as usual” *baseline* case will result in a small increase to this particle mass derived from NPF (17 µg m^{-3}). This mass of particles from NPF is seen to be substantial. We therefore propose that the currently anticipated reductions to SO_2 will be key in reducing NPF intensity and therefore potentially secondary particle mass in Beijing. More ambitious goals in the move towards NZ will only hasten this co-benefit, reducing secondary $PM_{2.5}$ mass concentrations.

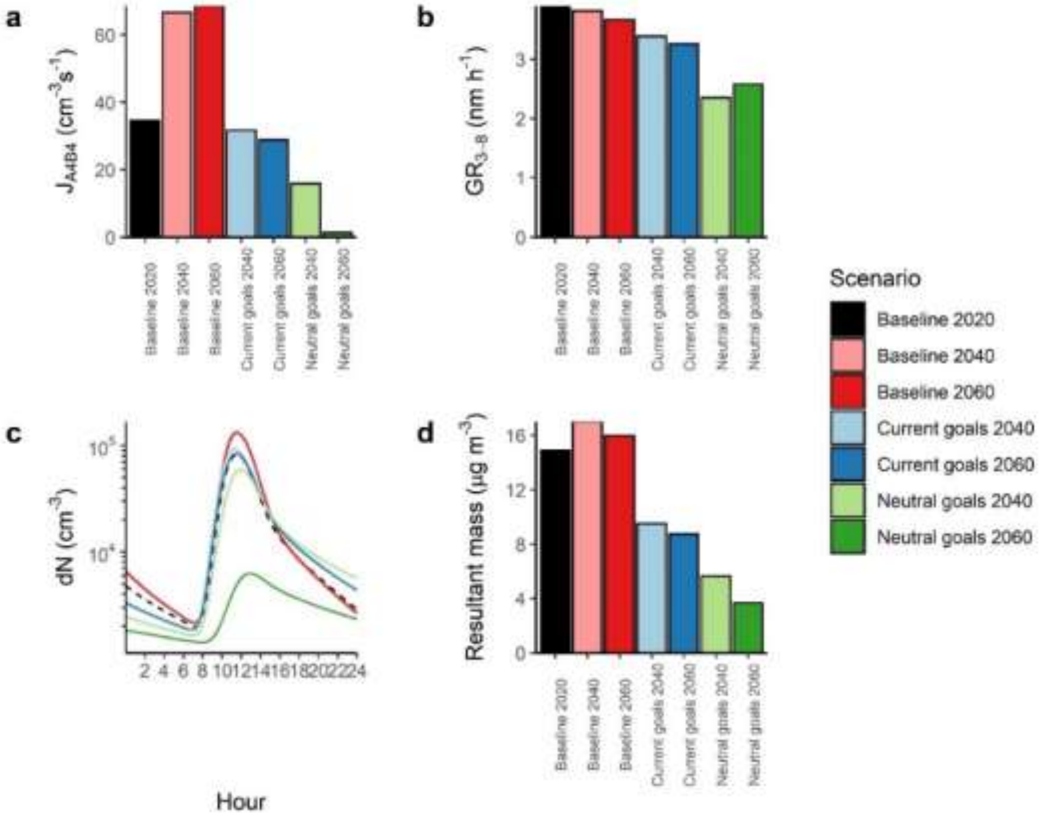


Figure 2.9: Effects of future emission scenarios on NPF showing (a) changes in mean particle formation rate, (b) changes in mean growth rates of 3-8 nm particles, (c) changes in the diurnal cycle of particles, and (d) changes to the mass derived from NPF after a 24-hour simulation run.

Future research priorities

- To predict future concentrations of amines, NH_3, speciated NMVOCs, and particle number size distributions;
- To further develop the current model to represent changes in size distributions, multiphase chemistry and additional inorganic species (such as nitric acid, HNO_3) contributing to particle growth;
- To determine NPF and growth rates under future atmospheric conditions associated with representative NZ/CN scenarios;
- To predict future impacts of NPF upon both particle number and mass concentrations
- To extend the model to make predictions for other cities in China and the UK;
- To evaluate the likely impacts of amine releases from carbon capture processes upon NPF in affected localities.

CS5: The effect of the drive to carbon neutrality on ozone in Beijing

Beth S. Nelson, James D. Lee (University of York)

Aim

- To determine the sensitivity of O_3 production in Beijing to reductions in NO_x and PM representative of future scenarios;
- To identify future research priorities in optimising policies to mitigate O_3 pollution.

Background

Ambient ozone concentrations in major urban areas of China have continued to increase despite recent reductions in the emissions of SO_2 (since 2006) and NO_x (since 2011) (Wang et al., 2017). The warm-season daily maximum 8-hour average (MDA8) ozone levels increased by 2.4 ppb (5.0%) year^{-1}, with over 90% of the sites showing positive trends and 30% with trends larger than 3.0 ppb year^{-1}. These elevated O_3 levels adversely affect agricultural crops and human health, with current projections indicating that ozone pollution is likely to worsen in future. Indeed this was demonstrated during the COVID-19 pandemic and related restrictions on transport and industry that were introduced around China. Numerous studies showed that O_3 increased, with an average increase of around 10%.

Due to O_3 being formed by complex photochemical reactions of NO_x, volatile organic compounds (VOCs), free radicals and PM, the picture is complicated and detailed chemical studies are required to fully understand the effect of future NO_x and other primary pollutant reductions. The recent APHH-Beijing project provides a unique dataset that allows this type of study to be carried out. Two field campaigns took place (in winter 2016 and summer 2017) at the Institute for Atmospheric Physics (IAP) in Beijing. A wide range of ozone precursor species were measured, including NO_x, O_3, SO_2, CO, nitrous acid (HONO), and large suite of VOCs, free radicals (OH, HO_2, RO_2) and particulate matter (number, size, composition) (Shi et al., 2019). This data allow us to evaluate the sensitivity of O_3 to changing NO_x and PM concentrations under NZ/CN scenarios.

Methods

A chemical box model, incorporating the highly detailed Master Chemical Mechanism (MCM, v3.3.1, http://mcm.york.ac.uk), was constrained to the full measurement suite mentioned above. The MCM is a *near explicit* description of the chemical degradation of VOCs, leading to ozone production. The model was used to calculate ozone production, at first under observed conditions, and then also after scaling the observational dataset to potential future pollutant concentrations.

As the relationship between ozone production and its precursor species is non-linear, the first stage of analysis was to vary the concentrations of the key ozone precursor species, VOCs and NO_x by a scaling factor between 0.01 and 2, whereby a VOC factor of 0.5 reduced the concentration of all anthropogenic VOCs (all measured VOCs, excluding isoprene), by half in the model. Over 400 model runs at a variety of different VOC and NO_x scaling factors were run, to produce the isopleth described by Figure 2.10. Changes in ozone production under different future scenarios, combining both climate and air quality policy, were investigated.

Results

Figure 2.10 shows that the chemical regime at the urban site in Beijing, China is indicative of a VOC-limited regime. As a result, reducing concentrations of NO_x without a sufficient co-reduction in VOCs leads to an increase in *in situ* ozone production. This highlights the significance of ensuring adequate VOC reduction policies are in place alongside NO_x reduction strategies, to reverse the increase in ozone production.

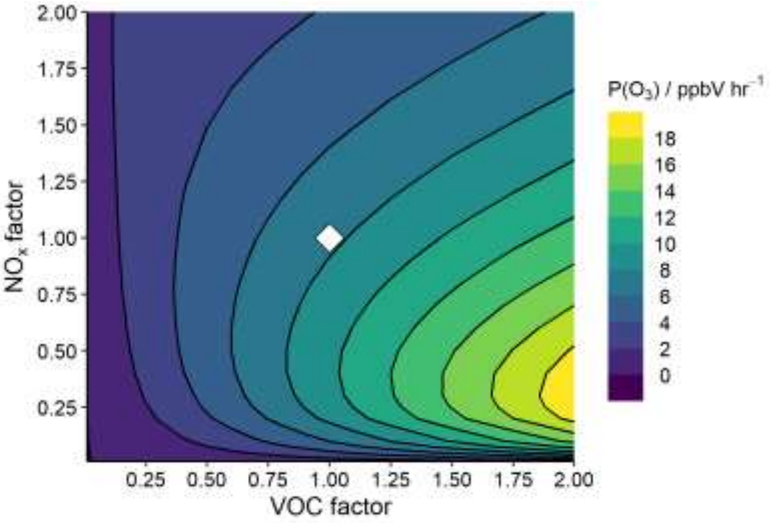


Figure 2.10: Ozone production isopleth, averaged between 05:00-15:00 local time. Changes in VOCs and NO_x are coloured by ozone production rate. The white diamond indicates the ozone production rate at observed concentrations of VOCs and NO_x.

To gauge the impact of changing air quality and climate change policies, as we head toward CN, anthropogenic VOCs and NO_x were then varied based on future scenarios defined by the Dynamic Project model for Emissions in China (http://meicmodel.org). Six different scenarios are defined in the DPEC emissions inventory, describing six unique combinations of socio-economic development, climate policy, and emission control policy scenarios. The DPEC scenarios combine frequently used climate scenarios, seen in IPCC reports, with the additional element of incorporating future air quality policy scenarios: BAU, Enhanced Control Policy (ECP), and Best Health Effect (BHE). More detailed information on these scenarios can be found in Tong et al. (2020). The results of this study show that, relative to the 2017 emissions inventory:

- Under BAU scenarios, VOCs increase by up to *ca.* 30%-40% up in 2040 before stabilising up to 2050. NO_x continues to increase up to *ca.* 110% in 2040, increasing more gradually towards 2050;
- Under ECP scenarios, VOCs initially decrease by *ca.* 20% up to 2030, then stabilise or increase slightly to be within 10 - 20% of 2017 values. NO_x decreases by *ca.* 20% were it remains up to 2050;
- Under BHE scenarios, VOC decreases continuously up to a 40%-50% reduction by 2050. NO_x also continues to decrease, to up to *ca.* 40%-60% in 2050.

The percentage changes since 2017 in VOCs and NO_x under both scenarios are shown in Figure 2.11.

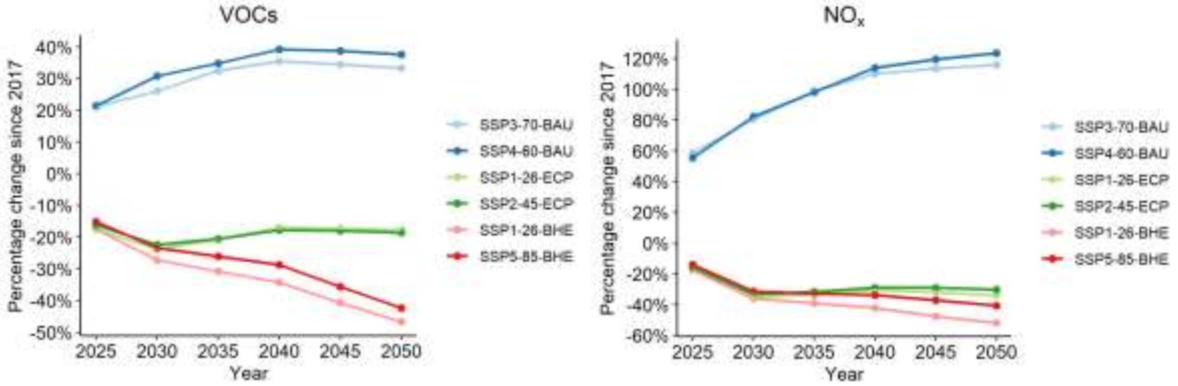


Figure 2.11: Percentage change in VOCs (left) and NO_x (right), under six future DPEC scenarios, since 2017 emissions inventories (http://meicmodel.org).

As Beijing was identified as being in a VOC-limited ozone production regime, and changes in NO_x roughly follow VOC trends, ozone production was expected to reduce in line with VOC reductions, with BHE scenarios leading to the greatest reductions in ozone production, followed by ECP and BAU scenarios. Figure 2.12 shows the change in ozone production for all scenarios up to 2050.

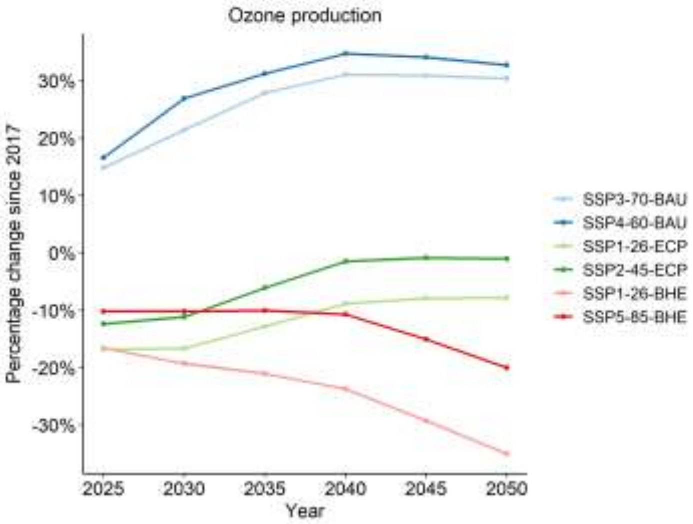


Figure 2.12: Percentage change in ozone production averaged between 05:00-15:00 local time from 2017 observations under six different DPEC scenarios (http:/meicmodel.org).

Generally, ozone production was found to increase by *ca.* 30% in 2050 when compared to 2017 observations for the BAU scenarios. Ozone production also initially decreased under the ECP scenarios, with a reduction of 10%-20%. However, after 2030, ozone production starts to increase again under these scenarios, to between a 0%-10% reduction compared to 2017 values in 2050. Under BHE scenarios, ozone production decreases, more gradually at first, before reducing to *ca.* 20%-35% of 2017 values by 2050. Some discrepancies were identified between scenarios with the same emission control policies, but different socioeconomic development and climate policies. This highlights the need to combine both climate and air quality policies when investigating the potential impact of policy on future ozone production rates.

Interestingly, the ozone production trends were did not exactly follow the VOC trends for each scenario (Figure 2.11). Until 2040, larger reductions in ozone production were observed for one of the ECP scenarios (SSP1-26-ECP), than one of the BHE scenarios (SSP5-85-BHE), despite larger reductions in bulk VOCs under the BHE scenario. This can be attributed to the types of VOC reduced under each scenario, and their propensity to form ozone. To investigate this further, observed concentrations of VOCs were varied in the chemical box model by class (Figure 2.13). Modelled ozone production was found to be more sensitive to changes in the alkene class, with a reduction in ozone production of *ca.* 30% when alkenes were halved. On closer inspection of the individual VOC species reduced under each DPEC scenario, many alkenes were found to be reduced more greatly under ECP scenarios than BHE scenarios, accounting for the discrepancy observed in Figure 2.12 (see Figure 2.13).

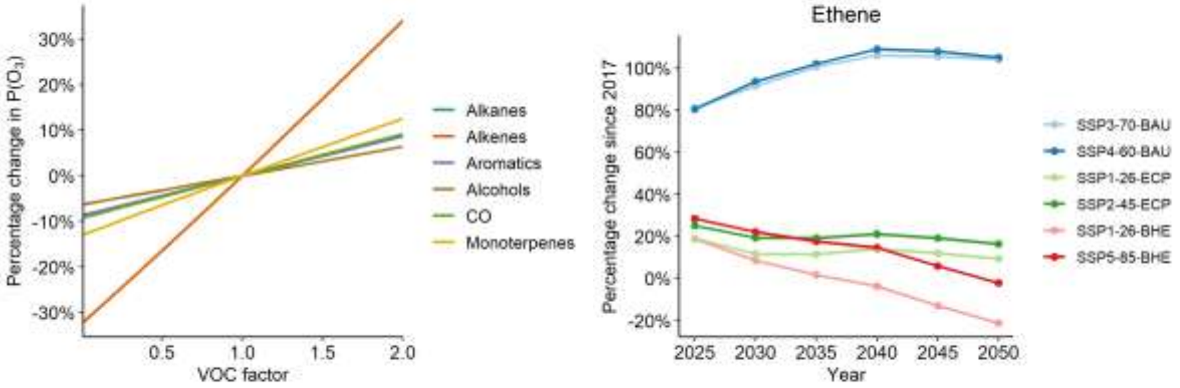


Figure 2.13: Percentage change in ozone production from 2017 observations when VOCs are varied by class (left), and the percentage change in ethene under the six DPEC scenarios (right), (http:/meicmodel.org).

We further found that ozone production is Beijing is even more sensitive to changes in isoprene than the sum of the alkene class (Figure 2.14).

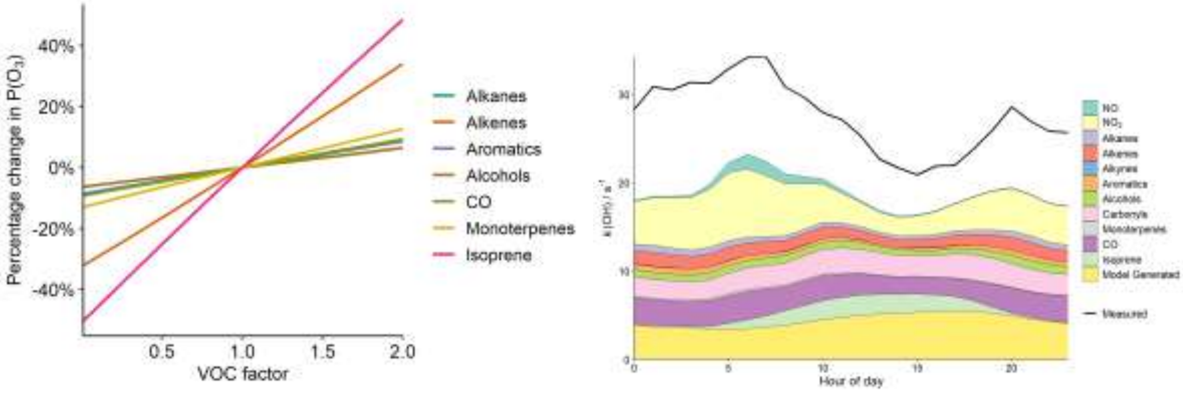


Figure 2.14: Percentage change in ozone production from 2017 observations when VOCs are varied by class (left), and stacked area plot of OH modelled OH reactivity by compound class, compared to measured OH reactivity (right) (Whalley et al., 2021).

Future research priorities

- To evaluate the sensitivity of O_3 to biogenic VOCs, including isoprene in future scenarios;
- To evaluate the impact of changes in temperature and photolysis rates on O_3 formation sensitivity;
- To determine the concentration of a wider range of VOCs in the city to better close the gap in OH budget and to describe the VOC chemistry more comprehensively.

CS6: Impacts of net zero policies on regional ozone in China

Zhenze Liu, Oliver Wild (Lancaster University), Ruth Doherty (University of Edinburgh), Steven Turnock, Fiona O’Connor (Met Office)

Aim

- To quantify the expected benefits for surface ozone in China arising from potential NZ policies and to identify the drivers of these changes from different sectors, external sources and climate;
- To investigate how high ozone episodes are likely to change in future;
- To explore the use of machine learning to bias correct simulation of ozone episodes;
- To identify future research priorities.

Background

Surface ozone is increasingly becoming a problem for air quality in China as current policies target particulate matter (reduction of which leads to faster ozone formation) and NO_x (reduction of which leads to higher ozone under VOC limited conditions) (Hollaway et al., 2019). The path to NZ provides an opportunity for air quality improvements and needs to ensure that ozone concentrations are reduced to levels that cause minimal damage to human health and crop yields. The long-term transition in China from coal to renewables for electricity generation will lead to substantial geographical changes in precursor emissions that will impact regional ozone. In addition, the rapid transition to EVs already underway in China may have substantial benefits for urban pollutant levels that the UK could usefully learn from. These regional emission changes build on changing global ozone concentrations driven by ongoing climate change and by the changing abundance of atmospheric methane, but the consequences of these for surface ozone remain poorly characterised.

Methods

The UKESM1 global earth system model was used to investigate present day (2013-17), NZ (2060, SSP119) and BAU (2060, SSP370) scenarios for surface ozone in China. Sensitivity studies were performed to investigate the contributions of transport, industry, power and industrial sources in China to regional ozone, to explore the impact of future changes in methane concentrations and climate, and to quantify how emission changes outside China affect surface ozone in China. In addition to exploring monthly mean ozone in summer and winter, hourly ozone concentrations were diagnosed to investigate the occurrence of high ozone episodes, and a novel machine learning approach was applied to remove the known biases in simulating these episodes and to generate a more robust and reliable assessment of the likely changes in high ozone. We use SSP pathways to represent global emission scenarios, replacing these with the more detailed DPEC emission inventories over China, and perform 10-year model simulations with UKESM1 for each scenario. A multilayer perceptron neural network approach was then developed and applied to reproduce the model bias in daily mean surface ozone compared to the observation-based China Air Quality Reanalysis (CAQRA) for 2013-2017, permitting daily grid-point based bias correction of the model results under present and future conditions.

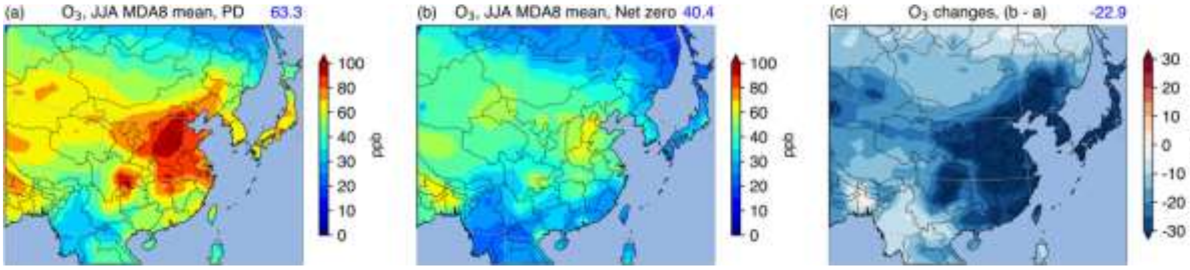


Figure 2.15: Summertime mean daily maximum 8-hr ozone (MDA8) under present day conditions (a) and global NZ conditions in 2060 (b), along with the net change in ozone (c), based on simulations with the UKESM1 model.

Results

We find that sources over China itself strongly dominate regional ozone changes in summertime, with a large benefit expected (23 ppb reduction in summer daytime ozone, see Fig. 2.15) following NZ policies. However, changes in emissions outside China make a substantial contribution across most of China, accounting for about one third of the mean ozone reduction in summertime. Controlling global emissions of atmospheric CH_4 contributes about 4 ppb throughout the year. Climate change makes a relatively small contribution to ozone changes over China in 2060, averaging a 0.5 ppb reduction over the year, although this masks regional and temporal variations that reveal competing processes including summertime ozone production from temperature sensitive natural VOC sources, and faster removal over maritime areas associated with greater atmospheric humidity. Considering the contribution of different anthropogenic emission sectors within China separately, we find that emissions from the transport and industrial sectors have the greatest impacts on summertime ozone, with a smaller effect from power generation and the smallest effect from residential sources, largely reflecting the magnitude of the contribution of each sector to the total regional NO_x sources.

High ozone episodes are likely to become much less frequent in future along NZ scenarios. Model simulations with UKESM1 see a reduction in days with ozone levels over the North China Plain (including Beijing) exceeding 50 ppb from 68 to 26 days per year by 2060 under NZ conditions. Applying bias correction using the deep learning approach greatly improves UKESM1 simulation of surface ozone under present-day conditions, and the summertime mean ozone bias drops from 3.0 ppb to 0.1 ppb. Applying the same approach to bias correct future daily ozone leads to a decrease in the expected ozone reductions, highlighting the tendency for current state of the art chemistry-climate models to overestimate surface ozone in summertime in polluted continental regions.

We find that with bias correction there is a larger reduction in the number of daily mean ozone exceedances from 60 to 17 days per year. In the absence of international adoption of NZ policies outside China (China following NZ, the rest of the world following business as usual), the number of exceedances would be 33 days per year, emphasising the importance of regional oxidant transport and changes in background tropospheric composition. Similarly, adopting strict NZ policies for air pollutant emissions internationally without addressing rising global methane concentrations would lead to ozone exceedances over the North China Plain for 36 days per year, emphasising the importance of tackling methane as a key ozone precursor on a global scale. Our results highlight that while episodes of high ozone are not eliminated under NZ conditions, they are expected to be dramatically reduced, with considerable benefits expected for human health and ecosystems.

Future Research Priorities

- To identify the optimal combination and timing of NZ policies to rapidly benefit climate without increasing urban ozone concentrations because reducing NOx and PM faster than VOC (as is currently the case) is expected to lead to increased ozone concentrations in the short term;
- To provide a more robust assessment of ozone changes at local and urban scales (3-5 km) and particularly at the street scale where the urban ozone decrement due to traffic is expected to reduce, as these have direct implications for human exposure;
- To further develop machine learning approaches to bias correct model-simulated ozone episodes to improve assessment of future short-term ozone exposure;
- To apply the machine learning approach with the large ensemble of realizations of future climate in CMIP6 to explore how climate changes alone may be expected to influence short-term ozone exposure.

CS7: Evaluating health benefits of net zero transport emissions in China and the UK

Frank Kelly (Imperial College London), Tong Zhu (Peking University), Sean Beevers, Miranda Loh (Institute of Occupational Medicine), Lora Fleming (University of Exeter), Mei Zheng (Peking University)

Aim

- To test policies, and research questions, that are likely to impact on air pollution, including the rapid uptake of EVs in different transport sectors (e.g. public and private transport, commercial and construction industry) in both China and UK;
- To examine how different policies will lead to improvement in public health.

Background

To achieve both the UK’s and China’s NZ/CN transport targets, policies may need to be more ambitious and/or be implemented earlier than planned. To ensure that co-benefits of transport sector GHGs and air pollutant reduction strategies are utilised most effectively, we need a better understanding of the impacts of each country's policies on public health (Watt et al., 2015; Kelly, 2016; Kelly and Zhu, 2016).

In the UK the transport sector is now the main source of GHGs and air pollutants, while in China both the energy sector and the transport sector are main producers of GHGs and the main source of air pollutants that harm health. Transportation changes in both countries will therefore be a key aspect of climate change actions. However, a simple shift from internal combustion vehicles to EVs will not be sufficient (due to ongoing non-exhaust emissions) to achieve the air quality improvements needed in urban areas.

Supporting public transport, and increased cycling and walking, as well as switching to EVs, will lead to environmental and health benefits from more physical activity and lower air pollution. It will be important to address the limited public transport in poorer and rural areas, and concerns about reliability and affordability. Well-targeted actions should therefore simultaneously benefit human health and accelerate progress towards the UK target of NZ GHG emissions by 2050 and China by 2060.

Methods

With air quality modelling we predicted air pollution concentrations, health and economic impacts at baseline (2019) and for a range of policy scenarios out to 2050 (UK) and 2060 (China), including the rapid uptake of EVs in different transport sectors (e.g. public and private transport, commercial and construction industries) in both China and UK, and examined how these will lead to improvement in public health. We explored the benefit of earlier adoption of these policies and the impact of different transport actions on air quality.

Results

Modelled estimates of the health benefits that could be achieved by climate mitigation policies were found to vary depending on the assumptions about the amount of change achieved in key exposures and the exposure-response relationships.

Increasing the proportion of regular cyclists in England from 4.8% to 25% would result in 2.2% reduction in passenger-related CO_2 emissions and 2.1% reduction in years of life lost due to premature mortality. A partial reduction in car travel with active travel (2-fold increase in distance walked; 8-fold increase in distance cycled) and implement of low-carbon-emission cars (95 g km^{-1} CO_2 compared to current 177 g km^{-1} CO_2) results in a 2.5-fold decrease in per person CO_2 emissions. This equates to a reduction of more than 500 premature deaths per million people through improvements in health outcomes related to physical activity and air pollution.

Conversion of China's fossil fuel vehicles to EVs would reduce 30%-70% of $PM_{2.5}$ and 30%-80% of NO_2 and provide significant health benefits. In the UK the transport (26%) and energy (22%) sectors are both major emitters of GHG emissions. An increased shift to EVs would alter this balance unless an increased proportion of energy was derived from renewable sources.

Predicted health benefits from these changes to transportation are likely to be underestimates as they do not account for associated benefits from noise and road injury reductions and benefits of physical activity.

Future research priorities

- To evaluate the direct and indirect health and other co-benefits of cleaner air due to climate actions, which will likely change a negative return on investment to be positive;
- To identify mitigation actions that deliver climate and air quality co-benefits that can save and improve millions of lives and grow economies within the short term;
- To determine the economic costs versus health (and equity) benefits of climate change/air quality actions, which will help policy makers take forward expensive mitigation strategies;

- To identify factors influencing both incremental and transformational behaviour change and areas for targeted behavioural change interventions to address health and climate actions;
- To explore the balance of positive and negative health impacts posed by the NZ transition, including assessment of occupational health impacts;
- To further explore the co-benefits of significantly enhanced public transport systems in cities – taking into account the climate change, air quality, health and equity outcomes.

CS8: Evaluating air quality related health and equity impacts due to net zero/carbon neutrality options

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Aim

- To evaluate the existing literature on health impacts of air quality changes due to NZ/CN policies, and any inequalities which may arise;
- To develop an inventory of observational data available in the UK which could be used for evaluating air quality changes and related health impacts over time, and evidencing impacts of NZ/CN policies;
- To identify observational and data science gaps for evidencing the impacts of NZ/CN policies on air quality and health (equity).

Methods

Rapid review

We conducted a rapid review of the literature since 2018 on the pathways between NZ policies, air quality and human health. We applied a systematic search strategy to the Web of Science database and screened titles and abstracts for relevancy. The focus was on post-2018 literature as a paper by Gao et al (2018) had done a similar review on public health co-benefits of climate policies, covering papers evaluating a number of sectors, including energy generation, transportation, food and agriculture, households, and industry.

Monitoring site inventory

As part of an effort to identify data for evaluation of UK-based NZ/CN policies, we collected sources of observational data on air quality across the UK, including the spatial and temporal availability of these data and the species available. These include Automatic Urban Rural Network (AURN) stations, local-managed sites, research supersites, LondonAir sites, and satellite data. We also summarised sources of health data which could be linked to air quality data for evaluations of health impacts of air quality changes.

Results

Rapid review results

Our rapid review found that most studies evaluating NZ/CN policies followed a similar study design. This design involved a scenario-based simulation projecting impacts of policies on future GHG reductions and associated air pollution concentrations and health impacts. Policies evaluated since 2018 were mostly in the energy or land transportation sector, or involved a ‘holistic’ approach, which refers to examining a climate target, and assuming a mix of policies to achieve this.

Most studies took place in China or the USA, with a few in Europe or other Asian countries. Only two studies researched the global effect. No studies were done in other low and middle income countries or countries in the southern hemisphere. Most studies tended to investigate effects of NC/CN policies on $PM_{2.5}$ and premature mortality. Thus, it was not possible to establish the total multi-pollutant and more subtle health impacts.

Few studies directly considered inequality as part of the analysis. Williams et al. (2018) found that deprived populations in the UK would still be most exposed to air pollution under any scenario, assuming that their living conditions were largely the same from 2011 to 2035.

Monitoring site inventory results

We found that air monitoring coverage is heavily skewed towards urban areas, particularly in London (Figure 2.16). The most commonly measured pollutants include PM_{10}, $PM_{2.5}$, NO_x or NO_2, and ozone. Some sites will include a much wider range of species including metals and volatile and semi-volatile organic compounds.

There are few rural background sites with extensive monitoring, which limits our ability to evaluate background source contributions and air quality exposures for rural community. Some AURN sites were shut down or were downgraded to focus on NO_2 only and removed monitoring of $PM_{2.5}$ (as the biggest health risk). This is primarily because $PM_{2.5}$ mostly met the air quality objectives but NO_2 did not but this makes it difficult to evaluate trends in air quality, and therefore impacts of policies, in the long-term.

Satellite data provides a much larger spatial coverage, but at lower resolution and accuracy. However, it can provide a consistent source of data for evaluating larger scale (e.g. national or international level) change over time for air quality. It can also be used in conjunction with ground-level monitoring (e.g. to roughly fill in gaps where monitoring does not exist) to provide a fuller picture of air quality in a country.

Administrative data allows for analyses of health impacts across different geographical scales over time, however the signal of health effects due to air quality changes can be difficult to detect given the relatively small effect compared to other risk factors.

An alternative to simulation-only or observational data-only approaches for policy evaluation is to use a hybrid approach blending observational and simulation approaches. For example, air quality changes could be evaluated based on emission changes among different sectors due to NZ/CN policy, or health impacts could be derived as an attributable fraction based on existing exposure-response functions and population mortality and morbidity statistics.

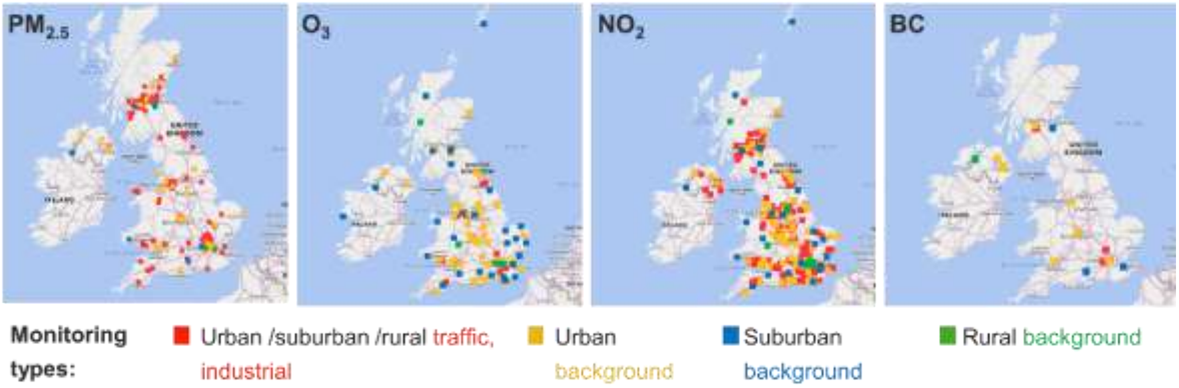

Figure 2.16: Location of monitoring sites across the UK for different air pollutants. (1) For $PM_{2.5}$, the UK has 170 sites as representatives of urban/suburban/rural traffic and industrial environment, 49 sites as urban background, 5 sites as suburban background, and 8 sites as rural background; (2) for O_3, the UK has 39 sites as urban/suburban/rural traffic and industrial, 61 sites as urban background, 5 sites as suburban background, 31 sites as rural background; (3) for NO_2, the UK has 437 sites as urban/suburban/rural traffic and industrial, 145 sites as urban background, 14 sites as suburban background, 29 sites as rural background; (4) for Black Carbon (BC, 880 nm), the UK has 3 sites as urban traffic, 7 sites as urban background, 1 site as suburban background, 3 sites as rural background.

Future research priorities

- To study the NZ/CN policy impacts globally, particularly in low-and-middle income countries and across borders, to better understand transboundary impacts and potential unintended inequalities in impacts;
- To include formal analysis of effects on different populations, especially vulnerable groups when evaluating air quality exposure and health impacts should include;
- To evaluate the impacts of NZ/CN policies with more ambitious GHG targets and including a wider range of sectors;
- To expand current studies on NZ/CN policy impacts on air quality and health to include multiple air pollutants which could affect health and ecosystems;
- To develop observational and data science strategies to evidencing the impacts of NZ/CN policies on air quality and health including using or hybrid observational and simulation studies;
- To incorporate more comparisons of *ex-ante* or pre-policy predicted impacts from simulations, with *ex-post*, or observed impacts over time after policy implementation;
- To incorporate evaluations into the policy planning processes.

CS9: Marginal health benefits per unit of CO_2 mitigation in various emission sources

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Aim

- To evaluate the technology costs and health co-benefits at the facility level to optimise the NZ policies under different NZ pathways;
- To help emerging economies to achieve the CN and air quality goal in a synergetic manner that integrates health effects in decision-making process.

Background

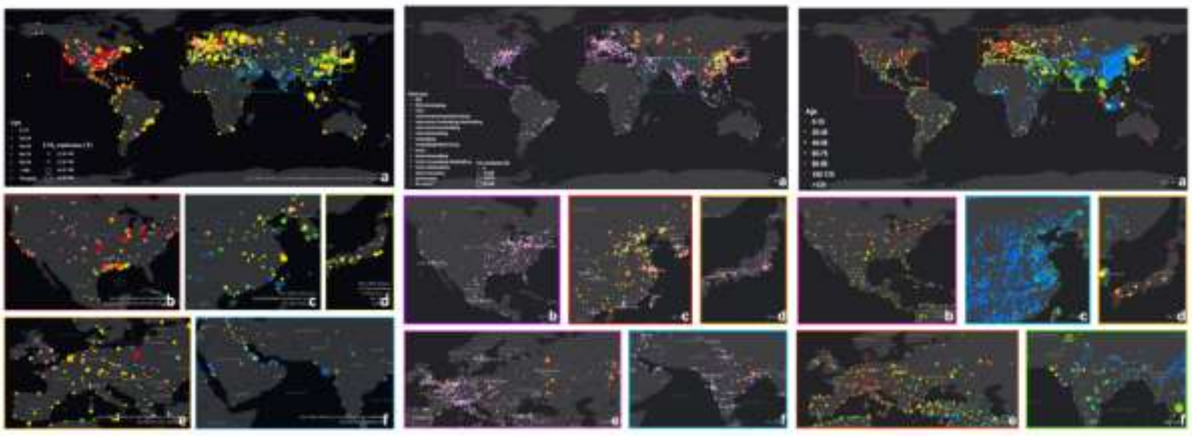
Currently, the assessment of the synergistic effects of decarbonization and air pollution reduction, including air quality improvement and population health effects, has generally remained at the national and regional scales. However, due to the variation in energy structure, industry chain processes, and geographical location of different industries, carbon mitigation efforts from different industrial sectors will lead to greatly varied co-benefits of air quality improvement. Furthermore, when considering atmospheric transport and transformation processes, as well as the uneven distribution of China's population, mitigation measures of the same industry may result in different health co-benefits across different geographical regions. Therefore, a co-benefit assessment with high spatial and temporal resolution and detailed sectoral information will provide greater scientific support for sectoral and regional deployment of mitigation measures, with the aim to maximize the co-benefits of air quality improvement and population health protection based on similar carbon reduction achievements. On the other hand, air quality improvement and population health protection have immediate benefits, and the economic effect of health benefits is more significant, which is conducive to further promoting the implementation of carbon emission reduction measures.

Methods

This study combined multi-sectoral input-output tables and high-resolution energy inventories of Chinese provinces to assess the impact of per unit carbon emission reduction from different sectors at the production and consumption ends on the reduction of multiple air pollutants and their precursors. The air quality model and its accompanying models are used to simulate the influence of pollutant emissions from different regions and sectors on the population health losses in China. By coupling the two steps above, this study provides a high temporal and spatial resolution analysis of the health co-benefits of carbon emission reductions of typical emission-intensive sectors from the production and consumption perspectives.

Results

This study firstly built a global plant level database for oil refinery, stell and cement industries (Figure 2.17). Based on the sensitivity analysis of population health effects to gridded pollutant emissions and the sub-source accounting of production-based carbon emissions, the study obtained the health benefits of synergistic emission reductions from different sources as well as their spatial distribution characteristics (Figure 2.18). Carbon reduction from domestic sources is mainly through the shifting from solid fuels to cleaner energy such as electricity and natural gas. Combustion efficiency improvement is the most effective way to simultaneously minimize the health risk of population pollution exposure. Transportation sources are the second-largest mitigation contributor. Power plants source, although was the largest CO_2 emitter, have the lowest pollution reduction potential and contribute the least to population health benefits due to their already stringent tailpipe control measures.



(a) Global Oil refinery (b) Global steel emissions (c) Global cement emissions

Figure 2.17: Plant level emissions of (a) global oil refinery, (b) global steel and (c) global cement.

Investigators of this CS also organized a workshop titled “Maximizing NZ/CN benefits on the economy” on the 14th April 2022. This workshop highlights the significance of conducting facility level analysis of technology costs and health co-benefits to optimise the NZ policies under different NZ pathways.

Future research priorities

- To establish plant-level emission databases (CO_2, primary $PM_{2.5}$, and secondary $PM_{2.5}$ and ozone precursors) of key industrial sectors and monitor the mitigation progress;
- To construct NZ technology toolbox of key industrial sectors, including information on technical details, applicable conditions, available commercial years, etc.;
- To establish appropriate indices at the plant level to represent the health co-benefit per unit carbon abatement;
- To estimate the distributional health and economic effects on various regions, income groups and age groups;
- To interpret the results into policy implications with qualitative and quantitative uncertainty analysis.

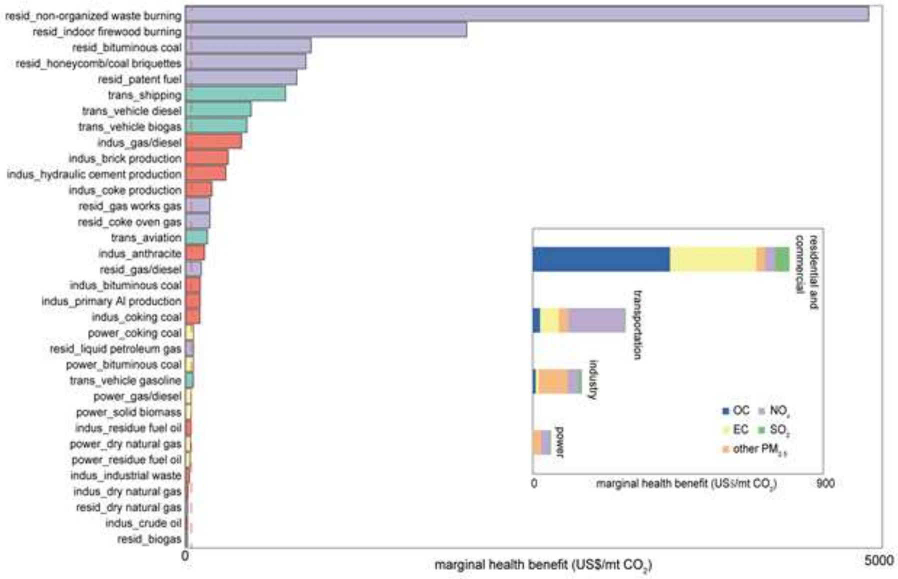


Figure 2.18: The marginal health benefits per unit of CO_2 mitigation in various emission sources in China

2.3 Summary of case studies

The CSs covered a range of topics, from emission, to process studies, to health and economic appraisals, in relation to NZ and air quality. CS1 evaluated the data inversion approach, using low cost sensor network and reference air quality observations, to improve emission inventories of GHGs and air pollutants. They demonstrated the value of such novel approaches, particularly when incorporating three-dimensional observations, and called for the wider application in other cities in the UK and China. CS8 reviewed existing literature on air quality-related health and equity impacts of NZ/CN and pointed out the needs of comprehensive studies in countries other than US and China, particularly in developing countries. It also reviewed the current observational and data science capabilities in the UK. They concluded that an integrated data approach to policy evaluation will increase the evidence base for the benefits of NZ/CN policies on air quality and health, and to adjust policies to maximise their benefits. Given that official monitoring stations are not always in abundance, data optimisation could be best achieved by integrating long-term observations of criteria and speciated pollutants, low cost sensor networks, satellite and mobile platforms.

CS3 applied traditional air quality modelling to evaluate the potential impact of NZ policies on air quality in the west Midlands. CS4 and 5 applied process modelling to understand the formation and growth rates of new particles and ozone sensitivity under future scenarios in Beijing. They identified the need to predict future air quality concentrations, particularly the number size distributions, anthropogenic and biogenic VOCs in cities.

CS2 applied hybrid machine learning and chemical transport modelling approaches to evaluate the uncertainties in estimating air quality impacts due to the NZ/CN policies in China. CS6 also used a hybrid modelling approach to study the impacts of NZ policies on regional ozone in China.These two CSs tested the novel approaches that could be applied to elsewhere including in China. They identified the need to understand the joint impacts of climate change and NZ/CN policies on emissions (including from sub-sectors), air quality and health, and to explore how best to optimize policies to maximise co-benefits, including the optimal combination of policies as well as the timing of different actions.

CS7 and 9 looked at health and economic aspects associated with the air quality co- or dis-benefits of the NZ/CN polices. They highlighted the importance of behaviour change in reducing emissions and of incorporating health co-benefits into the cost-benefit analysis in developing climate policies and technologies.

Overall, these CSs generated significant new research, including more than 10 papers/manuscripts (see Chapter 6), tested new data science and modelling approaches and identified future research priorities. Together, they offer a broad appraisal of the background issues which need to be addressed as NZ/CN policies are developed, and define a research agenda to tackle many of the key issues.

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Chapter 3 : International Workshop on Net Zero and Air Quality

3.1 Introduction

To support the COP-AQ project objectives, we organized an International Workshop on Net Zero and Air Quality. The overall aim was to capture the current understanding of the co-benefits or dis-benefits of NZ/CN policy options on air quality relating to health and economic impacts, and to identify future research questions and priorities.

This workshop was held virtually from 11th -13th January 2022. The talks were given by leading researchers in the field, including Tong Zhu, Frank Kelly, Paul Monks, Shu Tao, Shuxiao Wang, Dabo Guan, Hong Liao, Eric Saikawa, Tzung-May Fu, Ally Lewis, Paul Wilkinson, and Ruth Doherty. The recordings of the talks are available on the COP-AQ website.

The workshop attracted 252 registrations across the world.

3.2 Summary of talks

The following section provides a summary of all the talks, while the actual presentations are available online (see Section 6.2).

Prof. Shu Tao (Peking University) presented **"Recent trend of air pollution in China - A sectorial-resolved-emission-inventory-based evaluation"**. They applied sectorial-resolved emission inventory to evaluate the impacts of residential emissions on air quality and health in China as well as benefits of past policies. Using the banning of beehive coke ovens in 1996 as an example (Xu et al., 2018, 2019), they estimated that the total number of premature deaths due to the exposure to $PM_{2.5}$ from beehive coke ovens was 365,000 for the period between 1982 and 2014 which is around three times lower than if beehive coke ovens had not been banned. However, this number would have halved if beehive coke ovens were dismissed immediately after the ban was in force. They showed that during 1992-2012, the transition to clean energy, together with the upgrading of domestic stoves which were driven by the socioeconomic development (Tao et al., 2018; Meng et al., 2021), contributed to the reductions in ambient and indoor $PM_{2.5}$ and premature deaths associated with the exposure to $PM_{2.5}$ from residential emissions (Meng et al., 2021; Shen et al., 2019). Residential emissions are critical due to the associated health impacts. They estimated that although the residential sector contributed only 7.5% of the energy consumption in China for 2014, emissions were proportionally much higher and contributed 67% of premature deaths attributed to $PM_{2.5}$ exposure (Yun et al., 2020). They further investigated the air quality and health benefits of clean heating campaign to substitute residential solid fuels with electricity or natural gas in the Beijing–Tianjin–Hebei area from 2017 to 2021. They reported that a 60% substitution would lead to 60% reduction in ambient $PM_{2.5}$ associated to residential emission and 40% reduction in the overall $PM_{2.5}$ concentrations (Meng et al., 2019).

Prof. Tzung-May Fu (Southern University of Science and Technology) presented **"Sensitivities of ozone air pollution in the Beijing-Tianjin-Hebei area to local and upwind precursor emissions using adjoint modelling"**. This talk focused on O_3 pollution, a growing air pollution problem in China. To tackle O_3 problem, a major challenge is to reduce the emissions of NMVOCs. But first, we need a detailed source attribution for surface O_3 during severe pollution including the geographical and sectorial origin of the chemical species contributing to O_3 pollution. This is required to guide VOC reduction and alleviate the severe O_3 pollution. They studied O_3 sensitivity to local and regional emissions of O_3 precursors in the BTH area (Wang et al., 2021). They found that during severe events, O_3 pollution is sensitive to local and regional emissions of O_3 precursors, while during slight-exceedance events, O_3 is more sensitive to local emissions. In addition, O_3 formation tend to be NO_x-limited during heavy pollution, and VOC-limited on less polluted days. They further identified key sectors for NMVOC control to alleviate severe O_3 pollution including paint use, industry and gas vehicles. This information provides guidance for effective mitigation of O_3 pollution in the

BTH area. They further highlighted the need of a systemic approach to quantify the change in precursor emissions as a result of GHG mitigation before fully evaluating the impacts of NZ strategies on O_3 pollution. They also discussed the potential change in the speciation of VOCs and how this might affect O_3 sensitivities, and what is the implications of this change on air quality and health.

Prof. Shuxiao Wang (Tsinghua University) presented **"Air quality and health benefits under carbon neutrality policies"**. They showed that low-carbon energy policies more stringent than current nationally determined contribution (NDC) pathways are needed to achieve both the air quality target for $PM_{2.5}$ (35 µg m^{-3} by 2035) and CO_2 mitigation (Xing et al., 2020). They proposed that the adjustment of the energy structure with higher share of renewables and natural gas and less coal, and energy conservation policies in particular for the industrial and building sector will lead to the achievement of air quality standards and more reductions in CO_2 emissions, beyond the Paris agreement (Xing et al., 2020). Their modelling also suggest that sustainable development under 1.5 °C pathways can bring significant health co-benefits from air quality improvement (including 1,589, 000 deaths avoided due to lower $PM_{2.5}$ exposure and 526,000 deaths avoided due to lower O_3 exposure in 2050), and offset the impact of climate-change driven meteorological changes on air pollution. They also called for the land use management to reduce dust source areas to mitigate increasing risk of dust to future air quality in Northern China due to climate change (Liu et al., 2021).

Prof. Hong Liao (Nanjing University of Information Science and Technology) presented **"$PM_{2.5}$ and O_3 air quality and associated health impacts in China from 2015 to 2060 under carbon neutral pathways".** They first highlighted the improvement in air quality in China in recent year but pointed out the increasing O_3 pollution problem. They quantified the potential impacts of CN strategies on air pollution and associated health effects from 2015-2060. In the sustainability scenario (SSP1-1.9), CN is achieved by 2060 with CO_2 emissions mainly arising from the energy and industrial sectors. In the fossil-fuel development scenarios (SSP5-8.5), a peak in carbon emissions is expected by around 2070 with carbon emissions primarily from the energy, transportation, and industrial sectors. The expected reduction in air pollutant levels including BC, CO, NO_x, OC, SO_2, and NMVOC varies between 66%-97% in the SSP1-1.9 scenario, and between 24%-67% in the SSP5-8.5 scenario. The model results indicates that annual mean concentrations of $PM_{2.5}$ over five most polluted regions in China will decrease to be below 21 µg m^{-3} by 2060 in the SSP1-1.9 scenario, while smaller reductions are expected in the SSP5-8.5 scenario. In addition, O_3 concentrations will decrease by 30% in the SSP1-1.9 scenario, but further increase in the SSP5-8.5 scenario. Consequently, the mortality associated with $PM_{2.5}$ and O_3 exposure (considering also the population aging) is expected to increase by 35% in the SSP1-1.9 scenario, while a significantly larger increase in mortality is predicted in the SSP5-8.5 scenario (around 150%). They called for more consideration of the combined effect of future reductions in GHGs causing less warming, and aerosols causing less cooling in the climate change mitigation. The overall stronger warming effect (e.g., Dang and Liao, 2019) due to less aerosols in the air, and the changing meteorological parameters driven by climate change could contribute to the poorer air quality (e.g., Yang et al., 2016; Li et al., 2019, 2020), and an increased frequency of severe haze events in megacities (Cai et al., 2017). They identified the future research needs to account for changes in both emissions and climate when projecting air pollution and health effects, to quantify the impacts of reduced air pollution on global warming, to understand the interactions between vegetation-air pollutants-carbon-climate, and to quantify the combined effects of air quality and climate change.

Prof. Tong Zhu (Peking University) presented **"Coordinate air pollution control and climate change mitigations to maximize co-health benefits"**. They first pointed out the reduction in $PM_{2.5}$ due to clean air actions in China which contributed to 14% reduction in premature deaths due to long-term exposure, and 60% reduction in deaths associated with acute exposure due to the decreasing number of heavily polluted days (Xue et al., 2019). But $PM_{2.5}$ concentrations remain far above the new air quality guidelines from WHO. They discussed a recent study by Cheng et al. (2021) which suggested that a transition to low-carbon clean energy accompanied with climate mitigation strategies is required to reduce

$PM_{2.5}$ exposure of most of the Chinese population to below 10 µg m^{-3} by 2060 as end-of-pipe control measures will not be sufficient (Cheng et al. 2021). They showed that reducing emissions from the residential sector is of high priority for improving air quality and reducing the population exposure to air pollutants (Liu et al., 2016), while the conversion to EVs can contribute to 30%-70% reduction of $PM_{2.5}$ across China (Wang et al., 2021).

Prof. Paul Monks (BEIS Chief Scientist, University of Leicester) presented **"Net Zero and air quality - A systems problem"**. They explained that the UK's NZ GHG emissions by 2050 can be achieved through multiple actions including reducing the demand for carbon-intensive activities, improving efficiency in the use of energy and resources, taking up low-carbon solutions (e.g., replacing fossil fuels with hydrogen and electric-drive technology, and installation of carbon capture and storage), expansion of low-carbon energy supplies, land use change and CO_2 removal (CCC, 2020). They pointed out that an economic-wide transformation is required, starting from an energy transition through the reduction in the demand/consumption of electricity and changing of fuel supplies such increased use of renewable energy and natural gas and phase-out coal (Wilson et al., 2021). They argued that doubling of electrical generation is a potential pathway for supporting transport, heating, and industry decarbonization (BEIS, 2021a). They advocated for the need for a systemic approach to NZ and air quality management during the policy-making processes.

Prof. Frank Kelly (Imperial College London) presented **"Health, climate change and the air quality challenges ahead".** They firstly pointed out that climate change could lead to higher O_3 and particulate concentrations and pollen counts, increasing the risk of premature deaths, acute and chronic cardiovascular and respiratory diseases. Extended droughts, high winds, and changes in vegetation due to climate change may also lead to increased risk of natural events such as wildfires and desert storms which will impact air quality and will have further health effects. They found an increased risk of child mortality in low and middle -income countries because of exposure to landscape wildfire smoke which are increasing due to climate change (Xue et al., 2021). Furthermore, social injustices are likely to increase further in megacity due to climate change as green spaces and the heath island are not distributed evenly across urban areas. Air pollution, short-lived climate pollutants and GHGs share many common sources. Addressing these sources in an integrated fashion can achieve multiple public health, environmental and climate change benefits at lower costs. Most efforts to mitigate climate change will also have significant air quality and thus health benefits. They called for further research into the combined benefits of climate actions and the resulting improvement in air quality and health to support policy-making.

Prof. Dabo Guan (Tsinghua University) presented **"Socioeconomic benefits of the net zero emission transition".** They first provided an update on the carbon emission pledged in China - peak by 2030, CN by 2060. The time to reach CN from the peak is much shorter than those in Europe (including the UK) and the US, which are around 70 and 40 years (CEAD, 2021). They predicted that the rise in temperature by above 1.5 °C will be costly in lives and livelihoods due to increased frequency of extreme weather events, droughts and crop failure, sea level rise and floods (CEAD, 2021). They also reported that high climate risk affects food supply and consumption (Wang et al., 2020, Bunn et al., 2015, Schroth et al., 2016, Xie et al., 2018). All of these have direct and indirect impacts on the regional economy and wider economic system (Mendoza-Tinoco et al., 2017, 2020). They estimated that the overall economic costs of air pollution induced by health loss in China is 346.26 billion yuan (1.1% GDP) (Xia et al. 2016). They highlighted the importance of incorporating the mental health impact in cost-benefit analyses of air pollution action plans.

Prof. Ally Lewis (Chair of DEFRA Air Quality Expert Group, University of York) presented **"Adoption of hydrogen as a fuel - Potential impacts on air quality"**. This talk discussed the impacts of the application of hydrogen (H_2) as an alternative fuel in NZ strategies. H_2 can be deployed as an energy source in two main ways including through electrochemical fuel cells and combustion in gas burners and ignition engines (Lewis, 2021a). Electrochemical fuel cells directly generate electricity and only produce water as a by-product, but they are expensive, transformational, and require very pure H_2 (e.g., green H_2). Domestic gas burners (e.g., gas boilers) can be retrofitted to use H_2-natural gas blends - these are simple and cheap end-use equipment, and can burn impure H_2 (e.g., blue and grey H_2). However, the combustion of H_2 generates water vapor and NO_x as by-products. NO_x emissions varies depending on the amount of H_2 in the fuel blends. As H_2 is added to a combustion system, the increasingly fuel-lean condition leads to lower NO_x emissions because of the lower combustion temperature, but there is a trade-off with energy efficiency (Lewis, 2021a). Under the current UK H_2 strategy, H_2 would be mostly burnt in engines and boilers rather than being used in fuel cells (BEIS, 2021b). However, the impacts of blending H_2 in the UK natural gas grid are highly uncertain. Wright and Lewis (2021) found that the addition of 20% H_2 (the maximum amount which can be accommodated in existing infrastructures) would lead to a change in NO_x emissions in the range from –50% to +154% relative to natural gas.The most likely outcome of adding H_2 is an increase of around 25% in NO_x emissions from domestic heating corresponding to a mean damage cost of around 400 million GBP per year, which is considerably higher than the carbon price saving from blending in H_2 (Wright and Lewis, 2021). By 2040, domestic heating will be possibly the main source of NO_x in cities in the UK because of the electrification of road vehicles. H_2 boilers will be most likely concentrated in areas of high-density housing, often associated with low-income households, which will lead to a widening of inequality in exposure to NO_2 (Lewis, 2021b). Finally, they concluded that the mitigations of NO_x emissions from H_2 combustion systems can be achieved through new regulation and innovation in after-treatment technologies. They discussed about the need to consider air quality benefits when prioritizing the use of hydrogen in different sector.

Prof. Paul Wilkinson (London School of Hygiene & Tropical Medicine) presented **"Risks and benefits of climate actions"**. Here, this talk first highlighted the wider economic contexts, particularly the "unintended consequences", of climate actions. It then focused on home energy efficiency actions, which can positively or negatively affect indoor environment. They explored the impacts of enhanced home energy efficiency on air exchange rate and thus indoor air quality. They estimated the annual life years gained due to increased home energy efficient 2020-2110 in England and Wales under Balanced Pathway for two different ventilation scenarios – when there is no intervention on ventilation, there will be life loss due to poorer air quality. Finally, they called for a tailored approach and a combination of different actions to minimize adverse effects.

Prof. Ruth Doherty (University of Edinburgh) presented **"Future climate and emissions impacts on air quality heading towards net zero".** This talk discussed future emissions and climate scenarios in Europe, UK and East Asia, and O_3 sensitivities.They presented the annual mean O_3 and $PM_{2.5}$ over Europe and East Asia estimated by the atmospheric chemistry transport model CMIP6 under the NZ SSP scenarios SSP1-1.9 and SSP1-2.6 (Turnock et al., 2020). They estimated that the SSP1-2.6 scenario could lead to a decrease in O_3 by around 12 ppb in Europe and East Asia, while $PM_{2.5}$ may decrease by around 2 $\mu g\ m^{-3}$ in Europe, and around 8 $\mu g\ m^{-3}$ in East Asia. By contrast, the high fossil fuel development scenario SSP3-7.0 showed an increase in both annual mean surface O_3 and $PM_{2.5}$. Although the NZ SSP scenarios assume large reduction in NO_x, CO, NMVOC (e.g., >70% in the SSP1-1.9 scenario), the UKESM model estimated an increase in winter O_3 concentration over China and large parts of Europe. For the SSP1-2.6 scenario, the UKESM showed an increase also in summer O_3 concentration for some parts of China (Liu et al., in preparation). Liu et al. (2022) examined regional O_3 sensitivity to NO_x and VOC at present day and under the high fossil fuel development scenario SSP3-7.0. They found that North America, Europe, and East Asia are the main VOC-limited regions at present day, but North America and Europe become more NO_x-limited under the SSP3-7.0 scenario mainly due to reductions in NO_x emissions. South Asia becomes the dominant VOC-limited region under future pathways (Liu et al., 2022). In the UK, changes in CH_4 emissions can dominate the changes in surface O_3 with a wide range of response under different SSP scenarios. Under the NZ SSP scenarios, O_3 showed a decrease of around 14 ppb, while $PM_{2.5}$ may decrease by around 1.5 $\mu g\ m^{-3}$ (Royal Society, 2021). Using the ADMS urban model, CERC estimates that annual mean $PM_{2.5}$ in central London is mostly between 9-11 $\mu g\ m^{-3}$, which means that under the current NZ scenarios, $PM_{2.5}$ in most parts of this city will still exceed the new proposed air quality guidelines. Related research questions include: can we meet the new WHO guidelines under NZ, how to better control O_3, how to better understand model uncertainties and evaluate emission strategies, and how to improve indoor air quality.

Prof. Eri Saikawa (Emory University) presented **"Climate-smart agriculture: Potential for mitigating climate change and air pollution".** This talk focuses specifically on agriculture, a key air pollutant source for GHGs and air pollutants (Saikawa et al., 2014). They found a significant increase in N_2O emissions in the Asian agricultural sector, most likely due to an increase in the use of nitrogenous fertilizers (Saikawa et al., 2014). They argued for a Climate Smart Agriculture (CSA), which aims to increase agricultural productivity and incomes, improve adaptation and build resilience to climate change as well as mitigate GHG emissions. They tested various techniques for a more sustainable agriculture management (Peters et al., 2020, Hill et al., 2021), some of which have the potential to mitigate climate change as these have shown to increase CH_4 uptake of soils (Wang et al., 2022). But they recognized that mitigation of soil GHGs and air pollutant emissions in agriculture is a big challenge. Future research should account for the need to control the emissions of both GHGs and ammonia from agriculture.

3.4 Summary

The 12 talks covered a range of topics in the broad area of NZ/CN and air quality. Tao Shu and Tong Zhu showed the recent trends in air pollution and Tao Shu discussed how energy transition, particularly in the residential sector has contributed to improved air quality and health in China. Tzung-May Fu, Shuxiao Wang, Hao Liao and Ruth Doherty all covered ozone pollution, including their sensitivities to emission changes and under carbon neutraility policies. Shuxiao Wang, Hong Liao, Tong Zhu and Ruth Dohery discussed the potential impacts of carbon netuality pathways on $PM_{2.5}$ and health. Paul Monks, Tong Zhu and Frank Kelly highlighted the need of a systemic approach to air quality and climate change management to maximize co-benefits on health. Dabo Guan examined the socioeconomic benefits of NZ transition, while Ally Lewis discussed the potential of H_2 gas as a clean fuel and their impact on the NO_x emissions and air quality inequality from the residential sector. Paul Wilkinson took a different angle and looked at the "unintended consequences" of home energy efficiency transition and how this affect indoor air quality and health. Eric Saikawa focused on agriculture emission and explored ways to minimize emissions of GHGs and air pollutants.

While all talks highlighted a range of past and ongoing work in the area of NZ/CN, health and equity, they identified huge uncertainties in understanding of emissions and processes of air pollutants, and their impacts on health and economy under different NZ/CN pathways. These insights including relevant research questions were integrated into the working group review below (see Section 5.2.1 and appendix).

3.5 References:

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Chapter 4 : Capacity building activities

As part of the COP-AQ project we organised the Winter School 2021 on Data Science for Climate and Air Quality Research, which consisted of five training sessions delivered by COP-AQ members and partners. All training sessions were free to attend, and the recordings of the sessions were made available on the COP-AQ website.

The objectives were:

- To introduce the theoretical basis of the openair R package and machine learning;
- To provide practical training by applying the theory to CSs;
- To provide hands-on experience in using existing codes for climate, air quality, and health research.

Training session 1 “Introduction to openair” by Prof. David Carslaw (University of York) introduced the openair R package and provided a demonstration of some of its applications in air quality research.

Training session 2 “Machine learning for intervention studies” by Dr Qili Dai (Nankai University) and Dr Congbo Song (University of Birmingham) discussed recent advances in weather normalization of air pollutant concentrations and their application in policy evaluation.

Training session 3 “Emulation of air quality in China” by Dr Luke Conibear and Prof. Dom Spracklen (University of Leeds) introduced the emulation of atmospheric models with machine learning models and provided practical training on how to apply emulators for simulation of air quality and health impacts and the basics of emulator development.

Training session 4 “Data science for air pollution exposure science and personal monitoring” by Dr Yiqun Han, Dr Hanbin Zhang (Imperial College London), and Dr Lia Chatzidiakou (University of Cambridge) introduced the applications of personal sensors in air quality research, the study designs and methods of using personal sensors in exposure science and environmental epidemiological studies, and the recent advances in the research field. Real-world measurement dataset for hands-on analysis were also provided.

Training session 5 “Machine learning for airborne particle identification from spectral image datasets” by Prof. David Topping (University of Manchester) introduced a broad family of methods used for classification of aerosol particles from spectral datasets. Bio-aerosol datasets were used as a demonstrator of potential application.

In total, these training sessions attracted 404 counts of participations (with some people attended more than one session).

Chapter 5 : Resources and list of publications or manuscripts

The following resources are made available to the wider community, including presentations at the workshops and the training sessions.

5.1 Publications and manuscripts

The following papers/manuscripts have acknowledged the funding support from the COP-AQ project.

1) Chen, P., Wu, Y., Meng, J., He, P., Li, D., Coffman, D. M., ... & Guan, D. (2022). The heterogeneous role of energy policies in the energy transition of Asia–Pacific emerging economies. Nature Energy, 7, 588–596. https://doi.org/10.1038/s41560-022-01029-2
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3) Zheng, H., Long, Y., Wood, R., Moran, D., Zhang, Z., Meng, J., ... & Guan, D. (2022). Ageing society in developed countries challenges carbon mitigation. Nature Climate Change, 12, 241-248. https://doi.org/10.1038/s41558-022-01302-y
4) Shan, Y., Guan, Y., Hang, Y., Zheng, H., Li., Y., Guan., D., Li, j., Zhou, Y., Li, L., Hubacek, K. (2022). City-level emission peak and drivers in China. Science Bulletin. In Press.
5) Conibear, L., Reddington, C.L., Silver, B.J., Arnold, S.R., Turnock, S.T., Klimont, Z., & Spracklen, D.V. (2022a). The contribution of emission sources to the future air pollution disease burden in China. Environmnetal Research. Letters, 17, 064027. https://doi.org/10.1088/1748-9326/ac6f6f
6) Conibear, L., Reddington, C.L., Silver, B.J., Chen, Y., Arnold, S.R., & Spracklen, D.V. (2022b). Emission Sector Impacts on Air Quality and Public Health in China From 2010 to 2020. GeoHealth, 6, e2021GH000567. https://doi.org/10.1029/2021GH000567
7) Conibear, L., Reddington, C.L., Silver, B.J., Chen, Y., Knote, C., Arnold, S.R., & Spracklen, D.V. (2022c) Sensitivity of Air Pollution Exposure and Disease Burden to Emission Changes in China Using Machine Learning Emulation. GeoHealth, 6, e2021GH000570. https://doi.org/10.1029/2021GH000570
8) Brean, J., Rowell, A., Beddows, D.C.S., Shi, Z., Harrison, R.M. (2022). Estimates of future new particle formation under different emission scenarios in Beijing. Submitted to Science Advances.
9) Song, C., Liu, B., Cheng, K., Cole, M.A., Qili, Dai, Elliott, R.J.R., Shi, Z., (2022). Major benefits of clean heating policy on air quality and health in China. Submitted to Environmental Science & Technology.
10) Tong, C., Loh, M., Cherrie, M., Shi, Z. Evidence of net-zero policies on air pollution and health: a rapid review. To be submitted to Science of the Total Environment
11) Liu, Z., Wild, O., Doherty, R. M., O'Connor, F. M., Turnock, S. T. Benefits of net zero policies for regional ozone in China. In prep.

5.2 Resources from the International Workshop on Net Zero and Air Quality

All talks are recorded and deposited for public access.

Recent trend of air pollution in China - a sectorially resolved emission-inventory based evaluation
Prof. Shu Tao (Member of the Chinese Academy of Sciences; Peking University)
Recording of the talk: https://youtu.be/Xa1wwLldB6I

Sensitivities of ozone air pollution in the Beijing-Tianjin-Hebei area to local and upwind precursor emissions using adjoint modelling
Prof. Tzung-May Fu (Southern University of Science and Technology)
Recording of the talk: https://youtu.be/K9gM5a7gAtM

Air quality and health benefits under carbon neutrality policies
Prof. Shuxiao Wang (Tsinghua University)
Recording of the talk: https://youtu.be/iGWuvTtQ2e4

Coordinate air pollution control and climate change mitigations to maximize the co-health benefits
Prof. Tong Zhu (Member of the Chinese Academy of Sciences; Peking University)
Recording of the talk: https://youtu.be/rluUASc4kMM

$PM_{2.5}$ and O_3 air quality and associated health impacts in China from 2015 to 2060 under carbon neutral pathway
Prof. Hong Liao (Nanjing University of Information Science and Technology)
Recording of the talk: https://youtu.be/gGt0WJjUv-Y

Net zero and air quality - A systems problem
Prof. Paul Monks (BEIS Chief Scientist, Department of Business, Energy and Industrial Strategy; University of Leicester)
Recording of the talk: https://youtu.be/INKOYLh4V4s

Health, climate change and the air quality challenges ahead
Prof. Frank Kelly (Imperial College London)
Recording of the talk: https://youtu.be/K7sp-ykr_Gk

Socioeconomic benefits of the net-zero emission transition
Prof. Dabo Guan (Fellow of the Academy of Social Sciences; Tsinghua University)
Recording of the talk: https://youtu.be/2f1MNWmILLo

Adoption of hydrogen as a fuel - potential impacts on air quality
Prof. Ally Lewis (Chair of DEFRA Air Quality Expert Group; University of York)
Recording of the talk: https://youtu.be/zLDC3FDAe1g

Risks and benefits of climate actions
Prof. Paul Wilkinson (London School of Hygiene and Tropical Medicine)
Recording of the talk: https://youtu.be/v203XH_WSKQ

Future climate and emissions impacts on air quality as we head towards net zero
Prof. Ruth Doherty (University of Edinburgh)
Recording of the talk: https://youtu.be/xx0R5RcqCtE

Climate-smart agriculture: Potential for mitigating climate change and air pollution
Prof. Eri Saikawa (Emory University)
Recording of the talk: https://youtu.be/v5ksRFfbpoo

5.3 Training materials

Session 1 - Introduction to openair
Prof. David Carslaw (University of York)
Aim: To introduce openair and its applications in air quality research.
Recording of the session: https://youtu.be/t7vr2mUVTE4

Session 2 - Machine learning for intervention studies
Dr Qili Dai (Nankai University) and Dr Congbo Song (University of Birmingham)
Aim: To introduce recent advances in weather normalization of air pollutant concentrations and their application in policy evaluation.
Recording of the session: https://youtu.be/CHOLTuugjo0

Session 3 - Emulation of air quality in China
Dr Luke Conibear and Prof. Dom Spracklen (University of Leeds)
Aim: To provide training in the methods of statistical emulation for air quality research and their application in policy evaluation.
Recording of the session: https://youtu.be/zbt7aa2QIAA

Session 4 - Data science for air pollution exposure science and personal monitoring
Dr Yiqun Han, Dr Hanbin Zhang (Imperial College London), and Dr Lia Chatzidiakou (University of Cambridge)
Aim: To introduce applications of personal sensors in air quality research.
Recording of the session: https://youtu.be/JQaCedyCPPg

Session 5 - Machine learning for airborne particle identification from spectral image datasets
Prof. David Topping (University of Manchester)
Aim: To introduce the diverse set of tools now used to try and resolve characteristics of particulate matter from instrument response functions.
Recording of the session: https://youtu.be/7c-uMHKvkPI