Atmospheric Pollution and Human Health in a Chinese Megacity (APHH-Beijing) Programme

Final Report

Atmospheric Pollution and Human Health in a Chinese Megacity (APHH-Beijing) Programme

Final Report

Edited by Professor Zongbo Shi (University of Birmingham)

Lead investigators (in alphabetical order):
James Allan (University of Manchester), Benjamin Barratt (King's College London), William Bloss (University of Birmingham), Hugh Coe (University of Manchester), Ruth Doherty (University of Edinburgh), Pingqing Fu (Institute of Atmospheric Physics), Dabo Guan (University of East Anglia - UEA), Sue Grimmond (University of Reading), Xinbiao Guo (Peking University), Jacqui Hamilton (University of York), Roy Harrison (University of Birmingham), Kebin He (Tsinghua University), Dwayne Heard (University of Leeds), Nick Hewitt (Lancaster University), James Lee (University of York), Ally Lewis (University of York), Jie Li (Institute of Atmospheric Chemistry - IAP), Miranda Loh (Institute of Occupational Medicine - IOM), Rod Jones (University of Cambridge), Markus Kalberer (University of Cambridge), Frank Kelly (King's College London), Mark Miller (University of Edinburgh), Paul Monks (University of Lancaster), Eiko Nemitz (UK Centre for Ecology and Hydrology - UKCEH), Paul Palmer (University of Edinburgh), Claire Reeves (University of East Anglia - UEA), Longyi Shao (China University of Mining and Technology-Beijing), Zongbo Shi (University of Birmingham), Zhiwei Sun (Capital Medical University), Shu Tao (Peking University), Shengrui Tong (Institute of Chemistry), Xinming Wang (Guangzhou Institute of Geochemistry - GIG), Lisa Whalley (University of Leeds), Oliver Wild (Lancaster University), Zhijun Wu (Peking University), Pinhua Xie (Anhui Institute of Optics and Fine Mechanics), Qiang Zhang (Tsinghua University), Mei Zheng (Peking University), Tong Zhu (Peking University)

Drafted by Jingsha Xu, Zongbo Shi, Roy Harrison, William Bloss

Cover design and report formatting by Chantal Jackson

How to cite Shi, Z., Xu, J., Harrison, R.M., Bloss, W.J., Allan, J., Barratt, B., Coe, H., Doherty, R., Fu, P., Guan, D., Grimmond, S., Guo, X., He, K., Heard, D., Hewitt, N., Lee, J., Lewis, A., Li, J., Loh, M., Jones, R., Kalberer, M., Kelly, F., Miller, M., Monks, P., Netmitz, E., Palmer, P., Reeves, C., Shao, L., Sun, Z., Tao, S., Tong, S., Wang, X., Wild, O., Wu, Z., Xie, P., Zhang, Q., Zheng, M., Zhu, T., 2021. Atmospheric pollution and human health in a Chinese megacity (APHH-Beijing) programme: final report. Working Paper, doi: 10.25500/epapers.bham.00003381.

Correspondence Zongbo Shi (z.shi@bham.ac.uk)

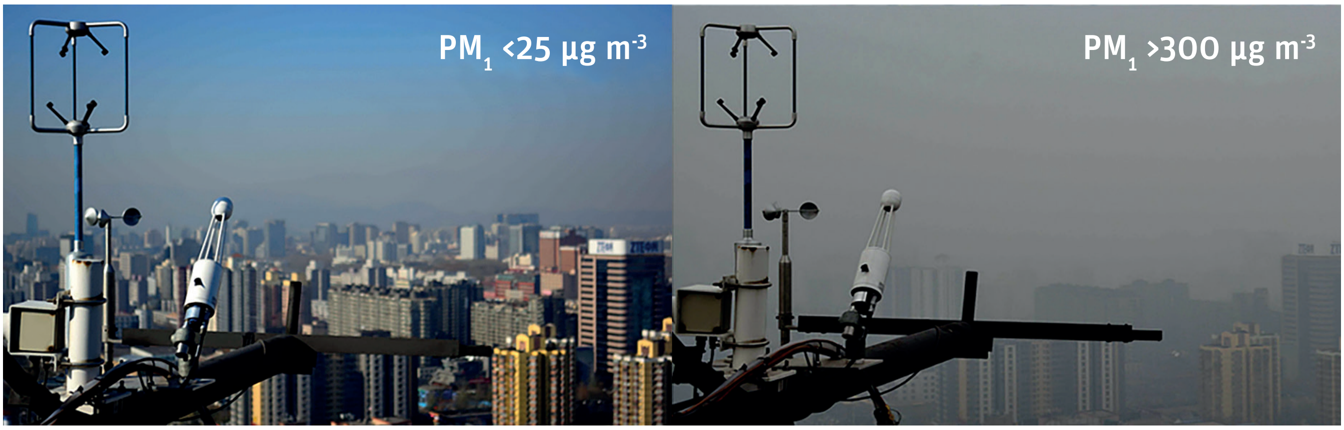


Image credit - Ben Langford, UKCEH
Cover image - Ben Langford, UKCEH

Executive Summary

In 2016, over 150 UK and Chinese scientists joined forces to understand the causes and impacts - emission sources, atmospheric processes and health effects - of air pollution in Beijing, with the ultimate aim of informing **air pollution solutions and thus improving public health**. The *Atmospheric Pollution and Human Health in a Chinese Megacity (APHH-Beijing)* research programme succeeded in delivering its ambitious objectives and significant additional science, through a large-scale, coordinated multidisciplinary collaboration. APHH-Beijing conducted the largest international air pollution field campaigns to date in Beijing in 2016 and 2017, generating new insight into air pollution characteristics using novel observational and modelling tools. The multi-faceted capabilities of the APHH-Beijing team addressed key policy-relevant air pollution challenges, such as the role of road traffic and long-range transport in influencing air quality, by combining approaches across disciplines, institutions and countries. To date, the APHH-Beijing team has contributed to over **400 international peer-reviewed scientific journal papers** including in multidisciplinary journals and 47 in the APHH-Beijing Atmospheric Chemistry & Physics / Atmospheric Measurement Techniques special Issue. More importantly, APHH-Beijing generated a range of scientific insights which can support the development of mitigation strategies to improve air quality and public health and reduce air quality inequality. In this report, we highlight some of the research outcomes that have potential implications for policymaking:

1. The measured emission fluxes of key air pollutants in the city centre, including NO_x, VOCs, and black carbon, are much lower than predicted by the (downscaled) Multi-resolution emission inventory for China (MEIC). The city centre's surface layer even locally becomes a sink rather than a source for fine particles, PM_1, in the summer. However, the concentrations of these pollutants were very high, indicating a significant contribution from non-local sources.

2. Models and observations consistently pointed to the key contribution of regional sources to Beijing's $PM_{2.5}$ pollution. Anthropogenic and biogenic VOCs also contribute significantly to secondary particles in Beijing. Reducing black carbon levels, arising from long range transport events, can potentially suppress aerosol-meteorology feedbacks and shorten or reduce the severity of haze events.

   Policy suggestion 1. Focus on emission reductions (PM, VOC and BC) from outside central Beijing area.

   Policy suggestion 2. Monitor emission flux of air pollutants, including from aircraft platforms, to validate emission inventory and support decision making.

3. Multiple methods show consistently that road traffic is not a major source of primary particles, but does remain a significant source of NO_x.

   Policy suggestion 3. Control NO_x emissions from road traffic to reduce NO_2 but anticipate a limited benefit with respect to the associated primary $PM_{2.5}$ emissions.

4. China's clean energy transition from 1992-2012 resulted in very substantial reductions in the ambient $PM_{2.5}$ levels, however solid fuel combustion still contributed about 20% of the overall population weighted $PM_{2.5}$.

5. Personal exposure to poor air quality in the peri-urban area is much higher than in central Beijing, mainly due to residential coal combustion and biomass burning, with implications for inequalities in air pollution impacts.

   Policy suggestion 4. Prioritize the control of emissions from residential solid fuel combustion, for both heating and cooking, to reduce air pollution and personal exposure.

6. Ozone pollution is high in the summer, and levels have not improved in the past few years. Ozone pollution has the potential to worsen as future NO_x and $PM_{2.5}$ controls are implemented, unless key VOC emissions are regulated. Aromatic VOCs from fuel evaporation, and alcohols, ketones and aldehydes from domestic and industrial solvent consumption, are the largest anthropogenic contributors to local ozone formation.

   Policy suggestion 5. Accelerate the control of VOCs in surrounding regions to mitigate ozone and $PM_{2.5}$ pollution, particularly aromatic VOCs from fuel evaporation and oxidised VOCs from domestic and industrial solvent consumption.

7. A new machine learning-based framework was developed to quantify the effects of clean air actions. The new method was applied to quantify the effects of Clean Air Actions in Beijing, and evaluated against traditional chemical transport modelling methods based on emissions inventories. The new framework also showed that the air quality benefits from the 2020 COVID lockdown were smaller than was observed or expected (and reported).

   Policy suggestion 6. Standardize machine learning techniques as an alternative tool to evaluate the effectiveness of clean air actions and for air quality management.

8. The ammonia emission flux is very high in the city centre, but does not seem to be dominated by traffic. Reduction of ammonia emissions has the potential to significantly reduce $PM_{2.5}$ mass concentrations.

   Policy suggestion 7. Control the emission of ammonia within the city after identifying its sources.

9. Commercial face masks offer potential personal protection from $PM_{2.5}$ pollution, but leakage can reduce their effectiveness. Air purifiers can effectively reduce indoor $PM_{2.5}$ levels and the impact of air pollution on health.

10. Increases in air pollution are associated with a deleterious mental health effects.

    Policy suggestion 8. Advocate personal protection measures, such as using face-masks and air purifiers, particularly by people with pre-existing conditions, the elderly and the young, during pollution events.

Overall, APHH-Beijing significantly advanced understanding of air pollution in Beijing, supporting policy development which will provide widespread human health improvements across a significant population, particularly for the vulnerable people. APHH-Beijing outcomes will also support United Nations sustainable development goals including "Sustainable cities and communities", "Reduced inequality", "Good Health and Well-being", and "Affordable and Clean Energy". APHH-Beijing scientists have engaged with stakeholders from the beginning of the programme and delivered a policy brief to policymakers including from the Ministry of Ecology and Environment and Beijing Bureau of Ecology and Environment. Some of the APHH-Beijing research outcomes, such as the updated high resolution emission inventories and air pollutant emissions from residential sources, have already contributed to policymaking. The programme enhanced UK-China collaboration, facilitated training of the next generation of scientists, and left a legacy of enhanced scientific understanding and policy impact in China, the UK and beyond for the future.

APHH-Beijing Technical Report

1. BACKGROUND AND OBJECTIVES

APHH-Beijing is the first major UK-China project jointly funded by UKRI (NERC, MRC) and NSFC, as part of the the UK-China Research and Innovation Partnership Fund. The APHH-Beijing programme includes five separate but related projects:

- *Sources and Emissions of Air Pollutants in Beijing (AIRPOLL)*: lead PIs - Roy Harrison, Kebin He.
- *An Integrated Study of Air Pollution Processes in Beijing (AIRPRO)*: lead PIs - Ally Lewis, Pingqing Fu.
- *Effects of Air Pollution on Cardiopulmonary Disease in Urban And Peri-Urban Residents in Beijing (AIRLESS)*: lead PIs - Frank Kelly, Tong Zhu.
- *Air Pollution Impacts on Cardiopulmonary Disease in Beijing: An integrated study of Exposure Science, Toxicogenomics and Environmental Epidemiology (APIC-ESTEE)*: lead PIs - Miranda Loh, Zhiwei Sun.
- *Integrated Assessment of the Emission-Health-Socioeconomics Nexus and Air Pollution Mitigation Solutions and interventions in Beijing (INHANCE)*: lead PIs - Dabo Guan, Shu Tao.

Overall Science Coordinator: Zongbo Shi.

AIRPOLL is by far the most comprehensive investigation of air pollutant sources and emissions in Beijing to date. AIRPRO focused on understanding the basic processes controlling gas and aerosol pollution, meteorological dynamics, and the links between them, within Beijing's atmosphere (after emission). AIRLESS and APIC-ESTEE focused on cardiovascular and respiratory disease and sought to address uncertainties between personal exposure, toxicology of air pollutants and acute cardiopulmonary response in Beijing. INHANCE was designed as an enabler project to deliver integrated and science-based policy design, drawing upon all investigations. The objectives of APHH-Beijing were[1]:

- to determine the emission fluxes of key air pollutants and to measure the contributions of different sources, economic sectors and regional transport to air pollution in Beijing;
- to improve understanding of the processes by which pollutants are transformed or removed through transport, chemical reactions and photolysis, and the rates of formation and conversion of particulate matter (PM) via atmospheric reactions;
- to improve understanding on how the detailed properties of PM evolve and can influence their physical properties and behaviour in the atmosphere and elucidate the mechanisms whereby those properties may interact and give feedback on urban-scale and regional meteorology;
- to exploit new satellite observations and regional models to place the in-situ campaigns into a wider context;
- to determine the personal exposure of Beijing inhabitants to key health-related pollutants and assess the association between air pollution exposure and key cardiopulmonary measures;
- to determine the contribution of specific activities, environments and pollution sources to the personal exposure of the Beijing population to air pollutants;
- to enhance our understanding of the health effects in susceptible individuals over time periods when there are large fluctuations in pollutants compared with normal controls and to identify health outcomes of air pollution; and
- to estimate physical and mental impacts of air pollution and examine how Beijing can improve its air quality more cost-effectively.

In the past 4 years, APHH-Beijing has successfully delivered the key objectives of the programme and additional multidisciplinary science through integration of individual projects. The integration has led to highly successful field campaigns[1] as well as the publication of over 400 scientific papers including in multidisciplinary journals and 47 papers in the APHH-Beijing ACP/AMT special Issue, with further publications pending. This report aims to capture some of the research highlights and successful practices, lessons learned and remaining science questions to support the design of future research programmes.

2. SCIENCE HIGHLIGHTS AND THEIR POLICY IMPLICATIONS

APHH-Beijing has generated a series of new and published scientific results. Here, we highlighted a few novel findings, focusing on those that have potential policy implications.

2.1 First Application of Eddy Covariance to Air Pollutant Emission Flux Measurements in China (UKCEH, York, Lancaster, Manchester, GIG, Tsinghua, IAP)

APHH-Beijing made the first direct observations of emission fluxes in Beijing of a range of air pollutants including NO_x, NH_3, CO, CO_2, O_3 and individual volatile organic compounds (VOCs), particulate matter (PM) and its chemical components (black carbon, NH_4^+, NO_3^-, SO_4^{2-}, Cl^- and organic matter). This was achieved by the application of the eddy covariance technique with a range of fast-response analsyers at the Institute of Atmospheric Physics (IAP) meteorological tower in central Beijing in winter 2016 and summer 2017. This method provides a direct test of emission inventories and new scientific process understandings. Key outcomes are:

- The NO_x emission fluxes are similar in summer and winter (3.55 vs. 4.41 mg m^{-2} h^{-1}), peaking during the morning and evening rush hour periods, indicating a major traffic source. The measured flux is substantially lower than that downscaled from the MEIC (Multi-resolution Emission Inventory) based on the commonly used proxy method (Fig. 1) [2].

- Although the concentrations of aromatic VOCs (such as toluene and benzene) in central Beijing are very high, their surface-atmosphere flux is very low, and they must originate largely from outside of central Beijing. Downscaling from MEIC would result in an order of magnitude higher emissions in the centre of Beijing than measured [2].

- Organic matter dominates chemically speciated PM_1 fluxes at IAP (black carbon, NH_4^+, NO_3^-, SO_4^{2-}, Cl^- and organic aerosol mass). Emission of primary aerosol components in PM_1 is dominated by cooking sources, followed by traffic sources and solid fuel burning in winter [3].

- Total black carbon emission from the downscaled MEIC overestimate the actual flux by a factor of 59 and 47 during the winter and summer periods, respectively [4]. Emissions of black carbon in the city centre were dominated by vehicle emissions.

- High concentrations of black carbon are observed during winter haze events, but flux measurements indicate that these originate from outside of central Beijing [4].

- Surprisingly, in summer, the city centre's surface layer is a sink rather than a source of PM_1. This is due to the higher temperatures in the surface layer compared with the air above, leading to evaporation of (semi-)volatile aerosol components such as ammonium nitrate. This a process not resolved by most atmospheric chemistry and transport models [3].

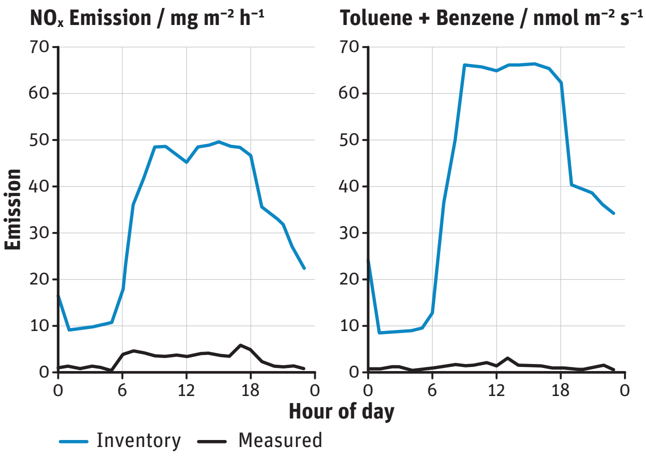


Figure 1. Measured NO_x and toluene+benzene versus downscaled MEIC emissions based on a proxy method in central Beijing[2]. Diurnal variation from the downscaled MEIC estimates are used for the diurnal cycles for emissions of all sectors (sum of emissions from transport, industry, residential and power).

Policy Implications:

- The observation-based approach developed within the APHH-Beijing programme can be applied elsewhere to validate local emission inventories and provide direct policy-relevant insight to emissions control choices.

- Emission inventory requires continuous updating and is validated by flux observations.

- The scope for policy interventions focusing on anthropogenic VOC emission from central Beijing is limited. Emissions controls in regions surrounding the megacity are necessary to achieve substantial reductions in VOC concentrations within the city.

- Source apportionment of the measured PM_1 flux identified cooking (oil) emissions as the largest single PM_1 source, suggesting that a more stringent control of this local source may be needed within the city.

- Local emissions overall make a small contribution to concentrations of $PM_{2.5}$ compared with long-range transport of pollutants which suggests that targeting further emission reduction measures at the wider region rather than central Beijing itself would be advisable.

2.2. Traffic emissions and their contribution to air pollution in Beijing (Peking, Birmingham, Edinburgh, Lancaster, Reading, IAP, York)

APHH-Beijing has applied multiple methods to quantify the contribution of vehicle emissions to air pollution in Beijing and surrounding regions, including:

- High resolution traffic emission inventories show that in the Beijing-Tianjin-Hebei (BTH) region, light-duty passenger vehicles and heavy-duty trucks are the largest contributors to road traffic primary $PM_{2.5}$ emissions, whereas heavy duty trucks and buses together contribute about 50% of road traffic NO_x emissions; light-duty passenger vehicles contribute 56% of total road traffic hydrocarbons. Emission scenario analyses showed that eliminating old vehicles could reduce emissions efficiently but the unit cost for emission reduction increases from Beijing, to Tianjin and to Hebei [5].

- The roadside increment of $PM_{2.5}$, defined as the difference between $PM_{2.5}$ levels at roadside and urban background sites, only accounts for 7.5% of the city average, suggesting a very small contribution of primary road traffic to urban $PM_{2.5}$ mass. But road traffic represents a significant source of NO_2 (Fig. 2). The urban increment in $PM_{2.5}$ (difference between $PM_{2.5}$ at urban background and rural sites) is also very small, suggesting a limited contribution of urban emissions to Beijing's $PM_{2.5}$ levels [6].

- Using a newly developed urban-scale traffic pollution dispersion model with a horizontal resolution of 5m inside street canyons, the effects of canyon geometry on the distribution of NO_x and CO from traffic emissions were investigated in central Beijing. It was found that an increase in building height leads to heavier pollution inside canyons and lower pollution outside canyons at pedestrian level and higher domain-averaged concentrations over the area. In addition, canyons with highly even or highly uneven building heights on each side of the street tend to lower the urban-scale air pollution concentrations at pedestrian level [7].

- Receptor modelling shows that road traffic (gasoline+diesel) contributed only 12% and 6% of particulate organic carbon (OC) in Beijing during winter 2016 and summer 2017, respectively [8].

- An optimized gridded inventory considering results from the flux observations was developed. Using this new inventory and high resolution ADMS modelling, we showed that the contribution of primary emissions from road traffic to $PM_{2.5}$ is much smaller than to NO_2 (Fig. 2) [9].

Policy Implications:

- Beijing, Tianjin and Hebei should adopt differentiated policies for the control of road vehicle pollution based on their differing vehicle emissions contributions.

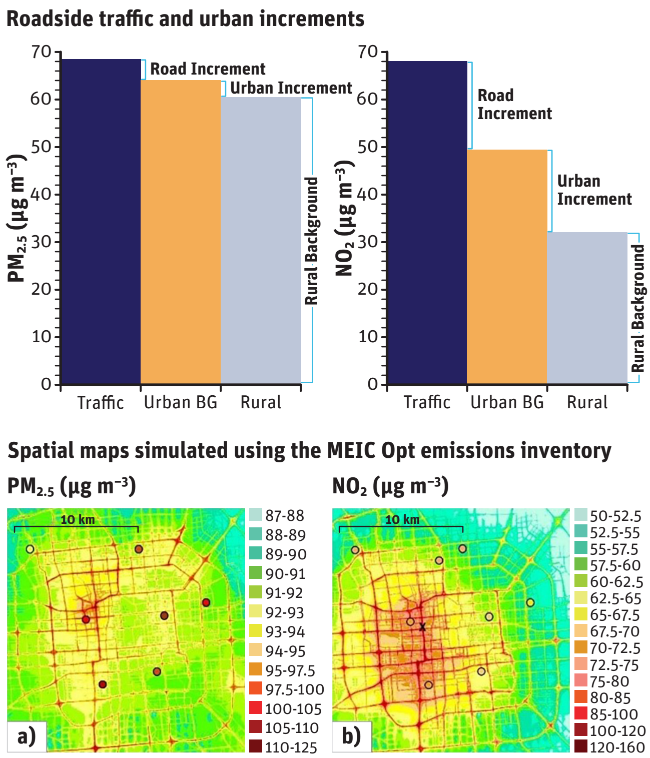


Figure 2. (top) Average roadside and urban increments of $PM_{2.5}$ and NO_2 (de-weathered data) over three years (2016-2018) for Beijing [6]; (bottom) Spatial maps of mean $PM_{2.5}$ (a) and NO_2 (b) concentrations for the winter campaign period (5 November to 10 December 2016), simulated using the MEIC Optimised emissions inventory. Mean measured concentrations at monitoring sites (NO_2 and $PM_{2.5}$) and the IAP field site (NO_2) are represented by coloured dots [9].

- Further controls on traffic emissions, including the transition to an electric fleet, are needed to reduce NO_2 concentrations but this will have a limited benefit for reduction of the concentration of primary fine particles.

- Street canyon geometry strongly influences human exposure to traffic pollutants in the populated megacity. Careful planning of street layout and canyon geometry and consideration of traffic demand and local weather patterns may significantly reduce inhalation of unhealthy air by urban residents.

2.3 **Ozone Pollution and Oxidant Chemistry** (York, Leeds, Peking, Lancaster, IAP, Birmingham)

APHH-Beijing contributes to an improved understanding of ozone pollution in the Beijing region.

- Central Beijing presents an unusual gas phase chemical mixture, unlike that observed in many other megacities around the world. It reflects NO_x emissions of a large modern transport fleet alongside VOCs reflective of high levels of industrial activity and solvent-related emissions. This atypical urban combination creates high potential for summertime photochemical ozone production and can lead to unusually elevated (> 150 ppb) ground-level urban ozone concentrations, due to limited availability of surface NO in the city centre to remove O_3 by chemical reaction [10].

- The key VOCs in Beijing are indicative of solvent usage, and the most abundant species are small oxygenated VOCs, such as methanol, acetaldehyde and acetone in winter [11].

- Biogenic compounds make significant contribution to the photochemical ozone creation potential (POCP), photochemical peroxyacyl nitrates (PAN) creation potential (PPCP) and potential OH reactivity emitted from the city but currently contribute only a small proportion of total reactivity in the atmosphere [11]. This is due to the relatively low emission flux at the city centre.

- Average summertime Beijing ozone formation conditions are shown in Fig. 3, with the central diamond indicating typical 3 pm conditions. As can be seen from the diamond position on the contour plot, to further reduce NO (moving left on the x axis) would lead to further increases in ozone in the city. In ~70% of summertime conditions, a reduction in VOCs leads to an improvement in ozone air quality [10].

- An improved Random Forest algorithm shows that O_3 increased by 14.8(±5.3)% in Beijing due to the COVID-19 lockdown in spring 2020 although the total gaseous oxidant (O_x=NO_2+O_3) showed correspondingly limited change; a slower pace of VOC emission reduction, relative to that for NO_x, could risk a further increase in O_3 pollution [12].

- The first, fully observation-driven assessment of the impacts of haze on urban photochemistry through the effects of aerosol on photolysis, demonstrates that haze has a major impact on ozone and hydroxyl radicals in the urban boundary layer. Reduced haze has the potential to worsen O_3 pollution by enhancing photochemistry [13].

- The dominant primary source of OH radicals was nitrous acid (HONO), present at levels up to 11 ppb in winter (compared to 1-2 ppb in London) [14].

- Commercial NO_2 analysers used in the air quality network may overestimate the true abundance of NO_2 due to retrieval of HONO as NO_2 (but we note follow the established international methodologies) [15].

- OH levels were largely maintained during haze conditions in wintertime, despite significant reductions in actinic flux, indicating that local production of secondary pollutants continues during haze events, likely linked to precursor abundance [14].

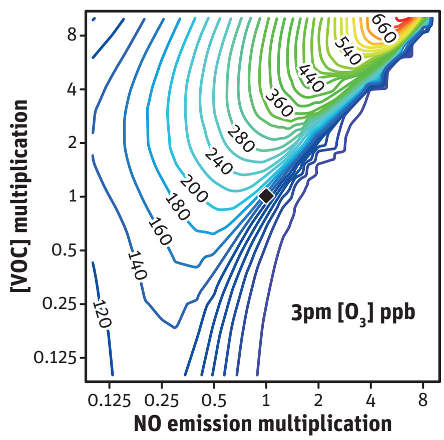


Figure 3. O_3 isopleth diagram as a function of NO and VOCs (the central diamond indicating the average of Beijing under typical 3 pm conditions during summer APHH-Beijing campaign). 1 in the x or y axis means NO emission or concentration of all measured VOCs during APHH-Beijing summer campaign; 0.5 means half of the NO emission or VOC concentration during APHH-Beijing summer campaign [10].

- Detailed model analyses demonstrated that the oxidation products of larger VOCs in the Beijing atmosphere produce more organic peroxy radicals than was previously thought, implying greater local ozone production under high NO_x conditions [16].

Policy Implications:

- Beijing ozone control needs to consider accelerating the control of VOCs, especially aromatic VOCs from fuel evaporation and alcohols, ketones and aldehydes from domestic and industrial solvent consumption.
- There may be regional and city sources of solvent use that would benefit from stricter abatement measures, as the relatively high VOC concentrations are not primarily a consequence of road transport emissions.
- Biogenic VOC emissions may become increasingly more important to atmospheric chemistry. Governments should discourage or restrict the planting of those types of trees that contribute to air pollution.

2.4 Interaction between Haze and Meteorology and Implications for Haze Event Prevention
(Manchester, Reading)

APHH-Beijing developed a novel method to determine mixing layer height and applied a Large Eddy Simulation model modified for an urban boundary layer that can resolve turbulent exchange and treats pollution, radiation and dynamics fully interactively [17].

- A new method was developed to determine mixed layer height using automatic lidar and ceilometers [17].
- Aerosol particles can scatter and absorb solar radiation to cause net cooling at the surface and warming above, which alters the thermal profile of the atmosphere, reducing turbulence due to buoyancy. Reduced turbulent mixing suppresses boundary layer development during the day, minimises the vertical mixing of pollutants and increases surface aerosol concentrations. This positive feedback loop between aerosols, radiation and meteorology can lead to sustained periods of stagnation and has been found to enhance pollution events (Fig. 4) [18].
- The contribution of aerosol-meteorology feedbacks alone is not enough to suppress the boundary layer to levels observed in Beijing. The initial meteorological conditions brought about by synoptic influences are paramount for the formation of haze episodes in Beijing. During stagnant synoptic conditions, the feedback is stronger, so there is a cycle of increasing stagnation and increasing concentrations [18].
- Further reductions in Black Carbon (BC) concentrations at the surface in the centre of Beijing (due to local emission reductions) than above the planetary boundary layer (due to regional pollution and high level emissions) leads to heating aloft and limited mixing and thus more stagnant meteorological conditions during subsequent days of a pollution event [19].
- Locally emitted BC in Beijing could reach the upper boundary layer through vertical mixing when synoptic conditions change. This upper level BC would then work to suppress boundary layer development and enhance haze further [19].

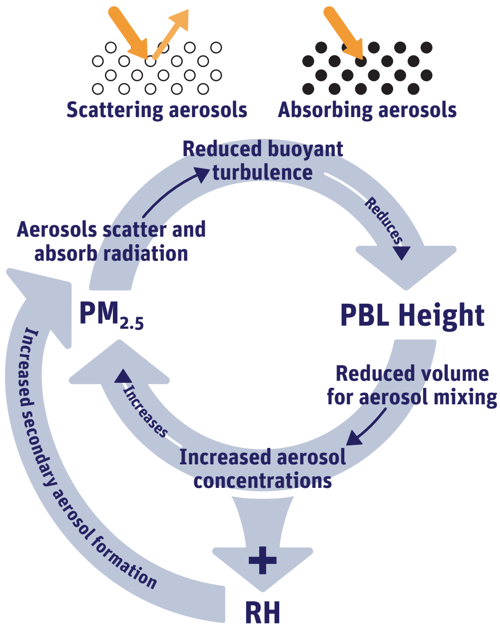


Figure 4. Aerosol – radiation – meteorology feedback loop[18].

Policy Implications:

- Reducing black carbon (BC) emissions from both inside and outside Beijing could limit the suppression of the boundary layer and potentially reduce the aerosol-meteorology feedback effects on haze formation.
- Emission control should not be limited to ground level BC, but also needs to consider the upper level (above the boundary layer) BC, likely to be associated with elevated sources outside the city.

- If pollution events are predicted to occur, emission reduction measures should be taken in advance to reduce the influence of the aerosol cooling effect on the mixing layer height, which may effectively limit the occurrence or severity of heavy pollution events.

2.5. Sources of Ammonia and Possible Control Measures (IAP, UKCEH)

APHH-Beijing has applied multiple approaches to apportion the sources of ammonia, which is a key precursor to $PM_{2.5}$ formation.

- High-resolution flux observations found a significant local inner-city ammonia emission[3] with the diurnal cycles following those of biogenic sources and evaporative emissions rather than fossil fuel markers (Fig. 5)[11]. This suggests that urban ammonia emissions are unlikely to be dominated by traffic sources, contradicting the MEIC emission inventory, but that as substantial contribution derives from temperature-driven sources, such as evaporation from wastewater, urban fertiliser use or deposited particles on surfaces[3].
- The NH_3 concentration is very high[20], and the flux in urban Beijing in the summer is of similar magnitude as the annual average flux expected from a typical N-fertilized agricultural field[3].
- N isotope analysis shows that agricultural emissions (including livestock, wastes and fertiliser) contribute to 47% of the surface NH_4^+ in $PM_{2.5}$ in urban Beijing and reach 56% at high altitudes[21].
- NH_4NO_3 is the most important factor driving the increasing aerosol water content (AWC) with haze, with NO_3^- controlling the periods before a pollution event and NH_4^+ during the most polluted stage. An increase of RH promotes a positive feedback, with "AWC-heterogeneous reactions" contributing to the formation of severe haze[22].
- Modelling results by NAQPMS show a reduction of 20% in ammonia emissions causes a decrease in $PM_{2.5}$ concentration by 5~11% under current emissions conditions in the North China Plain (NCP)[22].

Policy Implications:

- The control of ammonia emission is an effective method to further improve the air quality in Beijing.
- It is essential to control urban ammonia emissions.

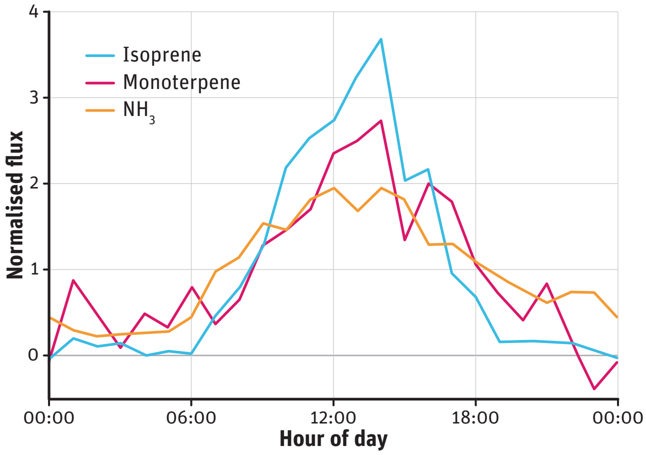


Figure 5. Diurnal cycle of normalized fluxes of ammonia, isoprene, and monoterpene[3,11].

2.6 Evaluation of the effectiveness of air pollution action plans (Birmingham, Tsinghua, Peking)

APHH-Beijing has applied a machine learning method (Random Forest algorithm) and a WRF-CMAQ model separately to quantify the role of emission control in an improving air quality trend in Beijing.

- The Random Forest model performs much better than traditional statistical and air quality models in disentangling the effects of meteorology from emission changes[23].
- Both Random Forest and WRF-CMAQ models show that emission reductions are driving the air quality improvement in Beijing but meteorological conditions have an important impact on the year-to-year variations in ambient air quality[23, 24].
- If not for the favourable meteorological conditions, $PM_{2.5}$ mass concentration in 2017 would have been more than 60 μg m^{-3}, failing the set target[23].
- Emission controls from 2013-2017 drove a reduction of 34 %, 24 %, 17 %, 68 %, and 33 % in the concentrations of $PM_{2.5}$, PM_{10}, NO_2, SO_2, and CO. O_3 pollution shows no sign of improvement[23].
- The marked decrease in $PM_{2.5}$ and SO_2 is largely attributable to a reduction in coal combustion[23].

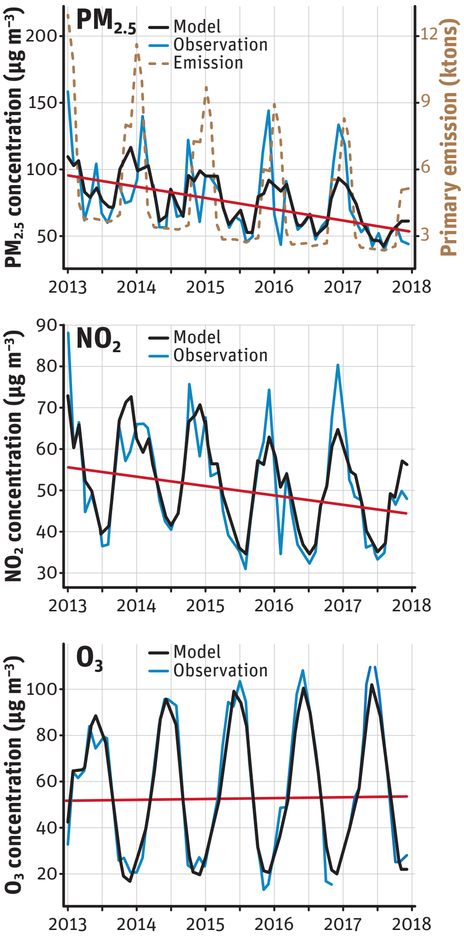


Figure 6. Air quality and primary emissions trends [23]. Trends of monthly average $PM_{2.5}$, NO_2 and O_3 and after normalization of weather conditions (first vertical axis), and the primary emissions from the MEIC inventory (secondary vertical axis). "Model" in the figure means the modelled concentration of a pollutant after weather normalization. The red line shows the Theil–Sen trend after weather normalization. The black and blue dotted lines represent weather-normalized and ambient (observed) concentration of air pollutants. The red dotted line represents total primary emissions.

- The rapid decrease in $PM_{2.5}$ concentrations in Beijing during 2013–2017 was dominated by local (20.6 µg m^{-3}, 65.4 %) and regional (7.1 µg m^{-3}, 22.5 %) emission reductions [24].

- Based on a multiregion multisector Computable General Equilibrium model, the current Environmental Protection Tax (EPT) policy in China has a limited effect on modulating air pollutants emissions (e.g., the current EPT rates may lead to less than 90Gg for NO_x (4.7%) or SO_2 (4.4%) emissions reduction over Heibei province, and less than 10Gg emissions reduction over Beijing or Tianjin city) [25].

- An improved Random Forest algorithm shows that the decline in NO_2 concentrations in Beijing attributable to the COVID-19 lockdown in spring 2020 was not as large as expected, with a reduction of 18.5(±9.2)%. The increase in $PM_{2.5}$ after the COVID-19 lockdown in Beijing is more likely to be driven by secondary aerosol formation and long-range transport rather than increased local oxidative capacity [12].

Policy Implications:

- The new Random Forest model is an effective and less complex tool for evaluating the effectiveness of air pollution control measures including correction for the role of meteorology in influencing air quality.

- Future air quality targets may need to consider adding a term "under average meteorological conditions" or the target could be easier or more difficult to achieve depending on meteorological conditions.

- Restrictions on coal burning and biomass burning in Beijing effectively reduced $PM_{2.5}$ pollution.

- Restrictions on economic and social activities as strict as those applied during the COVID-19 lockdown in Beijing are unlikely to be sufficient to reduce all key air pollutants substantially (O_3, NO_2 and $PM_{2.5}$).

2.7 Sources of $PM_{2.5}$ and CO Pollution in Beijing, including from Neighbouring Provinces

(Birmingham, IAP, York, Manchester, UKCEH, PEKING, Tsinghua, Leicester)

APHH-Beijing applied a number of complementary methods for source apportionment of $PM_{2.5}$ and to understand their uncertainties.

- Multiple receptor models or a receptor / chemical transport hybrid model applied to apportion the sources of $PM_{2.5}$ in Beijing showed that although there are some consistencies, modelled contributions for several sources such as cooking and traffic differed significantly. Care should be taken when interpreting results from a single method [8, 26-29].

- Organic matter contributes 58.9±9.7 and 75.0±12.1% of $PM_{2.5}$ mass at an urban and a rural site in Beijing during winter in 2016. The CMB model showed that biomass burning and coal combustion were key primary sources [8, 26].

- Observations and modelling consistently confirmed the key role of long-range transport from outside Beijing to air pollution levels in Beijing. However, the exact contribution is uncertain and will vary with season [27, 30, 31].

- NAQPMS modelling shows that regional transport of air masses to Beijing mainly includes four routes (Fig. 7): 1) Western route: north Shanxi Province - Shijiazhuang - Baoding - Beijing; 2) Middle route: Zhengzhou - Anyang - Handan - Xingtai - Shijiazhuang – Baoding and Beijing, etc; 3) Eastern route: Heze - Hengshui - Cangzhou - Langfang; 4) The interaction between neighbouring cities such as Beijing, Tianjin and Tangshan [32].

- A model simulation suggests that Hebei is as the most important source region of both BC (55%) and CO (39%) transported to Beijing. Averaged over the 4-year period from 2013 to 2016, the largest contributors to the total CO pollution in Beijing are the transportation, industrial and residential sectors with approximately 36 %, 33 % and 29 % respectively [30].

- Another model simulation suggests that the contribution of CO pollution from outside Beijing accounts for an average of approximately 45 % of the total CO pollution in Beijing. However, the relatively small spatial variation of CO within the Beijing city centre suggests a relatively small contribution of local sources to CO pollution [33].

- Observations of $PM_{2.5}$ composition alongside gas phase VOCs and inorganic pollutants indicate evidence for a significant role of biogenic-anthropogenic interactions during haze events through the formation of organosulfate compounds [34]. During some summer haze events ($PM_{2.5}$ > 75 µg m^{-3}) up to a third of the observed sulfate aerosol was in form of organosulfates[35] The analysis of organic matter also shows that reactive aromatic volatile organic matter is an important source of secondary organic aerosol [36].

- Alkylbenzenes, monoterpenes, and isoprene are important precursor VOCs for highly oxygenated molecules in Beijing, which contribute to new particle formation [37].

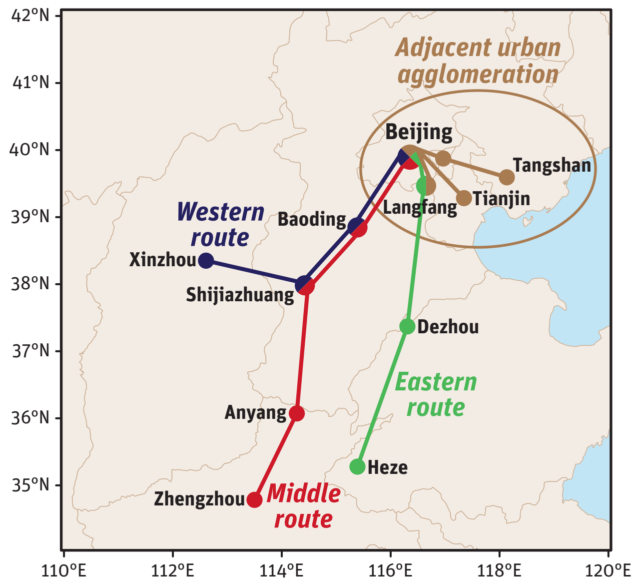


Figure 7. Schematic diagram of regional transport routes during heavy pollution in winter[32].

Policy Implications:

- Controlling non-local pollution is the key to further improving air quality in Beijing.

- Reducing the emission of reactive aromatic VOCs has the potential to reduce the concentration of $PM_{2.5}$.

- Current air quality forecasting models need to take into account emissions of biogenic VOCs for predicting ozone and $PM_{2.5}$.

- CMB that integrates both organic and inorganic tracers provides the most consistent results in comparison to other source apportionment methods.

2.8 Effects of Air Pollution on Human Health and Beneficial Effect of Masks and Air Purifier Interventions (Peking, IOM, KCL)

APHH-Beijing has carried both panel studies and laboratory experiments to study the effects of personal interventions in improving air quality and health.

- Most of the commercially available face masks (Fig. 8a) are able to filter out at least 90% of $PM_{2.5}$ but the level of protection depends on the fit of the mask, with the least effective mask leaking, on average, almost 70% of PM [38].

- Air purifiers reduce indoor $PM_{2.5}$ concentrations (Fig. 8b) and personal exposure [39].

- Personal exposure in the peri-urban area is much higher than the urban area, which is mainly due to coal combustion and biomass burning emissions [40].
- Vulnerable populations, such as overweight individuals, are more susceptible to $PM_{2.5}$ and BC pollution [41].

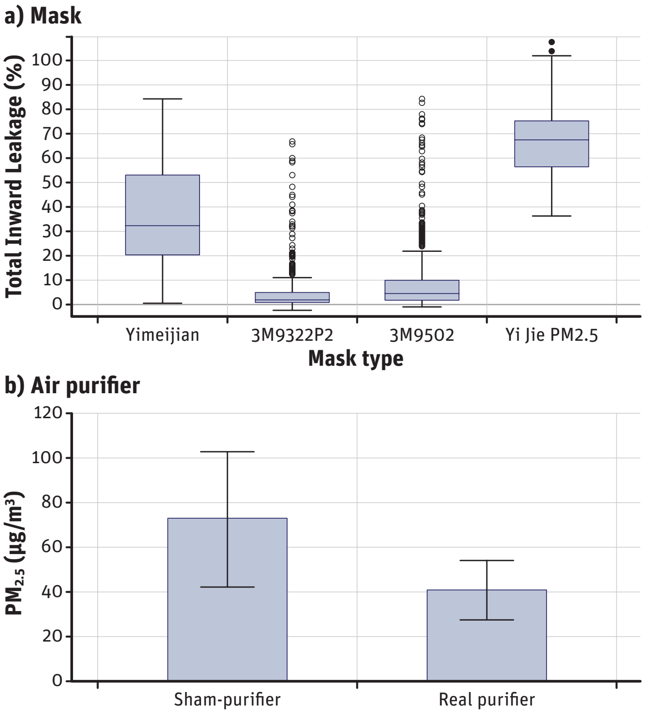


Figure 8. (a) Boxplot showing the total inward leakage for each mask tested in the volunteer trial. Boxes indicate the 25th–75th percentiles (the IQR), and the lines inside the boxes indicate the median (50th percentile). The whiskers indicate values within 1.5 times the IQR, and the dots are the outliers [38]; (b) Comparison of air pollutant levels in homes with a sham- or real purifier (bar indicating mean values and whisker the standard deviation) [39].

Policy Implications:

- Using face-masks and air purifiers can effectively reduce personal exposure to PM , especially during pollution events.
- Supporting vulnerable people (such as those with COPD or heart conditions) to reduce their personal exposures to air pollution will reduce the population health impacts of pollution.
- Transition from coal and biomass burning for heating and cooking will improve indoor and outdoor air quality, reducing exposures particularly for rural populations.

2.9 Effects of Air Pollution on Mental Health (Peking, UEA)

APHH-Beijing has evaluated the impact of air pollution on mental health, which provide insights into the potential benefits of air pollution mitigation.

- Negative emotions, assessed by subjective well-being, occur when the AQI (Air Quality Index) of $PM_{2.5}$ increases to about 150 [42].
- People's subjective well-being falls rapidly with increasing air pollution. Above $PM_{2.5}$ levels of about 150, subject wellbeing indicator continues to decrease but at a slightly slower speed until $PM_{2.5}$ AQI increases to the second threshold 184, which suggests that people began to become numb and insensitive to pollution [42]. Passing the third threshold of 277 AQI, people's sense of pollution becomes sensitive again [42].
- Increases in air pollution are associated with higher probabilities of declined mental health[43].

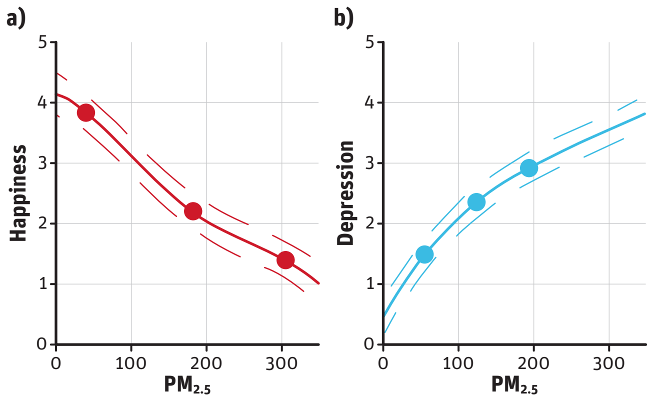


Figure 9. Polynomial fitting of air pollutants and perceptual data for all observers [42]. $PM_{2.5}$ is selected to represent the increase in air pollution combinations, including $PM_{2.5}$, SO_2, NO_2, O_3 and CO. As $PM_{2.5}$ increases, the other pollutants increase with fixed ratios. Solid lines in all sub-figures are statistically fitted lines and dashed lines are 95% confidence intervals (CI). (a) The changes in the positive emotions of happiness (dark red); (b) The changes in the negative emotions of depression (sky blue) with changes in air pollution.

Policy Implications:

- Consideration may be given to using specific AQI thresholds to protect the mental health of the population when setting standards, such as AQI at 150,184 and 277, rather than 100, 200 or 300.

- Improvement in air quality has the potential to benefit mental as well as physical health.

2.10. Health and Climate Impacts associated with Solid Fuel Use and Benefits from the Coal Ban Policy (Peking, UEA)

APHH-Beijing has conducted a series of modeling studies based on the data collected from extensive field survey and measurements, focusing on household energy use, residential emissions, and impacts on exposure and health. The major findings are:

- The rural residential energy mix in China, including Beijing and the surrounding areas, has experienced rapid switching from solid fuels to clean energy, driven primarily by socioeconomic development. Similar transition also occurred in other urban areas [44].

- Despite the rapid transition, both coal and biomass are still used extensively in rural China for cooking and heating, which contributes significantly to total anthropogenic emissions of key air pollutants and causes ambient air pollution, particularly severe indoor air pollution [44].

- The clean fuels or electricity (CFE) percentage for cooking (68%) in Beijing, Tianjin, and 26 other municipalities (2+26) (Figure 10) was significantly higher than the national average, likely due to its faster socioeconomic development. On the other hand, the fraction of solid fuels used for heating in the study region (89%) was about the same as the national average (85%), because of its longer heating period and colder winter [45].

- The clean energy transition during 1992 to 2012 resulted in a remarkable reduction in the contribution to ambient $PM_{2.5}$, avoiding 130,000 (90,000-160,000) premature deaths associated with $PM_{2.5}$ exposure per year. Despite this, the large quantities of solid fuels used still contributed 14±10 μg/m^3 to population-weighted $PM_{2.5}$ in 2012, which amounted to 21±4% of the overall population-weighted $PM_{2.5}$ from all sources [44].

- Rural residential emissions affect the air quality in both rural and urban areas, but the impacts are highly seasonal and location dependent [31, 44].

- A quantitative evaluation of the clean heating campaign that aimed at solving severe ambient air pollution in northern China by substituting residential solid fuels with electricity or natural gas in Beijing, Tianjin, and 26 other municipalities reveals that with targeted 60% substitution implemented, emission of primary $PM_{2.5}$ and contribution to ambient $PM_{2.5}$ concentration in 2021 are projected to be 30% and 41% of those without the campaign. Average indoor $PM_{2.5}$ concentrations in the living rooms in winter are projected to be reduced from 209 (190 to 230) μg/m^3 to 125 (99 to 150) μg/m^3, resulting in substantial exposure reduction [45].

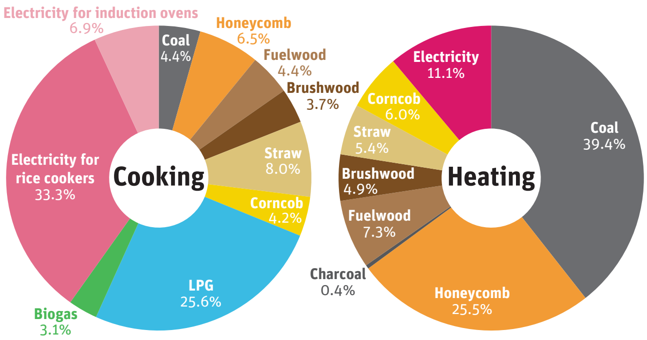


Figure 10. Time-sharing fractions of detailed residential energy types for cooking and heating in the "2+26" region [45].

- Clean household energy intervention or energy transition would benefit more for the women and children as they spend more time indoors [45].

Policy Implications:

- Controlling emissions of air pollutants from residential solid fuels, including both coal and biomass fuels should remain a priority to reduce ambient air pollution and personal exposure.

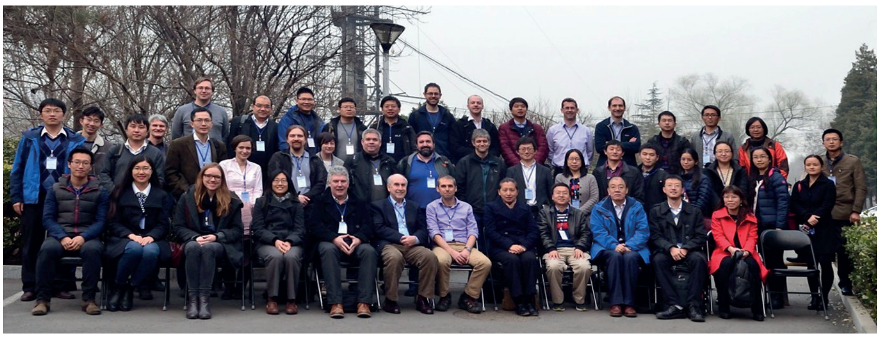
- Both cooking and heating should be targeted in order to reduce air pollutant emissions and mitigate health impacts.

- More effort should be devoted to mitigate indoor air pollution to prevent adverse health impacts, because indoor pollution attributable to residential emissions is as important as, if not more important than, ambient air pollution.

3. SUCCESS STORIES

APHH-Beijing stands as an exemplar for future large scale international interdisciplinary research programmes.

- **Highly successful field campaigns:** The APHH-Beijing campaigns effectively integrated the different funded projects. A rich set of measurements of high temporal-spatial resolution of particulate and gaseous pollutants, health outcomes, social, economic and behavioral information were collected simultaneously at both urban and peri-urban sites during two intensive campaigns. Such data enabled the programme to comprehensively understand the characteristics, formation processes, and sources of pollutants, and test a variety of hypotheses regarding the health effects of pollutant exposure, biological mechanisms, and susceptibility of the population.
- **Equal collaboration between Chinese and UK researchers:** the genuinely equal collaboration between Chinese and UK researchers, integrating complementary techniques, allowed new insights to be generated which were reflected in the research publication success (over 400 peer-reviewed publications) and significant policy-relevant insights.
- **Excellent collaboration between teams:** the participating research teams were highly collaborative. Trust and interoperability were fundamental for the realization of such a design in a large scale programme, which exemplifies the advantages of the combined skills of multidisciplinary partners.
- **Training of early career scientists:** NERC-NCAS PhD studentships made a huge contribution to the research programme. This is illustrated in the large amounts of high impact work, some of which are highlighted above. It also leaves a highly connected early career researcher network that will drive scientific collaboration in years to come.
- **Regular programme meetings:** substantive annual programme meetings were an effective tool to integrate research across the programme and encourage multi-institutional collaborations.
- **Meetings with policymakers:** face to face meetings with policymakers at an early stage provided valuable insights on policy priorities that shaped the research directions and at the final conference enhanced the communication of science to the policy-making processes. The science teams were invited to visit Beijing Bureau of Ecology and Environment to give further science briefings.
- **Programme coordination:** the science coordinator played a key role in the integration, delivery and overall success of the programme.
- **Data-model integration:** observation and modelling scientists worked very closely which ensured a close data-model integration and generated a number of publications.
- **Instrument intercomparison:** APHH-Beijing provided a great opportunity to test instrumentation performance for some of the difficult to measure chemical species in the atmosphere such as HONO and OH, and improve laboratory practices.
- **Data access and deposition:** Center for Environmental Data Analysis offered an ideal platform for depositing and accessing data.
- **Multiple approaches for the same scientific problem:** the opportunity to apply more than one approach has provided a better understanding of the complementarities (and uncertainties) in source apportionment methods applied to fine particles in Beijing.
- **International meetings:** Organization of international meetings and conference sessions, particularly the Faraday Discussion meeting, provided excellent opportunity to showcase and widen the academic impact of APHH-Beijing.
- **Engagement with funder representatives:** Funder representatives and local UKRI helped ensure the relevance of research and delivery of overall objectives and impacts.



4. INSIGHTS FOR FUTURE MULTI-DISCIPLINARY RESEARCH PROGRAMMES

- The strategic fit of the scheme should be the key criterion alongside science excellence when making funding decisions.
- Dedicated funding for overall scientific coordination is needed, in order to promote integration and impact.
- Research programmes should consider setting up cross-programme working groups, which have dedicated leader(s) and participant roles.
- Proposals should have embedded researcher secondments between countries to stimulate engagement.
- A full engagement with stakeholders is needed when designing the funding call.
- Realistic time is needed to prepare for large scale international personnel and instrument mobilization.
- An open access publication policy should be established by all funders as a requirement of a funding award.
- Unfunded partners who would like to contribute to the research programme should be encouraged, but must comply with the data policy.

IAP meteorological tower; Photo credit - Neil Mullinger, UKCEH

5. REMAINING SCIENCE QUESTIONS FOR FUTURE RESEARCH

APHH-Beijing significantly enhanced our understanding on the sources, processes and impacts of air pollution in Beijing. However, there are a number of science questions that require more research in order to further improve air quality in Beijing and beyond.

- What are the observed fluxes of air pollutants across the city (rather than a small area near the tower) and what is the relative importance of emissions within the city compared to the transport of pollutants into the city from the wider surrounding region?
- What are the local (urban) sources of ammonia and how can they be controlled?
- What sectors and geographic locations are responsible for the speciated volatile organic compounds in Beijing, and how will their control affect concentrations of ozone and secondary aerosol?
- How can the emissions of biogenic compounds such as isoprene be estimated, and how can air quality models be enhanced to incorporate our new understandings of biogenic-anthropogenic air pollution interactions?
- What are the sources of HONO and will reductions in HONO help to reduce the conversion of SO_2 and NO_2 to aerosols and the formation of O_3?
- How to quantify fugitive emissions from residential solid fuel burning and the associated impacts on indoor air quality?
- How can the sources of secondary organic aerosols be quantitatively attributed to their precursor compounds?
- How to improve proxies suitable for downscaling inventories for urban centres?
- How can the quantitative relationship between ozone and its precursors in the Beijing atmosphere in the future be predicted?
- What is the role of differential reduction in air pollutant concentrations (e.g., faster for SO_2 than BC) in aerosol-meteorology interaction and how will this affect the heavy pollution periods in the future?
- What are the fundamental formation mechanisms of new particles, including the role of intermediate-

volatile and semi-volatile organic compounds and biogenic compounds? And is there a way to suppress new particle formation or growth?

- What are the yields and formation mechanisms of secondary organic compounds (including organic sulphur and organic nitrogen compounds) from both anthropogenic and biogenic emissions?

- How to quantify indoor air $PM_{2.5}$ concentrations based on both outdoor-to-indoor penetration and internal emissions on a regional scale?

- How can personal exposure assessment be improved based on fixed point ambient observations and air quality modelling?

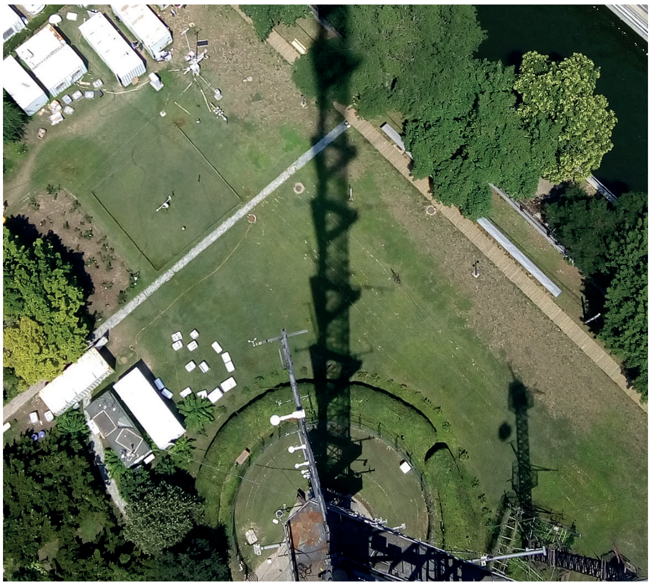
- What are the health effects under various exposure settings, especially with respect to impacts of personal level exposure on health?

- What are the impacts of residential energy use and emissions on the females who do most cooking in China?

- What is the impact of residential energy consumption on climate, taking the emissions of primary $PM_{2.5}$, secondary $PM_{2.5}$ precursors, and black carbon into consideration? What is the co-benefit for air quality, climate and health of residential energy switching?

- What are the most effective ways to combat the predicted increase in ozone as a result of traffic emission reduction, e.g., due to a transition to electric vehicles?

ACKNOWLEDGEMENT: We would like to thank the numerous APHH-Beijing researchers who carried out the research work. We thank Dr. Caroline Culshaw from NERC for her strong support throughout the programme. We thank NERC, MRC, and National Science Foundation of China as part of the UK-China Research and Innovation Partnership Fund for funding (NE/N007190/1; NE/S006699/1; NE/N007182/1; NE/N006887/1; NE/N007115/1; NE/N00695X/1; NE/N006895/1; NE/N00700X/1; NE/N006909/1; NE/N006941/1; NE/N007093/1; NE/N006925/1; NE/N007077/1; NE/S006680/1; NE/N007085/1; NE/N007018/1; NE/N007204/1; NE/S006729/2; NE/S006729/1; NE/N00714X/1; NE/S006648/1; NE/N006917/1; NE/N007158/1; NE/N006992/1; NE/N006992/2; NE/N006976/1; NE/N007123/1). Chantal Jackson and Mary Harding formatted the report.



Containers for field campaigns; Photo credit - Neil Mullinger, UKCEH

Installing instruments on IAP tower; Photo credit - Neil Mullinger, UKCEH

RELEVANT PUBLICATIONS

1. Shi, Z.; Vu, T.; Kotthaus, S.; Harrison, R. M.; Grimmond, S.; Yue, S.; Zhu, T.; Lee, J.; Han, Y.; Demuzere, M.; Dunmore, R. E.; Ren, L.; Liu, D.; Wang, Y.; Wild, O.; Allan, J.; Acton, W. J.; Barlow, J.; Barratt, B.; Beddows, D.; Bloss, W. J.; Calzolai, G.; Carruthers, D.; Carslaw, D. C.; Chan, Q.; Chatzidiakou, L.; Chen, Y.; Crilley, L.; Coe, H.; Dai, T.; Doherty, R.; Duan, F.; Fu, P.; Ge, B.; Ge, M.; Guan, D.; Hamilton, J. F.; He, K.; Heal, M.; Heard, D.; Hewitt, C. N.; Hollaway, M.; Hu, M.; Ji, D.; Jiang, X.; Jones, R.; Kalberer, M.; Kelly, F. J.; Kramer, L.; Langford, B.; Lin, C.; Lewis, A. C.; Li, J.; Li, W.; Liu, H.; Liu, J.; Loh, M.; Lu, K.; Lucarelli, F.; Mann, G.; McFiggans, G.; Miller, M. R.; Mills, G.; Monk, P.; Nemitz, E.; O'Connor, F.; Ouyang, B.; Palmer, P. I.; Percival, C.; Popoola, O.; Reeves, C.; Rickard, A. R.; Shao, L.; Shi, G.; Spracklen, D.; Stevenson, D.; Sun, Y.; Sun, Z.; Tao, S.; Tong, S.; Wang, Q.; Wang, W.; Wang, X.; Wang, X.; Wang, Z.; Wei, L.; Whalley, L.; Wu, X.; Wu, Z.; Xie, P.; Yang, F.; Zhang, Q.; Zhang, Y.; Zhang, Y.; Zheng, M., Introduction to the special issue "In-depth study of air pollution sources and processes within Beijing and its surrounding region (APHH-Beijing)". *Atmospheric Chemistry and Physics* **2019**, *19*, 7519-7546.
2. Squires, F. A.; Nemitz, E.; Langford, B.; Wild, O.; Drysdale, W. S.; Acton, W. J. F.; Fu, P.; Grimmond, C. S. B.; Hamilton, J. F.; Hewitt, C. N.; Hollaway, M.; Kotthaus, S.; Lee, J.; Metzger, S.; Pingintha-Durden, N.; Shaw, M.; Vaughan, A. R.; Wang, X.; Wu, R.; Zhang, Q.; Zhang, Y., Measurements of traffic-dominated pollutant emissions in a Chinese megacity. *Atmospheric Chemistry and Physics* **2020**, *20*, 8737-8761.
3. Nemitz, E. et al., Surface-atmosphere flux and sources of speciated PM_1 and ammonia in Beijing (unpublished results). **2021**.
4. Joshi, R.; Liu, D.; Nemitz, E.; Langford, B.; Mullinger, N.; Squires, F.; Lee, J.; Wu, Y.; Pan, X.; Fu, P.; Kotthaus, S.; Grimmond, S.; Zhang, Q.; Wu, R.; Wild, O.; Flynn, M.; Coe, H.; Allan, J., Direct measurements of black carbon fluxes in central Beijing using the eddy-covariance method. *Atmospheric Chemistry and Physics* **2020**, *20*, 1-27.
5. Yang, W.; Yu, C.; Yuan, W.; Wu, X.; Zhang, W.; Wang, X., High-resolution vehicle emission inventory and emission control policy scenario analysis, a case in the Beijing-Tianjin-Hebei (BTH) region, China. *Journal of Cleaner Production* **2018**, *203*, 530-539.
6. Harrison, R. M.; Vu, T. V.; Jafar, H.; Shi, Z., More Mileage in Reducing Urban Air Pollution from Road Traffic. *Environment International* **2021**, *149*, 106329.
7. Fu, X.; Liu, J.; Ban-Weiss, G. A.; Zhang, J.; Huang, X.; Ouyang, B.; Popoola, O.; Tao, S., Effects of canyon geometry on the distribution of traffic-related air pollution in a large urban area: Implications of a multi-canyon air pollution dispersion model. *Atmospheric Environment* **2017**, *165*, 111-121.
8. Xu, J.; Liu, D.; Wu, X.; Vu, T. V.; Zhang, Y.; Fu, P.; Sun, Y.; Xu, W.; Zheng, B.; Harrison, R. M.; Shi, Z., Source apportionment of fine aerosol at an urban site of Beijing using a chemical mass balance model. *Atmospheric Chemistry and Physics Discussions* **2020**, *20*, 1-28.
9. Biggart, M.; Stocker, J.; Doherty, R. M.; Wild, O.; Hollaway, M.; Carruthers, D.; Li, J.; Zhang, Q.; Wu, R.; Kotthaus, S.; Grimmond, S.; Squires, F. A.; Lee, J.; Shi, Z., Street-scale air quality modelling for Beijing during a winter 2016 measurement campaign. *Atmospheric Chemistry and Physics* **2020**, *20*, 2755-2780.
10. Lewis, A. et al., Sensitivity of Chinese ozone formation to relative reductions in NOx and VOCs: Beijing as a case study (unpublished results). **2021**.
11. Acton, W. J. F.; Huang, Z.; Davison, B.; Drysdale, W. S.; Fu, P.; Hollaway, M.; Langford, B.; Lee, J.; Liu, Y.; Metzger, S.; Mullinger, N.; Nemitz, E.; Reeves, C. E.; Squires, F. A.; Vaughan, A. R.; Wang, X.; Wang, Z.; Wild, O.; Zhang, Q.; Zhang, Y.; Hewitt, C. N., Surface-atmosphere fluxes of volatile organic compounds in Beijing. *Atmospheric Chemistry and Physics* **2020**, *20*, 1-36.
12. Shi, Z.; Song, C.; Liu, B.; Lu, G.; Xu, J.; Vu, T. V.; Elliot, R. J. R.; Li, W.; Bloss, W. J.; Harrison, R. M., Abrupt but smaller than expected changes in surface air quality attributable to COVID-19 lockdowns. *Science Advances* **2020**, *7*, eabd6696.
13. Hollaway, M.; Wild, O.; Yang, T.; Sun, Y.; Xu, W.; Xie, C.; Whalley, L.; Slater, E.; Heard, D.; Liu, D., Photochemical impacts of haze pollution in an urban environment. *Atmospheric Chemistry and Physics* **2019**, *19*, 9699-9714.
14. Slater, E. J.; Whalley, L. K.; Woodward-Massey, R.; Ye, C.; Lee, J. D.; Squires, F.; Hopkins, J. R.; Dunmore, R. E.; Shaw, M.; Hamilton, J. F.; Lewis, A. C.; Crilley, L. R.; Kramer, L.; Bloss, W.; Vu, T.; Sun, Y.; Xu, W.; Yue, S.; Ren, L.; Acton, W. J. F.; Hewitt, C. N.; Wang, X.; Fu, P.; Heard, D. E., Elevated levels of OH observed in haze events during wintertime in central Beijing. *Atmospheric Chemistry and Physics* **2020**, *20*, 14847-14871.
15. Bloss, W.J. et al., Overestimation of ground-level nitrogen dioxide concentrations due to HONO in commercial NO_2 analysers (unpublished results). **2021**.
16. Whalley, L. K.; Slater, E. J.; Woodward-Massey, R.; Ye, C.; Lee, J. D.; Squires, F.; Hopkins, J. R.; Dunmore, R. E.; Shaw, M.; Hamilton, J. F.; Lewis, A. C.; Mehra, A.; Worrall, S. D.; Bacak, A.; Bannan, T. J.; Coe, H.; Ouyang, B.; Jones, R. L.; Crilley, L. R.; Kramer, L. J.; Bloss, W. J.; Vu, T.; Kotthaus, S.; Grimmond, S.; Sun, Y.; Xu, W.; Yue, S.; Ren, L.; Acton, W. J. F.; Hewitt, C. N.; Wang, X.; Fu, P.; Heard, D. E., Evaluating the sensitivity of radical chemistry and ozone formation to ambient VOCs and NO_x in Beijing. *Atmospheric Chemistry and Physics* **2021**, *21*, 2125-2147.
17. Kotthaus, S; Grimmond, C.S.B., Atmospheric boundary layer characteristics from measurements. Part 1: A new method to track mixed layer height and classify clouds *Quarterly Journal of the Royal Meteorological Society* **2018**, *144*, 1525-1538
18. Slater, J.; Tonttila, J.; McFiggans, G.; Connolly, P.; Romakkaniemi, S.; Kühn, T.; Coe, H., Using a coupled LES-aerosol radiation model to investigate urban haze: Sensitivity to aerosol loading and meteorological conditions. *Atmospheric Chemistry and Physics* **2020**, *20*, 11893–11906.
19. Slater, J.; Tonttila, J.; McFiggans, G.; Coe, H.; Romakkaniemi, S.; Xu, W.; Wu, Z.; Sun, Y.; Fu, P., Using a coupled LES aerosol-radiation model to investigate the importance of aerosol-boundary layer feedback on a Beijing haze episode. *Faraday Discussions* **2020**, doi: 10.1039/D0FD00085J.
20. Wang, Q.; Zhang, Q.; Ma, Z.; Ge, B.; Xie, C.; Zhou, W.; Zhao, J.; Xu, W.; Du, W.; Fu, P.; Lee, J.; Nemitz, E.; Cowan, N.; Mullinger, N.; Cheng, X.; Zhou, L.; Yue, S.; Wang, Z.; Sun, Y., Temporal characteristics and vertical distribution of atmospheric ammonia and ammonium in winter in Beijing. *Science of the Total Environment* **2019**, *681*, 226-234.

21. Wu, L.; Ren, H.; Wang, P.; Chen, J.; Fang, Y.; Hu, W.; Ren, L.; Deng, J.; Song, Y.; Li, J.; Sun, Y.; Wang, Z.; Liu, C.-Q.; Ying, Q.; Fu, P., Aerosol ammonium in the urban boundary layer in Beijing: Insights from nitrogen isotope ratios and simulations in summer 2015. *Environmental Science & Technology Letters* **2019**, *6*, 389-395.

22. Ge, B.; Xu, X.; Ma, Z.; Pan, X.; Wang, Z.; Lin, W.; Ouyang, B.; Xu, D.; Lee, J.; Zheng, M.; Ji, D.; Sun, Y.; Dong, H.; Squires, F. A.; Fu, P.; Wang, Z., Role of ammonia on the feedback between AWC and inorganic aerosol formation during heavy pollution in the North China Plain. *Earth and Space Science* **2019**, *6*, 1675-1693.

23. Vu, T. V.; Shi, Z.; Cheng, J.; Zhang, Q.; He, K.; Wang, S.; Harrison, R. M., Assessing the impact of clean air action on air quality trends in Beijing using a machine learning technique. *Atmospheric Chemistry and Physics* **2019**, *19*, 11303-11314.

24. Cheng, J.; Su, J.; Cui, T.; Li, X.; Dong, X.; Sun, F.; Yang, Y.; Tong, D.; Zheng, Y.; Li, Y.; Li, J.; Zhang, Q.; He, K., Dominant role of emission reduction in $PM_{2.5}$ air quality improvement in Beijing during 2013–2017: a model-based decomposition analysis. *Atmospheric Chemistry and Physics* **2019**, *19*, 6125-6146.

25. Hu, X.; Sun, Y.; Liu, J.; Meng, J.; Wang, X.; Yang, H.; Xu, J.; Yi, K.; Xiang, S.; Li, Y.; Yun, X.; Ma, J.; Tao, S., The impact of environmental protection tax on sectoral and spatial distribution of air pollution emissions in China. *Environmental Research Letters* **2019**, *14*, 054013.

26. Wu, X.; Chen, C.; Vu, T. V.; Liu, D.; Baldo, C.; Shen, X.; Zhang, Q.; Cen, K.; Zheng, M.; He, K.; Shi, Z.; Harrison, R. M., Source apportionment of fine organic carbon (OC) using receptor modelling at a rural site of Beijing: Insight into seasonal and diurnal variation of source contributions. *Environmental Pollution* **2020**, *266*, 115078.

27. Du, H.; Li, J.; Chen, X.; Wang, Z.; Sun, Y.; Fu, P.; Li, J.; Gao, J.; Wei, Y., Modeling of aerosol property evolution during winter haze episodes over a megacity cluster in northern China: roles of regional transport and heterogeneous reactions of SO_2. *Atmospheric Chemistry and Physics* **2019**, *19*, 9351-9370.

28. Wild, O. et al., Investigating the temporal, sectoral and regional contributions to air pollution in Beijing (unpublished results) **2021**.

29. Liu, Y.; Zheng, M.; Yu, M.; Cai, X.; Du, H.; Li, J.; Zhou, T.; Yan, C.; Wang, X.; Shi, Z.; Harrison, R. M.; Zhang, Q.; He, K., High-time-resolution source apportionment of $PM_{2.5}$ in Beijing with multiple models. *Atmospheric Chemistry and Physics* **2019**, *19*, 6595-6609.

30. Liu, X.-Y.; He, K.-B.; Zhang, Q.; Lu, Z.-F.; Wang, S.-W.; Zhang, Y.-X.; Streets, D. G., Analysis of the origins of black carbon and carbon monoxide transported to Beijing, Tianjin, and Hebei in China. *Science of The Total Environment* **2019**, *653*, 1364-1376.

31. Chen, Y.; Shi, G.; Cai, J.; Shi, Z.; Wang, Z.; Yao, X.; Tian, M.; Peng, C.; Han, Y.; Zhu, T.; Liu, Y.; Yang, X.; Zheng, M.; Yang, F.; Zhang, Q.; He, K., Simultaneous measurements of urban and rural particles in Beijing – Part 2: Case studies of haze events and regional transport. *Atmospheric Chemistry and Physics* **2020**, *20*, 9249-9263.

32. Li, J. et al., Regional transport of air pollutants to Beijing (unpublished results). **2021**.

33. Panagi, M.; Fleming, Z. L.; Monks, P. S.; Ashfold, M. J.; Wild, O.; Hollaway, M.; Zhang, Q.; Squires, F. A.; Vande Hey, J. D., Investigating the regional contributions to air pollution in Beijing: a dispersion modelling study using CO as a tracer. *Atmospheric Chemistry and Physics* **2020**, *20*, 2825-2838.

34. Bryant, D. J.; Dixon, W. J.; Hopkins, J. R.; Dunmore, R. E.; Pereira, K. L.; Shaw, M.; Squires, F. A.; Bannan, T. J.; Mehra, A.; Worrall, S. D.; Bacak, A.; Coe, H.; Percival, C. J.; Whalley, L. K.; Heard, D. E.; Slater, E. J.; Ouyang, B.; Cui, T.; Surratt, J. D.; Liu, D.; Shi, Z.; Harrison, R.; Sun, Y.; Xu, W.; Lewis, A. C.; Lee, J. D.; Rickard, A. R.; Hamilton, J. F., Strong anthropogenic control of secondary organic aerosol formation from isoprene in Beijing. *Atmospheric Chemistry and Physics* **2020**, *20*, 7531-7552.

35. Hamilton, J. et al., Organosulfate aerosol in Beijing (unpublished results). **2021**.

36. Mehra, A.; Bannan, T.; Allan, J.; Percival, C.; Coe, H., Using highly time-resolved online mass spectrometry to examine biogenic and anthropogenic contributions to organic aerosol in Beijing. *Faraday Discussions* **2020**, doi: 10.1039/d0fd00080a, in press.

37. Brean, J.; Harrison, R. M.; Shi, Z.; Beddows, D. C. S.; Acton, W. J. F.; Hewitt, C. N.; Squires, F. A.; Lee, J., Observations of highly oxidized molecules and particle nucleation in the atmosphere of Beijing. *Atmospheric Chemistry and Physics* **2019**, *19*, 14933-14947.

38. Cherrie, J. W.; Apsley, A.; Cowie, H.; Steinle, S.; Mueller, W.; Lin, C.; Horwell, C. J.; Sleeuwenhoek, A.; Loh, M., Effectiveness of face masks used to protect Beijing residents against particulate air pollution. *Occupational and Environmental Medicine* **2018**, *75*, 446-452.

39. Dong, W.; Liu, S.; Chu, M.; Zhao, B.; Yang, D.; Chen, C.; Miller, M. R.; Loh, M.; Xu, J.; Chi, R.; Yang, X.; Guo, X.; Deng, F., Different cardiorespiratory effects of indoor air pollution intervention with ionization air purifier: Findings from a randomized, double-blind crossover study among school children in Beijing. *Environmental Pollution* **2019**, *254*, 113054.

40. Han, Y.; Chen, W.; Chatzidiakou, L.; Yan, L.; Zhang, H.; Chan, Q.; Barratt, B.; Jones, R.; Liu, J.; Wu, Y.; Zhao, M.; Zhang, J.; Kelly, F. J.; Zhu, T.; the AIRLESS team, Effects of AIR pollution on cardiopuLmonary disEaSe in urban and peri-urban reSidents in Beijing: protocol for the AIRLESS study. *Atmospheric Chemistry and Physics* **2020**, 15775–15792.

41. Hu, D.; Jia, X.; Cui, L.; Liu, J.; Chen, J.; Wang, Y.; Niu, W.; Xu, J.; Miller, M.R.; Loh, M.; Deng, F.; Guo, X., Exposure to fine particulate matter promotes platelet activation and thrombosis via obesity-related inflammation. *Journal of Hazardous Materials* **2021**, *413*, 125341.

42. Li, Y.; Guan, D.; Yu, Y.; Westland, S.; Wang, D.; Meng, J.; Wang, X.; He, K.; Tao, S., A psychophysical measurement on subjective well-being and air pollution. *Nature Communications* **2019**, *10*, 5473.

43. Xue, T.; Zhu, T.; Zheng, Y.; Zhang, Q., Declines in mental health associated with air pollution and temperature variability in China. *Nature Communications* **2019**, *10*, 2165.

44. Shen, G.; Ru, M.; Du, W.; Zhu, X.; Zhong, Q.; Chen, Y.; Shen, H.; Yun, X.; Meng, W.; Liu, J.; Cheng, H.; Hu, J.; Guan, D.; Tao, S., Impacts of air pollutants from rural Chinese households under the rapid residential energy transition. *Nature Communications* **2019**, *10*, 3405.

45. Meng, W.; Zhong, Q.; Chen, Y.; Shen, H.; Yun, X.; Smith, K. R.; Li, B.; Liu, J.; Wang, X.; Ma, J.; Cheng, H.; Zeng, E. Y.; Guan, D.; Russell, A. G.; Tao, S., Energy and air pollution benefits of household fuel policies in northern China. *Proceedings of the National Academy of Sciences* **2019**, *116*, 16773-16780.