PHILOSOPHICAL TRANSACTIONS A

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Global Air Quality, past present and future: an introduction

David Fowler[1], John A. Pyle[2], Mark A. Sutton[1] and Martin L. Williams[3]

[1]Centre for Ecology and Hydrology Bush Estate, Penicuik Midlothian EHH26 0QB, UK
[2]Department of Chemistry, University of Cambridge, Cambridge CB1 2EW, UK
[3]Imperial College London, London SW7 2AZ, UK

DF, 0000-0002-2999-2627; MAS, 0000-0002-1342-2072

Introduction

Cite this article: Fowler D, Pyle JA, Sutton MA, Williams ML. 2020 Global Air Quality, past present and future: an introduction. *Phil. Trans. R. Soc. A* **378**: 20190323.
http://dx.doi.org/10.1098/rsta.2019.0323

Accepted: 22 July 2020

One contribution of 17 to a discussion meeting issue 'Air quality, past present and future'.

Subject Areas:
atmospheric chemistry, environmental chemistry, atmospheric science, biogeochemistry, meteorology

Author for correspondence:
David Fowler
e-mail: dfo@ceh.ac.uk

Global Air Quality in 2019 was responsible for 7 million premature deaths, extensive crop loss and declines in biodiversity across Europe, North America and East Asia. Air pollutants also contribute directly to climate change through changes in the energy balance of the planet by some of the gaseous pollutants, notably ozone and also by particulate matter. There are therefore strong motives to understand the science, develop policies to mitigate effects and identify technical solutions to reduce emissions substantially.

The objectives of the Royal Society Air Quality Discussion Meeting in November 2019 were to describe the way air pollution developed, articulate the main characteristics of the current global air quality issues and assess the likely changes in the scale and distribution of air pollution through the twenty-first century. The policy responses to date have generally been slow to develop, in part because the effects were not anticipated and, to some extent when observed, were regarded as an acceptable burden for the benefits of new technologies. Many of the large-scale air pollution problems were discovered by scientists engaged in unrelated monitoring or research activities. Thus, the effects became widespread and severe before the scale of the problems were appreciated, as in the case of Acid Rain. The polluting industries and governments sometimes engaged, at least initially, in obfuscation activities in an attempt to minimize the importance of the problem. The slow policy response has been a feature of air pollution globally.

The meeting brought together a broad range of researchers and practitioners working in fields related to air pollution and its effects on human and environmental

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health, atmospheric chemistry and physics. The meeting was the first 'Science Plus' discussion meeting in which policy aspects of the subject were described and discussed alongside presentations of the disciplinary sciences. The policy aspects are a vital component of the broader subject, through the need to understand the science sufficiently to provide useful guidance to policy makers on possible mitigation pathways. However, the scope of a 2-day discussion meeting with just eighteen 30 min presentations and a panel discussion was necessarily limited. In many of the areas of science covered, there have been large, international conferences and hundreds of publications annually. The lectures and resulting published manuscripts from this meeting thus represent a highly selective cross section with many areas omitted, or mentioned only fleetingly.

Broadly the subject is divided into three sections, beginning with three papers examining the past, detailing the historical development of air pollution issues and their effects on human health, ecosystems and food security. The second and largest section, comprising 10 papers, describes the main current global air quality issues. The final section, comprising three papers, considers the likely trends in air quality and its effects through the current century. There are two papers describing policy aspects explicitly. Monks & Williams [1] consider the drivers of policy and role of science in development of air quality policy over the last 100 years, while Amann *et al.* [2] looks forward to the middle decades of this century to gauge the likely improvements in air quality from current conditions. We appear to be a decade or so after peak emissions of sulfur dioxide and close to peak emissions for NOx emissions and there are prospects of a gradual global improvement in air quality over the next four decades. It is notable that none of those presenting was willing to speculate in any detail much beyond the middle of the century.

The opening paper presents a chronology of the development of understanding of the issues arising from the emission of pollutant gases and particulate matter to the atmosphere by human activity [3]. Pollutants are not a new phenomenon, with early reports from Greece of poor air quality more than 2000 years ago. Poor air quality has long been a feature of cities and the scale of the problems grew to a global peak in the first decade of the twenty-first century. The scale of the emissions generated regional and transboundary pollution problems by the middle of the twentieth century and transboundary and intercontinental transport have become an important part of global air pollution in the last half century.

The effects of pollutants on human health have been the strongest driver of policy development, but effects on vegetation, food security and the wider environment have also been important. For natural ecosystems and specifically the effects of air pollution on vegetation, the historical narrative is also long, with observed effects in the eleventh century, described by Stevens *et al.* [4]. For vegetation, severe problems included regional exposure to phytotoxic levels of SO_2 and were greatest in the middle decades of the twentieth century in Europe and North America. These acute effects have now been resolved by greatly reducing emissions of SO_2. For other pollutants affecting vegetation, including the eutrophication of ecosystems by atmospheric deposition of nitrogen compounds that effectively fertilize ecosystems by atmospheric deposition, there are no signs of recovery. The most important ecological effects of nitrogen deposition on seminatural plant communities are changes in species composition, described by Stevens *et al.* Emissions of nitrogen oxides also contribute to tropospheric ozone production, and for food security, ozone is globally the most important air pollutant cause of reductions in productivity. The effects of ozone on food security are described by Emberson [5].

The central section of papers on current air quality issues begins with an overview of particulate matter (PM) by Harrison [6], characterizing size distributions, composition, sources and ambient concentrations in major global cities. A case study of sources of fine particulate matter in China [7] also provides important links to policy, as major cities in China became notable hot-spots for poor air quality between 2000 and 2010. Policies to reduce emissions of the major pollutants in China have substantially reduced emissions and exposure of the population to PM over the last decade.

The most important impacts of PM are currently the effects on human health and these remain the main driver of policy developments. Two contrasting approaches to study the effects of air pollutants on human health are epidemiology and toxicology, summarized by Gowers *et al.* [8]

and by Kelly *et al.* [9], respectively. While PM is a focus for research, monitoring and policy development to reduce the effects on human health, there remains the problem that the relative contributions of PM components to human health effects remain unknown. Thus most policy is currently directed towards reduction in PM mass rather than targeting any specific chemical component in order to reduce population exposure. Identifying the relative contributions of different chemical components of PM remains an important research objective.

Vegetation and trees in particular represent a sink for atmospheric PM and reactive gases. Trees have also been proposed as a potential solution for air quality problems in urban areas, by enhancing the rate of deposition to the surface. Nemitz *et al.* [10] describe the background principles and quantify using a chemistry-transport model the scale of air quality improvement possible with tree planting both at the city and country scale. They show that even very ambitious planting of trees in urban areas yields only a small improvement in air quality. They show that controlling the sources of the pollutants is the most effective strategy to reduce population exposure.

The role of nitrogen compounds on air quality has grown since the mid-twentieth century, especially with the declining role of sulfur dioxide emissions. The papers by Sutton *et al.* [11] and Liu *et al.* [12] both focus on the role of nitrogen compounds. Sutton *et al.* address the issue of ammonia and specifically its role in regulating the acidity of the atmosphere. We are familiar with the expression Acid Rain from the middle decades of the last century, but with the decline in emissions of SO_2 from 1980 onwards and NO_2 from the peak in 2018, the acidity of precipitation and aerosols has declined considerably and we now have the prospect of alkaline air as emissions of NH_3 continue to grow. Furthermore, a change in aerosol composition is leading to a change in the partitioning of atmospheric ammonia from aerosol towards the gas phase, leading to a change in transport distance of NH_x in the atmosphere and continued dominance of reduced nitrogen in driving effects on ecosystems [4]. The role of reactive nitrogen (N_r) in China is described by Liu *et al.* [12], showing emissions of NH_3 currently exceeding those of NO_x by 30% (as N) and playing a major role in the air quality issues in China. Notable reductions of emissions of NOx in China have been achieved over the last decade. Important uncertainties in the budget of ammonia over China are also described in this paper.

While large reductions in emissions of SO_2 and NO_2 have been achieved regionally and, in the case of SO_2, globally, emissions of VOC remain an important area for further policy. There have been substantial reductions in emissions of VOC from the road transport sector and from fugitive fuel emissions, but other sources, including solvents and industrial processes, now represent a substantial fraction of emissions. Lewis *et al.* [13] describe the changes in VOC emissions and speciation in the UK in recent decades and their implications for monitoring.

The final four papers in the issue are concerned with very recent trends, as a consequence of the SARS Covid-19 pandemic on ozone [14] and possible futures for global air quality. The forecasts of emissions depend on the willingness of nations to implement policies to control emissions, so *possible* futures are the only ones available. Forecasts of the future are always subject to unknowns. The progress since peak SO_2 emissions in the late twentieth century has been considerable and many countries have extensive plans for further reductions in emissions of SO_2, NO_x and VOC. There are also plans for reductions in emissions of NH_3 in some countries, but these seem unlikely to lead to a global reduction in NH_3 emissions. The agricultural sector is poorly regulated relative to road transport or manufacturing industry.

The likely trends in emissions through to the mid-twenty-first century rely on further policy interventions as discussed by Amann *et al.* [2]. They conclude that air pollution controls and measures to protect the climate and agricultural production *could* substantially reduce global air pollution, with a 75% reduction in PM2.5 exposure of the population. Some of the measures to reduce emissions of air pollutants are already envisaged within national policy objectives, and these improvements could be achieved with continued economic growth. It is notable that the progress to date in improving air quality has largely been consistent with Kuznets arguments that regulations to improve environmental quality are introduced as societies reach a point in their economic development allowing resources to be devoted to control measures. The meeting did not address the wider socio-economic developments and this precluded discussion of Kuznets arguments and whether it informs us of the timing or scale of future pollutant emissions. It is important to note that integrated assessment methods, such as those used by Amann and colleagues at IIASA have proved very effective in the development of international protocols to regulate the inter-country exchange of pollutants in Europe through the UNECE and EU over the last four decades.

The effects of changes in climate are an important consideration in coming decades. The Earth system model used by Archibald *et al.* [15] shows substantial increases in surface ozone in South and East Asia in the coming decades and important effects of climate change on tropospheric ozone. The changes in effects of pollutants on human health, ecosystems and food security during the current century are discussed by Von Schneidemesser *et al.* [16] who show the importance of South and East Asia. It is clear that policy developments in Asia in the medium term will be an important driver of the global magnitude of effects. The probable role of climate–air pollution interactions is also highlighted in this contribution.

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Tribute to Martin L. Williams

Professor Martin L. Williams

Martin Williams, one of the organisers of the Discussion meeting leading to this collection of papers and an author of one with Paul Monks, has been a leader of research and policy development to solve the problems of poor air quality in the UK and more widely through Europe throughout the last four decades. .

He graduated in chemistry from the University of Cardiff and continued into research gaining a PhD in Theoretical Chemistry from Bristol. Following a post doc in Canada, he was appointed to the Warren Spring laboratory in Stevenage, the UK's centre for air pollution research and coordination of national monitoring activities. Martin was head of the Air Pollution Division leading a team of 50 scientists in air quality research for government and business. He was a founder member of various expert groups advising government – Committee on the Medical Aspects of Air Pollutants, Expert Panel on Air Quality Standards, Photochemical Oxidants Review Group, Quality of Urban Air Review Group and was an advisor to the USEPA, WHO, the European Commission, NATO and the OECD.

In 1993 Martin moved to head the air quality science unit in the Department of the Environment where he formulated the research programmes and led the production of three national air quality strategies between 1993 and 2002. These were heavily science-based, and won commendations as exemplars of scientific inputs to policy. During this time, he was also elected chairman of the scientific arm of the UN Convention on Long Range Transboundary Air Pollution (CLRTAP) - the air pollution analogue of the climate change Convention - formulating and overseeing research in centres in Norway, Moscow, Vienna and Germany to underpin the negotiations of international policy agreements on emission reductions. Great improvements in air quality throughout Europe have been achieved through the protocols agreed within this process, much of it under Martin Williams leadership. Martin also worked closely with the European Commission, developing the scientific basis for legislation on air quality limits in EU Directives.

In 2010 Martin left Defra to join Kings College and return to academic research in air pollution. At this time, he was appointed to Defra's Air Quality Expert Group, and continued to chair the CLRTAP Executive Body and was a member of a WHO working group reviewing the literature on health effects of air pollution. With the recent move of the air pollution research team from Kings College to Imperial College, Martin contributed to the Group's foremost position in both UK and international air quality policy through chairing Defra's Air Quality Modelling Steering Group, set up to advise the Department on their strategic needs for air pollution modelling.

In June 2019 UK Research and Innovation and the Met Office launched an ambitious new programme to improve air quality and reduce its impact on health in the UK with the announcement of three Clean Air Champions. Their remit over the three years was to bring together the UK's world-class air quality research base to develop practical solutions for air quality issues, as part of the Clean Air programme. It could not have been more fitting that Martin was one of those Champions.

Martin died suddenly on Monday 21st September 2020.

David Fowler
Frank Kelly