Institution: University of Exeter		
Unit of Assessment: UoA 10 Mathematical Sciences		
Title of case study: Clearing the air: using data to drive improvements in global air quality and health		
Period when the underpinning research was undertaken: 2017 – 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Professor Gavin Shaddick	**Role(s) (e.g. job title):** Chair in Data Science and Statistics	**Period(s) employed by submitting HEI:** 2017 – current
Period when the claimed impact occurred: July 2017 - ongoing		
Is this case study continued from a case study submitted in 2014? NO		

1. Summary of the impact

Air pollution is widely recognised as a threat to global public health and economic development; it is the fifth highest cause of health-related deaths, ranking just below smoking. The World Health Organization (WHO) reports that 4.2 million deaths annually can be attributed to outdoor air pollution and that 91% of the world's population are exposed to unsafe levels of pollution. This quantification of global air quality and its impacts on health is a result of a data integration model for air quality (DIMAQ) developed by the University of Exeter that has transformed the availability of high-quality data on air pollution worldwide. The impacts of this research include:

- Progress by the WHO and the United Nations (UN) in driving forward the global agenda on air quality and health with its 194 member states;
- Stimulating worldwide development and implementation of new policies for reducing air pollution and improving health;
- Empowering nearly half a billion people who are now able to see the levels of air pollution in their towns and cities and get involved in the drive for cleaner air.

2. Underpinning research

Global assessments of air quality require comprehensive estimates of the exposures experienced by populations in every country. However, there are still many countries and regions in which measurements from monitoring networks are sparse, or non-existent.

While monitoring provides a far from complete picture of global air quality, information is available from other sources, such as remote sensing satellites, that can provide comprehensive coverage. However, making full use of these presents a number of challenges: (i) they do not incorporate the fine-scale variation in pollution that is required; (ii) each of the different data sources represent fundamentally different quantities; (iii) data at multiple scales of measurement in both space and time needs to be 'joined together' in a coherent fashion; and (iv) each of the data sources will have different error structures and uncertainties, and these may vary over both space and time.

The Data Integration Model for Air Quality (DIMAQ) [**3.1, 3.2**] addresses each of these challenges. Set within a Bayesian hierarchical modelling framework, DIMAQ provides a methodological and computational framework to combine information from ground monitoring, remote sensing satellites, chemical transport models, land-use, population density, topography and other sources of information to create high-resolution estimates of air pollution with comprehensive coverage. Notably, for the first time this work has provided a framework in which to propagate the uncertainty in exposure estimates through to estimates of burden of disease, and the ability to calculate probabilities of exceedance, e.g. the probability that levels of pollution in any area exceeded WHO Air Quality Guidelines (AQGs).

Professor Gavin Shaddick has been Chair of Data Science & Statistics at the University of Exeter since 2017 and has continued his work on DIMAQ that started when he was at the University of Bath. This case study focuses on the development of DIMAQ at Exeter and the subsequent impacts arising from its implementation. Subsequent to its initial release in 2016, both the underlying modelling and computational frameworks underpinning DIMAQ have been subject to major enhancements [**3.3, 3.4, 3.5**]. These have been driven by the international need to track changes and progress towards the Sustainable Development Goals (SDGs), to couple the evidence for effective interventions with global, regional and local trends in air pollution and to reflect the finer scale variation in air quality that is seen in urban areas.

In the original formulation of DIMAQ the coefficients within the calibration equations were allowed to vary on a country-by-country basis with yearly outputs treated independently. In the most recent version of DIMAQ these coefficients can vary smoothly over both space and time, making full use of the multi-year data now available in the WHO database of ambient air quality [**3.5**]. The inclusion of multi-year data required an update to the computational methods used to calculate the exposure estimates and associated measures of uncertainty. A new, simulation-based method was developed to obtain samples from the posterior distributions (of estimated PM2.5) on a high-resolution grid [**3.3, 3.5**] that, in addition to being computationally efficient, provides a coherent method for aggregation and propagating uncertainty. **The result is that for the first time, country-level, multi-year summaries of air quality, together with associated measures of uncertainty, are produced directly in the form required for the SDGs** (e.g. country-level average exposures for SDG indicator 11.6.2: Annual mean levels of fine particulate matter; population-distributions of exposure for SDG Indicator 3.9.1: Mortality rate attributed to household and ambient air pollution).

As a result of their work in developing DIMAQ and producing information that is crucial in health assessment, supporting progress towards the SDGs and in providing the evidence-base for policy makers, Shaddick and the University of Exeter have been invited to establish a WHO Collaborating Centre (CC) in Data Science for Air Quality, Climate Change and Environment, the WHO's first in the field of Data Science and Environment.

3. References to the research

[1] Shaddick, G., Thomas, M.L., Green, A., Brauer, M., van Donkelaar, A., Burnett, R., Chang, H.H., Cohen, A., Van Dingenen, R., Dora, C. and Gumy, S., 2018. Data integration model for air quality: a hierarchical approach to the global estimation of exposures to ambient air pollution. Journal of the Royal Statistical Society: Series C (Applied Statistics), 67(1), pp.231-253. https://doi.org/10.1111/rssc.12227

[2] Shaddick, G., Thomas, M.L., Amini, H., Broday, D., Cohen, A., Frostad, J., Green, A., Gumy, S., Liu, Y., Martin, R.V. and Pruss-Ustun, A., 2018. Data integration for the assessment of population exposure to ambient air pollution for global burden of disease assessment. Environmental Science & Technology, 52(16), pp.9069-9078. https://pubs.acs.org/doi/10.1021/acs.est.8b02864

[3] JD Stanaway, A Afshin, E Gakidou, SS Lim, & …&, **Shaddick, G** *et al*. Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2018. The Lancet 392 (2018): 1923-1994. See Supplementary Material for a detailed description of the enhanced DIMAQ model, referred to as 'DIMAQ2'. https://doi.org/10.1016/S0140-6736(18)32225-6

[4] Martin, R.V., Brauer, M., van Donkelaar, A., **Shaddick, G.**, Narain, U. and Dey, S., 2019. No one knows which city has the highest concentration of fine particulate matter. Atmospheric Environment: X, 3, p.100040. https://doi.org/10.1016/j.aeaoa.2019.100040.

[5] Shaddick, G., Thomas, ML, Mudu, P, Ruggeri, G, Gumy, S. 2020. Half the world's population are exposed to increasing air pollution. npj Clim Atmos Sci 3, 23 (2020). https://doi.org/10.1038/s41612-020-0124-2

4. Details of the impact

Air pollution is the most important environmental risk factor to global health: The World Health Organization (WHO) reports that 4.2 million deaths annually can be attributed to outdoor air pollution and that 91% of the world's population are exposed to harmful air. These figures are provided to the WHO by the University of Exeter team using the Data Integration Model for Air Quality (DIMAQ). DIMAQ has been key to WHO's activities in air quality and its custodial role for the Sustainable Development Goals (SDG) indicators related to air pollution (within SDG 3 'Good Health and Well-being' and SDG 11 'Sustainable Cities and Communities'). "DIMAQ provides the WHO with the methodology to produce information on global air quality at a level of accuracy that was, until recently, not possible. For the first time, the WHO have access to information on population-exposures to fine particulate matter (PM2.5) air pollution for every country, even those for which there is [sic] no recognised monitoring networks." (Technical Officer, Dept of Environment, Climate Change and Health, WHO) **[5.1]**.

Driving the global agenda on air quality and health

The SDGs call for international action in reducing air pollution: *"By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management"* (SDG11), and *"By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination"* (SDG3). The enhanced version of DIMAQ was developed to produce outputs that feed directly into the calculation of SDG indicators and since 2018 the team at the University of Exeter have used it to calculate, for each country, two of the SDG indicators: population-weighted exposures to fine particulate matter (SDG 11, indicator 11.6.2) and mortality rates attributable to ambient air pollution (SDG 3 indicator 3.9.1). These figures, together with supporting data and detailed methods, are shared with individual countries and are validated through a process of consultation between the WHO, the University of Exeter team and country representatives **[5.2]**. In the words of a WHO representative: "the information that DIMAQ produces is essential not just for performing health analysis and understanding the global scale of the problem, but in working with individual Member States to develop, adopt and implement policy interventions designed to reduce levels of air pollution, and to save lives" **[5.1]**.

In addition to the SDGs, the WHO's 'Triple Billion' programme aims to improve the health of billions by 2023, through a strategy of combined measurement and policy development. This is also reliant on DIMAQ: "In the case of ambient air pollution, DIMAQ plays an important role in providing the information that is required to track progress to the goal and to drive actions towards having 1 billion more people enjoying better health and well-being" (Technical Officer, Dept of Environment, Climate Change and Health, WHO) **[5.1, 5.3]**.

DIMAQ also contributes more widely to increasing the understanding of global air pollution and health and forms the basis of the latest assessments of the global burden of disease from the WHO **[5.4**], the Institute of Health Metric Evaluation's (IHME) 'Global Burden of Disease' **[5.5],** and the Health Effects Institute's 'State of Global Air 2019' **[5.6]**.

Stimulating policy commitments to tackle air pollution

Quantifying and monitoring the effects of exposure to air pollution in terms of public health is a critical component in policy discussion worldwide. The information from DIMAQ is playing a vital role in driving policy and investment which is providing: affordable and sustainable access to clean energy; cleaner transport and power generation; energy-efficient housing; and municipal waste management. Evidence of this was clear at the First WHO Global Conference on Air Pollution and Health: Improving air quality, combatting climate change – saving lives, held in Geneva 30 October – 1 November 2018 **[5.7]**. Comprehensive information on air quality and mortality produced by Professor Shaddick's team using the enhanced DIMAQ had been shared with countries during the preceding months. This included direct engagement with a number of countries prior to the conference to help them to understand the implications of the evidence from DIMAQ, so that, by understanding the scale of the issue, they could develop appropriate policy interventions to tackle the problem.

At the conference, where Professor Shaddick presented the results from DIMAQ and ran a workshop for representatives of member states, leaders from national and city governments, intergovernmental organizations, civil society, research and academia reflected on the scientific evidence on air pollution and health and the solutions to improve air quality. A major outcome of the conference was that participants agreed an aspiration goal of reducing the number of deaths from air pollution by two thirds by 2030, which would represent nearly 5 million premature deaths saved each year and a reduction in the estimated economic impact of premature deaths, estimated to be 4.4% of global GDP **[5.7]**. DIMAQ is a key element in this achievement, as it provided the air quality information which enabled countries to understand the seriousness of their own specific situation, as well as within the global context. It is also a key driver of implementation and is, and will continue to be, one of the main sources of data for monitoring the progress of countries towards this goal. At the conference more than 70 commitments were announced by individual countries, cities, UN organisations, intergovernmental organisations and civil society to tackle air pollution and achieve this goal **[5.7]**. Many of these are already being implemented in national policies, for example: Mongolia has banned household raw coal burning in the capital city Ulaanbataar (May 2019); the Netherlands Climate Act (2019) is enshrining in law that only new zero emission vehicles will be sold from 2030; Monaco is banning the use of heavy fuel oil in old buildings (from 2022) **[5.8]** and, quoting the video in **[5.7]**, Albania (Tirana) announced that "70% of all new transport investment will be for walking and cycling networks and 100% of the taxis will be electric by 2025 with the aim of reaching WHO targets for ambient air quality".

DIMAQ has also provided evidence for other organisations to assess the health and economic effects of air pollution across the world, providing a clear evidence base for action. Examples include the OECD's 2019 'Economic Outlook for Southeast Asia, China and India: *Responding to Environmental Hazards in Cities*' report **[5.9]**, and the United Nations programme for the Environment (UNEP) / Climate Clean Air Coalition in their report 'Integrated Assessment of Short-lived Climate Pollutants in Latin America and the Caribbean' **[5.10]**.

Empowering Citizens with data to support targeted actions

In 2016, the WHO, together with UNEP, the Climate & Clean Air Coalition and the World Bank, launched the BreatheLife campaign because they recognised the importance of engaging individuals and communities in ongoing actions, noting in their campaign materials that a key benefit of joining was the "ongoing data and content updates for raising awareness about the burden of air pollution to our health and our climate" **[5.11]**. DIMAQ is now central to that data provision, with the WHO noting that "DIMAQ produces the information and data shown in the interactive webpage for BreatheLife which allows people to see the levels of air pollution in their cities and to get involved in the drive for cleaner air" **[5.1].** An example of the visualisation of the outputs from the enhanced version of DIMAQ on the BreatheLife website can be seen in Figure 1 **[5.11]**. The BreatheLife network now has over 70 cities, regions and countries across six continents representing over 486 million citizens impacted by the drive towards cleaner air. In addition to the BreatheLife website, these outputs are also publicly available on the WHO website through an interactive map of air pollution that was developed as part of the most recent release of the WHO estimates of global air pollution and health **[5.12]**.

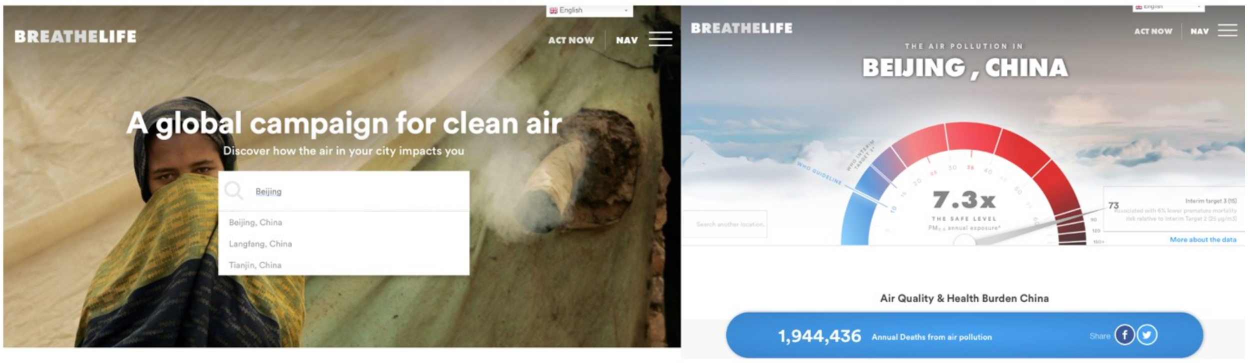

Figure 1: BreatheLife interactive web pages showing air pollution data for Beijing, China.

5. Sources to corroborate the impact

5.1: Letter of support from World Health Organization (Technical Officer, Dept of Environment, Climate Change and Health, WHO).

5.2: Details of WHO 2018 release of air quality estimates https://www.who.int/airpollution/ambient/AAP_exposure_Apr2018_final.pdf?ua=1 specifically acknowledged on page 4 and 6.

5.3: World Health Organization's Triple Billion Programme: i) Thirteenth General Programme of Work (GPW13) Methods for Impact Measurement (2020). https://www.who.int/about/what-we-do/thirteenth-general-programme-of-work-2019---2023; ii) World Health Organization on-line dashboard: Tracking the Triple Billion targets https://portal.who.int/triplebillions/

5.4: WHO Modelled Global Ambient Air Pollution estimates https://www.who.int/airpollution/data/modelled-estimates/en/

5.5: Institute of Health Metrics and Evaluation Global Burden of Disease – Data Visualisation Hub https://vizhub.healthdata.org/gbd-compare/

5.6: Health Effects Institute State of Global Air (2019) https://www.stateofglobalair.org/

5.7: First WHO Global Conference on Air Pollution and Health: i) Summary report www.who.int/phe/news/clean-air-for-health/en/; ii) Video of plenary session X that includes the country, city and institutional pledges and policy changes https://www.who.int/airpollution/events/conference/en/

5.8: Example policy changes related to pledges at the WHO Global Conference: i) Banning the use of fuel oil in buildings in Monaco 'The energy transition in the Principality', Government Communication Department; ii) Banning of household burning of raw coal in Ulaanbataar, Mongolia https://news.mn/en/789895/ ; iii) Tirana, Albania investment in green transportation https://stories-ebrd.com/green-cities/ iv) CO2 emissions and waste reduction in the Netherlands https://www.government.nl/topics/climate-change/climate-policy

5.9: OECD (2019), Economic Outlook for Southeast Asia, China and India 2019 – Update: Responding to Environmental Hazards in Cities, OECD Publishing, Paris pp.89-93.

5.10: Climate and Clean Air Coalition (CCAC), Mexico, Molina Center for Energy and the Environment (MCE2), United Nations Environment Programme (UNEP): Progress and Opportunities for Reducing SLCPs across Latin America and the Caribbean.

5.11: BreatheLife: i) 'Become a BreatheLife City' Flyer https://breathelife2030.org/wpcontent/uploads/2018/08/breathelifecityflyer0818.compressed.pdf; ii) BreatheLife Campaign Website https://breathelife2030.org/

5.12: Concentrations of fine particulate matter (PM2.5) Interactive Map: https://www.who.int/data/gho/data/indicators/indicator-details/GHO/concentrations-of-fine-particulate-matter-%28pm2-5%29

All web links were checked on 25th March 2021.