Institution: University of Bristol		
Unit of Assessment: 8) Chemistry		
Title of case study: Bristol research shapes national and global decision making on emissions of greenhouse gases and ozone depleting substances		
Period when the underpinning research was undertaken: 2000 - 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Matt Rigby Simon O'Doherty	Reader in Atmospheric Chemistry Professor of Atmospheric Chemistry	2012 - present 1991 - present
Period when the claimed impact occurred: 2015 - 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Genuine and measurable reduction in global emissions of greenhouse gases and stratospheric ozone depleting substances demand accurate monitoring and verification techniques. Working at the national and international scale, the University of Bristol's Atmospheric Chemistry Research Group has developed world leading-atmospheric measurement and modelling capabilities. This research has led to:

- The identification of the first major breach of the Montreal Protocol. New emissions of the banned ozone depleting substance, CFC-11, were identified from eastern China, and subsequently reduced following enforcement action.
- Enhancement of the UK's international reputation by ensuring accurate and transparent national GHG emissions reporting under the United Nations Framework Convention on Climate Change.

2. Underpinning research

Compliance with national and international policy on climate and the protection of the stratospheric ozone layer requires accurate regional and global atmospheric measurement networks and robust computational and statistical analysis methods. The close synergy at Bristol, between measurement and modelling efforts, is key to our ability to drive environmental impact by influencing national and international strategies on the management of the emissions of greenhouse gases (GHG) and ozone depleting substances (ODS).

UK and global atmospheric trace gas measurements:
Bristol has pioneered the development of a GHG and ODS emissions evaluation system for the UK - the Deriving Emissions related to Climate Change (**DECC**) network (O'Doherty is PI) [1,2]. The UK's measurement network is unique in the world because of its capacity to make measurements of all of the key gases regulated under the Kyoto and Montreal Protocols, including carbon dioxide, methane, nitrous oxide and a wide array of halocarbons. Currently, the network consists of the world renowned "baseline" station at Mace Head on the west coast of Ireland, which Bristol have run since 1986, and four sites within the UK on tall telecommunication towers, which have been developed and operated by Bristol since 2014.

This regional atmospheric expertise is combined with global measurement capability. Bristol leads two of the five "core" stations in the international Advanced Global Atmospheric Gases Experiment

(AGAGE), which has played a key role in quantifying global changes in GHG and ODS concentrations since the 1980s [1,3]. In collaboration with AGAGE partners, the Bristol team have developed state-of-the-art measurement techniques for observing hourly changes in GHG and ODS concentrations for more than 50 compounds, many of which exist in the atmosphere at the level of parts per trillion and smaller [1]. The AGAGE measurements underpin our understanding of historical trends in global radiative forcing of climate and stratospheric chlorine loading [3,4], featuring prominently in Intergovernmental Panel on Climate Change Assessment Reports and World Meteorological Organisation Scientific Assessments of Ozone Depletion (Rigby was a lead author in 2018).

Atmospheric modelling and emissions inference:
To infer GHG and ODS emissions from atmospheric concentration measurements, models are required that can simulate the dispersion of a gas from the surface to observation points. A major strength of the Bristol team is that measurement expertise is combined with world-leading modelling methods, capable of estimating GHG and ODS emissions from regional [2,3,5] to global scales [3,4,6], using in situ and satellite-based data. Our regional modelling capability allows emissions to be inferred at national and sub-national scales in regions of the world where atmospheric observations exist at sufficient density, and our global frameworks are capable of evaluating global emissions changes for all major GHGs and ODSs.

3. References to the research

Bold denotes researchers based in Bristol.

[1] **Stanley KM**, **Grant A**, **O'Doherty S**, **Young D**, Manning AJ, **Stavert AR**, Spain TG, Salameh PK, Harth CM, **Simmonds PG**, Sturges WT, Oram DE. and Derwent RG. Greenhouse gas measurements from a UK network of tall towers: technical description and first results, *Atmospheric Measurement Techniques,* 11, 1437–1458, (2018). 10.5194/amt-11-1437-2018

[2] **Say D**, Manning AJ, **O'Doherty S**, **Rigby M**, **Young D**. and **Grant A**. Re-Evaluation of the UK's HFC-134a Emissions Inventory Based on Atmospheric Observations., *Environmental Science & Technology,* 50, 11129–11136, (2016). 10.1021/acs.est.6b03630

[3] **Rigby M,** Park S, Saito T, **Western LM**, Redington AL, Fang X, Henne S, Manning AJ, Prinn RG, Dutton GS, Fraser PJ, **Ganesan AL**, Hall BD, Harth CM, Kim J, Kim K-R, Krummel PB, Lee T, Li S, Liang Q, **Lunt MF**, Montzka SA, Mühle J, **O'Doherty S**, Park M-K, Reimann S, Salameh PK, Simmonds P, **Tunnicliffe RL**, Weiss RF, Yokouchi Y. and **Young D.** Increase in CFC-11 emissions from eastern China based on atmospheric observations, *Nature,* 569, 546–550, (2019). 10.1038/s41586-019-1193-4

[4] **Stanley KM, Say D**, Mühle J, Harth CM, Krummel PB, **Young D, O'Doherty SJ,** Salameh PK, Simmonds PG, Weiss RF, Prinn RG, Fraser PJ. and **Rigby M.** Increase in global emissions of HFC-23 despite near-total expected reductions, *Nature Communications*, 11, 397, (2020). 10.1038/s41467-019-13899-4

[5] **Ganesan AL**, **Rigby M, Lunt MF**, Parker RJ, Boesch H, Goulding N, Umezawa T, Zahn A, Chatterjee A, Prinn RG, Tiwari YK, van der Schoot M. and Krummel PB. (2017) Atmospheric observations show accurate reporting and little growth in India's methane emissions. *Nat. Comm.* 8, 836, (2017). 10.1038/s41467-017-00994-7

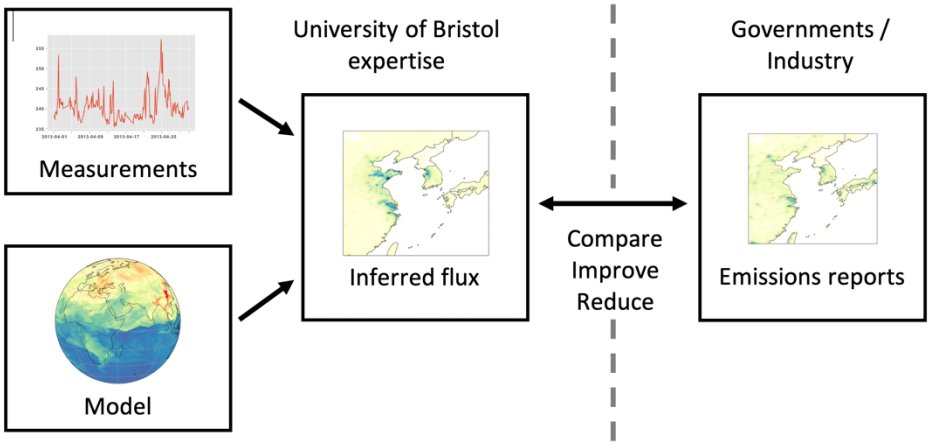
[6] Montzka SA, Dutton GS, Yu P, Ray E, Portmann RW, Daniel JS, Kuijpers L, Hall BD, Mondeel D, Siso C, Nance JD, **Rigby M,** Manning AJ, Hu L, Moore F, Miller BR, Elkins JW. An unexpected and persistent increase in global emissions of ozone-depleting CFC-11, *Nature,* 557, 413–417, (2018). 10.1038/s41586-018-0106-2

4. Details of the impact

We present two instances where research (illustrated below) has led to quantifiable impact:

(I). Evidence for production of an illegal ODS, banned under the Montreal Protocol, resulting in enforcement by Chinese authorities and a change in ODS monitoring policy

(II). Enhancing the UK's global reputation as a lead nation on climate policy by improving the transparency and accuracy of the national GHG emissions inventory



(I). Enforcement of global CFC-11 production ban resulting from atmospheric monitoring

University of Bristol modelling, along with global atmospheric data, identified an increase of around 10,000 tonnes per year in the global emissions of one of the primary substances responsible for ozone depletion, CFC-11 [6]. This study prompted the addition of an agenda item by the EU representative at the 40th Open-ended Working Group (OEWG) of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer (2018), who also cited the work in the discussion, "*The study, entitled 'An unexpected and persistent increase in global emissions of CFC-11'* [6]*, revealed that emissions of CFC-11 had increased in recent years despite the reported elimination of CFC-11 production under the Montreal Protocol*." [a1]. Concerns and actions were passed to the subsequent 30th Meeting of the Parties (MOP) delegates who expressed "*… widespread dismay that CFCs were once again being produced and used despite the efforts of the past 30 years, thereby threatening the reputation and success of the Montreal Protocol, until now widely hailed as the most successful global multilateral environmental agreement"* [b1]. At the 31st MOP in November 2019 [b2], delegates noted that a subsequent Bristol-led paper using global and eastern Asian AGAGE data "*(published in Rigby et al.* [*3*] *…) had determined that 40-60% of these global emission increases had originated in eastern China.*" Until publication of our work, certain parties felt that "*it was troubling that, for at least five years, there had been substantial amounts of unexplained emissions of CFC-11 that were not consistent with actions taken under the Montreal Protocol.*" Calculations presented at the 40th OEWG noted that a sustained future release of CFC-11 of the magnitudes identified in our papers "*would delay… the recovery of the ozone hole by 30 years*." [a1] In addition to their impact on the ozone layer, these unexpected emissions had an influence on climate equivalent to around one fifth of the UK's annual carbon dioxide emissions.

Following our initial publication [6], on-the-ground investigation by media and a non-governmental organisation confirmed that "*factories in China… have ignored a global ban and kept making or using the chemical, CFC-11, mostly to produce foam insulation for refrigerators and buildings*." [c1, d]. Furthermore, at MOP30 [b1], MOP31 [b2], and meetings of the UN Multilateral Fund [e], delegates from China outlined law enforcement activities that had been initiated after our

publications ("*Noting that numerous cases of illegal production facilities had been found in China* [b2]"), resulting in the closure or demolition of several illegal production facilities, the confiscation of some ODS, including CFC-11, and legal proceedings against perpetrators [a2,b1,b2,e]. To ensure that such breaches of the Montreal Protocol are detected and stopped more rapidly in the future, China has taken actions "*including strengthening legislation and building capacity, including through improved access to monitoring equipment, inspections of plants and establishment of a monitoring plan*" [b2].

Preliminary findings presented at the 31st MOP [b2] and subsequently reported in the media [c2] suggest that global and Chinese CFC-11 emissions dropped during 2018 or 2019, implying that enforcement activities initiated following our research have been successful.

(II). Ensuring the UK leads the world in the accuracy of its national GHG emission reports

The UK is one of only four countries in the world to use atmospheric observations to evaluate its National Inventory Report (NIR) to the United Nations Framework Convention on Climate Change (UNFCCC) [f] and was the first to pioneer this approach**.** The Bristol-led DECC network [1] provides extensive atmospheric observations and model interpretation to give robust transparent verification of the UK's national inventory. The UK's Department for Business, Energy and Industrial Strategy (BEIS) states that "*The largest impact of the Bristol-led DECC network is the benefit it provides to the UK's international standing. DECC network staff have… been central to drafting new best practice guidance for inventory compilation... the UK's successful example of bringing together policy makers, inventory compilers and atmospheric scientists will provide further opportunities to lead the world in this field*" [g]. Indeed, the Bristol-led DECC network has been highlighted as an exemplar in the World Meteorological Organisation (WMO) Integrated Global Greenhouse Gas Information System (IG^{3}IS) [h1], and in the International Panel on Climate Change (IPCC) 2019 Refinement to the 2006 Guidelines for National Greenhouse Gas Inventories [h2]. The WMO IG^{3}IS calls for other countries to "*build on the example of 'early mover' countries like UK*" in its implementation plan [h1], which has been adopted by the Subsidiary Body for Scientific and Technological Advice (SBSTA) to the UNFCCC [h3].

Bristol research has led to significant revisions of the UK GHG inventory, which demonstrates the UK's commitment to international "best practise". Our measurements and modelling [2], for example, showed that the UK's "*estimates of the fluorinated gas (F-gas) HFC-134a were ... significantly higher than those from the DECC network*" [g]. Based on this work, the BEIS "GHGI *team and inventory agency at Ricardo Energy and Environment began an in-depth investigation into our F-gas models to find the cause of its mis-estimation of emissions of HFC 134a. They found that the GHGI's assumptions on mobile air conditioning were overly simplistic and conservative*" [g]. In the UK's 2020 NIR, it is noted that "*Revisions to the refrigeration and air conditioning model… have been made, and this comparison is now in better agreement*" with the emissions derived from DECC network data [f]. Such changes enabled by the close links between Bristol-led research and BEIS, which "*have demonstrated world-leading science and fulfilled UNFCCC best practice requirements to continually improve our inventory*" [g].

The example provided by the UK has inspired other countries to adopt similar methodologies. India became the first non-Annex-1 (developing) country to report emissions of the GHG, methane, based on a Bristol-led study utilizing space-based data [5]. In India's Second Biennial Update Report (BUR) [i], it states *"A paper published in Nature Communications (Ganesan et al., 2017)* [5] *investigated India's methane emissions using a top-down approach and concluded that the magnitude of India's methane emissions was consistent with that reported in First BUR."* The

incorporation of this information provides Indian inventory compilers and policy makers with independent information with which to evaluate their emissions, thus improving the accuracy of their submissions. This research demonstrates a methodology that can be applied in the very large number of developing countries that do not have extensive data collection and is noted in the 2019 Refinement to the IPCC's 2006 Guidelines for National Greenhouse Gas Inventories [h2].

5. Sources to corroborate the impact

[a] Minutes of the Open-ended Working Group (OEWG) of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer:
1) Report of the fortieth meeting of the Open-ended Working Group of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer, UNEP/OzL.Pro.WG.1/40/7, Vienna, 11 – 14 Jul 2019, *(par 154 – 184).*
2) Report of the forty-first meeting of the Open-ended Working Group of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer, UNEP/OzL.Pro.WG.1/41/5, Bangkok, 1–5 Jul 2019, *(par 15 – 44).*

[b] Minutes of Meetings of Parties to the Montreal Protocol:
1) Report of the Thirtieth Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer, Quito, 5–9 Nov 2018, *(par 128 – 148).*
2) Report of the Thirty-First Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer, Rome, 4–8 Nov 2019, *(par 33 – 71).*

[c] Media articles:
1) Buckley C. and Fountain H.: In a High-Stakes Environmental Whodunit, Many Clues Point to China, *The New York Times*, 24th June 2018 (Accessed 19 June 2020).
2) Fountain, H.: Banned Ozone-Harming Gas, Once on the Rise, Declines Again, *The New York Times*, 4th November 2019 (Accessed 28 Oct 2020).

[d] Blowing it: Illegal Production and Use of Banned CFC-11 in China's Foam Blowing Industry, Environmental Protection Agency, London, UK, Jul 2018

[e] Addendum: Reports on Projects with Specific Reporting Requirements, Executive Committee of the Multilateral Fund for the Implementation of the Montreal Protocol, United Nations Environment Programme, Eighty-third meeting, UNEP/OzL.Pro/ExCom/83/11/Add.1, Montreal, 27 – 31 May 2019, *(par 51 – 62).*

[f] UK Greenhouse Gas Inventory, 1990 to 2018, Annual Report for Submission under the Framework Convention on Climate Change, Brown et al., Apr 2020

[g] Testimonial letter from the UK Department for Business, Energy and Industrial Strategy, Science Lead, Greenhouse Gas Inventory team

[h] UK DECC network cited as exemplar:
1) An Integrated Global Greenhouse Gas Information System (IG^3IS) Science Implementation Plan, World Meteorological Organisation (WMO), GAW report no. 245, De Cola, et al., 2018, *(cites [2,5]).*
2) 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 1, General Guidance and Reporting, Chapter 6: Quality Assurance/Quality Control and Verification, Maksuytov and Eggleston, et al., 2019, *(cites [5,6]).*
3) Report of the Subsidiary Body for Scientific and Technological Advice (SBSTA) on its forty-seventh session, Bonn, 6 - 15 Nov 2017, *(par 59 and associated footnote).*

[i] India: Second Biennial Update Report to the United Nations Framework Convention on Climate Change, Ministry of Environment, Forest and Climate Change, Government of India. ISBN: 978-81-938531-2-2, 2018, *(cites [5]).*