Institution: University of Bristol

Unit of Assessment: Chemistry UoA 8

Title of case study: CH1: Bristol Research Influences Global Response to Ozone-Depleting and Greenhouse Gases.

1. Summary of the impact (indicative maximum 100 words)

Successful policy formulation and effective action on ozone depletion and climate change, both of which have profound environmental implications, depend on the availability of credible data on atmospheric gases. Research conducted in the School of Chemistry at the University of Bristol between 1992 and 2013 has played a leading role in global efforts to achieve reliable, long-term measurement of climatically important gases such as CO_2, CH_4 and N_2O. When combined with models of atmospheric gas transport, these observations provide an independent means of assessing natural and man-made emissions. This work is used by the UK's Department of Energy and Climate Change (DECC) for monitoring compliance with international and domestic legislation, identifying priorities for improving inventory accuracy, assessing the UK's progress towards targets set in the Montreal and Kyoto Protocols, evaluating the impact of policy, and informing international negotiations. These data have been central to recent World Meteorological Office (WMO) Scientific Assessments of Ozone Depletion produced between 2007 and 2010 and to the Nobel Prize-winning Inter Governmental Panel on Climate Change (IPCC) Assessment of Climate Change published in 2007.

2. Underpinning research (indicative maximum 500 words)

The work carried out at the University of Bristol's **Atmospheric Chemistry Research Group** (ACRG) furthers understanding of emissions of climatically important gases at both regional and global scales. Globally, the analysis of long-term measurements of key radiatively and chemically active gases in the atmosphere generates insights into the role of these gases in global climate change and ozone depletion in the stratosphere. The observatories making these long-term (1987-present), high-frequency measurements are part of an internationally recognised global network of 10 observing stations called the **Advanced Global Atmospheric Gases Experiment** (AGAGE). **O'Doherty**, Professor of Atmospheric Chemistry, and head of the ACRG measurement group is a Co-Investigator of the AGAGE programme and lead scientist in charge of two of the AGAGE stations, Mace Head in Ireland and Ragged Point in Barbados. Since joining the network in 1991, **O'Doherty** has pioneered novel analytical techniques that now make AGAGE the only global network capable of measuring the full suite of substances regulated under the Montreal and Kyoto Protocols. Funded through a NERC Advanced Fellowship, **Rigby** (also in the ACRG) is developing methods for understanding global greenhouse gas emissions using AGAGE observations and chemical transport models.

The scientific highlights of Bristol's involvement with AGAGE, which are important in furthering our understanding of changes in global atmospheric composition, are summarised below, with links to the scientific outputs listed in Section 3 in brackets:

1. The determination, from atmospheric observations, of global and regional rates of emission and destruction of natural and anthropogenic compounds that contribute to climate change and stratospheric ozone depletion (**1-6**).
2. Improved accuracy in our understanding of the global distributions and temporal behaviours of natural and anthropogenic gases in the global atmosphere (**1-3,5**).
3. The identification and accurate measurement of new greenhouse gases and ozone-depleting substances in the global atmosphere (*eg* the recently discovered SO_2F_2, and high accuracy measurement of NF_3, C_4F_{10}, C_5F_{12}, C_6F_{14}, C_7F_{16} and C_8F_{18}) (**1,5**).
4. Quantification of the oxidising capacity of the troposphere (**5**).

The information derived from observational networks such as AGAGE has resulted in regulation of

the production and use of ozone-depleting substances (ODSs) under the Montreal Protocol. The rate of recovery of the ozone layer will depend critically on the rate of decrease of ODSs, which will be measured and interpreted by the AGAGE global network.

To support global climate legislation, it has been recognised that we must develop the capability to monitor greenhouse gas (GHG) emissions at national scales. The School of Chemistry at Bristol, in collaboration with the Met Office, is at the very forefront of this effort. The UK DECC Network, led by **O'Doherty** and funded by DECC, is a unique national GHG monitoring system, comprising four stations (with two more being added in 2013) making high-frequency measurements of key atmospheric trace gases. Since 2010, GHGs have been measured at tall-tower sampling sites at Tacolneston (Norfolk, UK), Angus (Dundee, Scotland) and Ridge Hill (Hereford, UK), complementing the long-term record from Mace Head in Ireland. Analysis and interpretation of these observations using state-of-the-art "inverse" modelling techniques enables the independent assessment of the UK's adherence to the Montreal Protocol as implemented by the Environmental Protection (Controls on Ozone-Depleting Substances) Regulations (2011). Furthermore, it improves emissions estimation to UK Devolved Administration (DA) level and provides verification of the UK GHG emission inventories submitted annually to the United Nations Framework Convention on Climate Change (UNFCCC) under the Kyoto Protocol.

3. References to the research (indicative maximum of six references)

Publications

(1) Global and regional emissions of HFC-125 (CHF_2CF_3) from in situ and air archive atmospheric observations at AGAGE and SOGE observatories, S. O'Doherty, D. M. Cunnold, B. R. Miller, J. Mühle, A. McCulloch, P.G. Simmonds, A. J. Manning, S. Reimann, M. K. Vollmer, B. R. Greally, R. G. Prinn, P. J. Fraser, L. P. Steele, P. B. Krummel, B. L., Dunse, L. W. Porter, C. R. Lunder, N. Schmidbauer, O. Hermansen, P. K. Salameh, C. M. Harth, R. H. J. Wang and R. F. Weiss, *J. Geophys. Res.*, 2009, **114**, D23304, DOI: 10.1029/2009JD012184.

(2) A new analytical inversion method for determining regional and global emissions of greenhouse gases: sensitivity studies and application to halocarbons, A. Stohl, P. Seibert, J. Arduini, S. Eckhardt, P. Fraser, B. R. Greally, M. Maione, S. O'Doherty, R. G. Prinn, S. Reimann, T. Saito, N. Schmidbauer, P. G. Simmonds, M. K. Vollmer, R. F. Weiss, and Y. Yokouchi, *Atmos. Chem. Phys.,* 2009, **9**, 1597-1620, DOI: 10.5194/acp-9-1597-2009.*

(3) A 15 year record of high-frequency, in situ measurements of hydrogen at Mace Head, Ireland, A. Grant, C. S. Witham, P. G. Simmonds, A. J. Manning, and S. O'Doherty, *Atmos. Chem. Phys.,* 2010, **10**, 1203-1214, DOI: 10.5194/acp-10-1203-2010.

(4) Inverse modelling of European CH_4 emissions 2001-2006, P. Bergamaschi, M. Krol, J. F. Meirink, F. Dentener, A. Segers, J. van Aardenne, S. Monni, A. T. Vermeulen, M. Schmidt, M. Ramonet, C. Yver, F. Meinhardt, E. G. Nisbet, R. E. Fisher, S. O'Doherty, and E. J. Dlugokencky, *J. Geophys. Res*., 2010, **115**, D22309, DOI: 10.1029/2010JD014180.

(5) Ozone Depleting Substances (ODSs) and Related Chemicals, Chapter 1 in Scientific Assessment of Ozone Depletion: 2010, S. A Montzka and S. Reimann (Coordinating Lead Authors), A. Engel, K. Kruger, S. O'Doherty, W.T. Sturges, *Global Ozone Research and Monitoring Project-Report*, 2011, No.**52**, 516, World Meteorological Organization, Geneva, Switzerland. (http://www.wmo.int/pages/prog/arep/gaw/ozone_2010/documents/chapter1.pdf).*

(6) Estimating UK methane and nitrous oxide emissions from 1990 to 2007 using an inversion modelling approach, A. Manning, S. O'Doherty, A. R. Jones, P. G. Simmonds and R. G. Derwent, *J. Geophys. Res.*, 2011, **116**, D0230, DOI: 10.1029/2010JD014763.*

Grants

2013-2017 Natural Environmental Research Council (NERC), Greenhouse gAs Uk and Global Emissions (GAUGE), **£974,180** (of £3m consortium proposal); Co-I O'Doherty.

2012-2017 Towards treaty verification for non-CO_2 greenhouse gases, NERC Advanced Research Fellowship, **£460,196**; PI is Rigby.

2011-2015 EU, InGOS, **€518,225**; PI is O'Doherty.

2011-2014	Department of Energy and Climate Change (DECC), Extension of Long-Term Atmospheric Measurements of Trace Gases, **£1,901,000**; PI is O'Doherty.
2011-2016	National Space and Atmospheric Administration (NASA), AGAGE Collaborative Project, **$712,049**; PI is O'Doherty.
2010-2011	Department of Energy and Climate Change (DECC), Extension of Long-Term Atmospheric Measurements of Trace Gases, **£230,000**; PI is O'Doherty.
2009-2014	National Oceanic and Atmospheric Administration (NOAA), AGAGE Measurements in Barbados, **$325,666**; PI is O'Doherty.
2008-2011	Irish EPA, Measurement of Trace Gases at Carnsore Point, **€564,860**; PI is O'Doherty.
2007-2010	Department of Energy and Climate Change (DECC), Measurements at Mace Head, **£623,244**; PI is O'Doherty.
2006-2009	EU, Eurohydros, **€124,000**; PI is O'Doherty.
2005-2008	NERC; Surface Ocean – Layer Atmosphere Study (SOLAS), **£165,395**; PI is O'Doherty.
2005-2007	Defra, Advanced Global Atmospheric Gases Experiment (AGAGE), **£282,469**; Principal Scientist is O'Doherty.
2005-2009	Marie Curie Action, Early Stage Training, BREATHE, **€1,064,360**; Co-PI is O'Doherty.
2003-2007	National Aeronautics and Space Administration (NASA), Advanced Global Atmospheric Gases Experiment (AGAGE), **$490,551**; Principal Scientist is O'Doherty.

4. Details of the impact (indicative maximum 750 words)

Monitoring of atmospheric concentrations of gases is important in assessing the impact of international policies related to the atmospheric environment and sources (Section 5) are indicated in brackets. The work carried out at Bristol provides, for the first time, an independent scientific verification of UK emissions (**a**) submitted by Parties to the Convention reporting under the UNFCCC and its Kyoto Protocol**.** A verification section written by **O'Doherty** is included in the UNFCCC documentation (**b**). The UK, Australia and Switzerland are the only countries to provide such verification. This type of research was identified as an area of importance at the UNFCCC, Conference of the Parties (COP15), the Copenhagen Accord, where parties were urged to "*ensure sustained long-term operation of essential in situ networks through provision of necessary resources*".

Long-term monitoring of this kind is similarly important in assessing the impact of international policies related to control measures on chlorofluorocarbons (CFCs), halons and hydrochlorofluorocarbons (HCFCs) introduced under the Montreal Protocol of Substances that Deplete the Ozone Layer. The effect of worldwide CFC controls can be seen by decreases in the long-term concentrations. Continued monitoring is required to assess the overall success of the Protocol leading to the recovery of the ozone layer, and the implications for atmospheric levels of replacement compounds such as HFCs (**c**).

The UK and international GHG reduction commitments, of which the Bristol-led measurements provide independent verification, translate into sector and company level obligations which impact across all regions of the UK. For example, there are a number of GHG reporting schemes applicable to businesses operating in the UK, such as the EU Emissions Trading System and the CRC Energy Efficiency Scheme (**a**).

The atmospheric observations have helped DECC prioritise research to improve the GHG inventory. For example, emissions derived from measurements of N_2O have resulted in a large research programme in Defra to better understand agricultural emissions that result from the application of man-made fertilizers. This gas is a potent GHG, with the fourth largest climate effect after CO_2, CH_4 and CFC-12 (**d**).

The information derived from this research will continue to inform governments responsible for formulating policies on climate change mitigation and adaption. In addition, a much wider range of

organisations that are responsible for planning climate-sensitive activities and investments will benefit. For example, NERC recently funded an £8.1m programme, "Greenhouse gas emissions and feedbacks" (**O'Doherty** and **Rigby** are co-investigators of this multi-University consortium), to increase the UK's ability to measure and predict sources and sinks of the major anthropogenic greenhouse gases. The DECC Network forms a central part of this national consortium (**e**).

Identification by AGAGE, of new ozone-depleting or global-warming substances of potential policy interest have been provided to DECC/Defra. For example, the analysis of unregulated compound NF_3 (a powerful GHG showing a steady growth in the atmosphere) was used by DECC as an evidence base for international negotiations. NF_3 was subsequently included in the list of possible new Kyoto Protocol gases due to its rapidly rising concentration and high global-warming potential.

The Mace Head measurements have been used in a large number of publications. This is widely regarded as the 'Gold Standard' dataset of European measurements. As such, it has been central to many European Union projects on verification of GHG emissions, such as CarboEurope, NitroEurope, Geomon, Eurohydros, ICOS, ACTRIS and InGOS. The work detailed in this document continues to play a key role in the WMO Assessments of Ozone Depletion for which **O'Doherty** served as a lead author in the 2010 report and **O'Doherty** and **Rigby** will serve as contributing authors in 2014. The University of Bristol also plays a key role in IPCC Assessment Reports with **O'Doherty** being a contributor to the 2007 report Working Group 1, Chapter 2 and **Rigby** being a contributor to the 2013 report. Of the first nine figures and tables in Chapter 2 of the 2007 report, seven showed, or were in part based on, AGAGE data (**f**).

The Bristol researchers are continuing to communicate the importance of global and regional GHG emissions verification to policymakers at the highest level. The work of **O'Doherty** and the ACRG featured prominently in a recent Parliamentary Office of Science and Technology POSTNote, to be read by members of parliament, entitled "Reporting Greenhouse Gas Emissions" (**g**).

5. Sources to corroborate the impact (indicative maximum of 10 references)

(a) Annual and final reports written for DECC are made public and can be accessed from the DECC website (https://www.gov.uk/government/publications/uk-greenhouse-gas-emissions-monitoring-and-verification/) and also Met Office website (http://www.metoffice.gov.uk/atmospheric-trends/). (Champion)

(b) UNFCCC UK National Inventory Submission (NIR), Section 1.6.2 and Annex 10. (http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/6598.php). (Champion)

(c) Data from the AGAGE network are available at the Carbon Dioxide Information Analysis Center (CDIAC); this is the primary climate-change data and analysis centre of the US Department of Energy (http://cdiac.ornl.gov/). Data are also made available to the World Data Centre for Greenhouse Gases; this is a WDC under the GAW programme (http://ds.data.jma.go.jp/gmd/wdcgg/). (Prinn and Weiss)

(d) DECC's Earth Observation strategy: (http://www.gov.uk/government/publications/earth-observation-strategy). (Champion)

(e) Greenhouse gases UK project website (http://www.greenhouse-gases.org.uk). (Prinn, Champion)

(f) Data from AGAGE is included in World Meteorological Organisation (WMO) Scientific Assessment of Ozone Depletion and Intergovernmental Panel on Climate Change (IPCC) assessments; these documents can be accessed from the following websites: (http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml) (http://www.wmo.int/pages/prog/arep/gaw/ozone_2010/ozone_asst_report.html). (Reimann, Prinn)

(g) The work at Mace Head has been selected by the Parliamentary Office of Science and Technology for inclusion in POSTNOTE No. 420, Jan. 2013 "Reporting GHG Emissions" (http://www.parliament.uk/briefing-papers/POST-PN-428). (Champion)

(h) Statements about the importance of the funded work can be obtained from different agencies: DECC ((Champion), NASA (Prinn and Weiss), NOAA (Butler).