Institution: University of East Anglia		
Unit of Assessment: 7 – Earth Systems and Environmental Sciences		
Title of case study: Protecting the Ozone Layer and Climate - Halocarbon Research Underpins the Montreal Protocol		
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:**
Claire Reeves	Professor of Atmospheric Science	1991 to 2020
David Oram	Research Fellow	1987 to present
Bill Sturges	Professor of Atmospheric Chemistry	1993 to present
Johannes Laube	NERC & ERC Fellow, Independent Research Fellow	2008-2018
Stuart Penkett	Professor	1985-2005
Period when the claimed impact occurred: 1 August 2013 to 31 December 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Our research has formed a vital part of the science that has driven policy- and decision-making within the Montreal Protocol on '*Substances that Deplete the Ozone Layer*', an international agreement adopted by all countries (Parties) that is arguably the most successful environmental agreement ever. Our research has contributed to United Nations sponsored quadrennial Assessments that regularly update the Parties of the latest scientific evidence. These Assessments have shaped the Adjustments and Amendments to the Protocol. They have led to reductions in emissions of many halocarbons, preventing catastrophic destruction of global ozone (otherwise projected to be 17% by 2020 and 67% by 2065) and consequently avoiding major worldwide impacts on climate, human health and ecosystems. Our research has specifically alerted the Parties to the presence, and increasing concentrations, of halogenated compounds in the atmosphere, provided evidence of potential non-compliance, and underpinned the 2016 Kigali Amendment, which is designed to avoid 0.5°C of global warming by 2100.

2. Underpinning research

Our School of Environmental Sciences is internationally renowned for measuring the abundance, and quantifying the sources, of atmospheric chlorine-, bromine- and fluorine-containing (halocarbon) trace gases. In line with the Montreal Protocol, we initially focused our research on ozone-depleting substances including chlorofluorocarbons (CFCs), halons and methyl bromide. As the use of these was phased out, 'replacement' compounds were introduced (hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs)) and we pivoted our attention towards these and other highly potent greenhouse gases (i.e., fully fluorinated compounds).

Our work makes use of a highly-sensitive laboratory-based mass spectrometer which has enabled us to be the first to detect many of these compounds in the atmosphere and also to be able to separate specific isomers (in contrast to other researchers who are constrained to reporting the sum of the isomers): HFC-227ea **[R1]**, CFC-112, CFC-112a, CFC-113a and HCFC-133a **[R2]**, as well as CFC-114, CFC-114a, CFC-216ba, CFC-216ca, HCFC-225ca, HFC-23, HFC-125, HFC-143a, HFC-152a, Halon-1202, SF_5CF_3, C_2F_6, c-C_4F_8, n-C_4F_{10}, n-C_5F_{12}, n-C_6F_{14}, n-C_7F_{16} and i-C_6F_{14}. We have also measured the chlorine and carbon isotopes of some halocarbons to probe their sources and sinks.

By examining long-term records, we have assessed the impact of human activities on the burden of these gases in the atmosphere. We collaborate with the Commonwealth Scientific and Industrial Research Organisation in Australia to analyse the Cape Grim (Tasmania) Air Archive which dates from 1978 **[**e.g. **R2**; **R4]**, and have extended this record backwards in time via measurements in deep polar snow (firn) **[**e.g. **R1**; **R2]** and ice, in part through UEA-led EU-funded projects. Coupled to this observational work is a modelling capability from which we have determined 'top-down' global emission estimates (i.e. constrained by atmospheric observations) for comparison with other emission estimates (including 'bottom-up' industrial estimates) **[**e.g. **R1**; **R2]**.

Our measurements from balloons, research aircraft and commercial aircraft have allowed us to assess concentration trends of halocarbons in the upper troposphere and stratosphere. These have made it possible to determine the important, but poorly known, contribution of the mostly unregulated halogenated 'very short-lived substances' (VSLS) to the stratospheric bromine and chlorine burden, to track changes in global circulation and to derive atmospheric lifetimes **[**e.g. **R1**; **R3**; **R4**; **R5]**. The latter are fundamental to the calculation of metrics used by policymakers such as ozone depletion potentials and global warming potentials.

Our research has identified southern and eastern Asia to be important sources of many of the halocarbons **[**e.g. **R6]**, including VSLS **[**e.g. **R3**; **R7]** and, critically, this is a region where these short-lived gases can be rapidly transported to the stratosphere and so impact stratospheric ozone.

Our research has been supported by sustained funding through active grants totalling over GBP2,000,000 during the current REF period (2014-2020), supplementing other funding during 2000-2013. The research has resulted in 65 papers in international peer-reviewed journals (2000-2020).

3. References to the research

<u>Underpinning research</u>: The underpinning research outputs have all been published in competitive, international, peer-reviewed journals and form part of a larger body of such published work. [Citations from Google Scholar]. **UEA authors** in bold

[R1] **'**Accelerating growth of HFC-227ea (1,1,1,2,3,3,3-Heptafluoropropane) in the atmosphere' **Laube, J.C.**, Martinerie, P., Witrant, E., Blunier, T., Schwander, J., Brenninkmeijer, C. A. M., Schuck, T. J., Bolder, M., Röckmann, T., van der Veen, C., Bönisch, H., Engel, A., **Mills, G. P.**, **Newland, M. J., Oram, D. E.**, **Reeves, C. E.** and **Sturges, W. T. (2010).** *Atmospheric Chemistry and Physics*, 10(13), 5903-5910. DOI: 10.5194/acp-10-5903-2010 [47 citations]

[R2] 'Newly detected ozone-depleting substances in the atmosphere' **Laube, J.C.**, **Newland, M.J.**, **Hogan, C.**, Brenninkmeijer, C.A.M., Fraser, P.J., Martinerie, P., **Oram, D.E.**, **Reeves, C.E.**, Rockmann, T., Schwander, J., Witrant, E. and **Sturges, W.T. (2014)** *Nature Geoscience,* 7, 266-269. DOI: 10.1038/NGEO2109 [78 citations]

[R3] 'Increasing concentrations of dichloromethane, CH_2Cl_2, inferred from CARIBIC air samples collected 1998–2012' Leedham-Elvidge, E.C., **Oram, D.E.**, **Laube, J.C.**, Baker, A.K., Montzka, S.A., **Humphrey, S.**, **O'Sullivan, D.A.**, and Brenninkmeijer, C.A.M. **(2015).** *Atmospheric Chemistry and Physics*, 15(4), 1939-1958. DOI: 10.5194/acp-15-1939-2015 [47 citations]

[R4] **'**Evaluation of stratospheric age-of-air from CF_4, C_2F_6, C_3F_8, CHF_3, HFC-125, HFC-227ea and SF_6; implications for the calculations of halocarbon lifetimes, fractional release factors and ozone depletion potentials' **Leedham Elvidge**, **E**., Bönisch, H., Brenninkmeijer, C.A.M., Engel, A., Fraser, P.J., **Gallacher, E.,** Langenfelds, R., Mühle, J., **Oram, D.E.**, Ray, E.A., **Ridley, A.R**., Röckmann, T**., Sturges, W.T.**, Weiss, R.F., and **Laube, J.C. (2018).** *Atmospheric Chemistry and Physics*, 18(5), 3369-3385. DOI: 10.5194/acp-18-3369-2018 [18 citations]

[R5] **'**Investigating stratospheric changes between 2009 and 2018 with aircraft, AirCores, a global model and a focus on CFC-11' **Laube, J.C.**, **Leedham Elvidge, E.C.**, **Adcock, K.E.**, Baier, B., Brenninkmeijer, C.A.M., Chen, H., **Droste, E.**, Grooß, J.-U., Heikkinen, P., **Hind, A.J.**, Kivi, R., Lojko, A**.**, Montzka, S. A., **Oram, D.E.**, Randall, S., Röckmann, T., **Sturges, W.T.**, Sweeney, C., **Thomas, M.**, **Tuffnell, E.**, and Ploeger, F. **(2020)**. *Atmospheric Chemistry and Physics,* 20(16), 9771-9782. DOI: 10.5194/acp-20-9771-2020 [3 citations]

[R6] **'**Investigation of East Asian emissions of CFC-11 using atmospheric observations in Taiwan'

Adcock, K.E., Ashfold, M.J., Chou, C.C.-K., **Gooch, L.J.**, **Hanif, N.M.**, **Laube, J.C.**, **Oram, D.E.**, Ou-Yang, C.-F., Panagi, M., **Sturges, W.T.** and **Reeves, C.E. (2020).** *Environmental Science and Technology*, 54(7), 3814-3822. DOI: 10.1021/acs.est.9b06433 [5 citations]

[R7] **'**A growing threat to the ozone layer from short-lived anthropogenic chlorocarbons' **Oram, D.E.**, Ashfold, M.J., **Laube, J.C.**, **Gooch, L.J.**, **Humphrey, S.**, **Sturges, W.T.**, **Leedham-Elvidge, E.**, **Forster, G.L.**, Harris, N.R.P., Mead, M.I., Samah, A.A., Phang, S.M., Ou-Yang, C.-F., Lin, N.-H., Wang, J.-L., Baker, A.K., Brenninkmeijer, C.A.M., and Sherry, D. **(2017).** *Atmospheric Chemistry and Physics*, 17(19), 11929-11941. DOI: 10.5194/acp-17-11929-2017 [56 citations]

4. Details of the impact

Impacts on Ozone Depletion and Global Warming

Through emission controls of halocarbons, the Montreal Protocol on *'Substances that Deplete the Ozone Layer'* has been hugely successful in avoiding further ozone depletion and has thus protected the global population and ecosystems from increased UV radiation and climate change. The Montreal Protocol is an international agreement adopted in 1987. Its success has depended upon continued assessment of its effectiveness and of compliance. These assessments are provided by UN Expert Panels (e.g. the Scientific Assessment Panel (SAP) and the Technology and Economic Assessment Panel (TEAP)), based on which the Protocol has been revised through Adjustments and Amendments. The Protocol is governed via annual Meetings of the Parties informed by the Open-Ended Working Group, Assessments and the Expert Panels.

Our research is part of an international body of science that has shaped and stimulated global policy- and decision-making through these Assessments and Panels. The 2014 and 2018 SAP Assessments **[S1**; **S2]** cited 20 and 29 of our papers published since 2000, respectively. Moreover, we were on the Expert Panels which produced these Assessments, either as Authors or Reviewers (**Laube, Penkett** and **Sturges** in 2014 and **Laube, Sturges, Oram** and **Reeves** in 2018). In both Assessments, our data were also included in updates of atmospheric halocarbon abundances. A testimonial to our involvement in this process is provided by the Co-Chair of the SAP and NASA's Chief Scientist for Atmospheres **[S3]**, who states,

"… UEA research on atmospheric halocarbons has formed a significant part of the science underpinning the Scientific Ozone Depletion Assessments. … These assessments are an integral part of the Montreal Protocol process and consequently UEA has made an extremely valuable contribution to what is arguably the most successful environmental agreement ever created. Research that I led (Newman et al, 2009, https://doi.org/10.5194/acp-9-2113-2009) demonstrated that if production of ozone depleting substances had not been regulated by the Montreal Protocol and its Amendments but instead been allowed to grow at 3% per year, 17% of the globally-averaged column ozone would have been destroyed by 2020 increasing to 67% by 2065. The summer UV index in northern mid-latitudes would also have increased from a baseline of 10 to more than 12 in 2020 and up to 30 in 2065, reducing the perceptible sunburn time from approximately 15 to 5 minutes. The Montreal Protocol saved the Earth from an existential threat."

We provide four examples, where the governance of the Montreal Protocol, including a major Amendment, can be linked to our specific research.

1) Inclusion of HFCs in the Montreal Protocol:

HFCs are "ozone-friendly" CFC replacements but are strong greenhouse gases. In the late 1990s we were the first to show the emergence, and rapidly rising abundance, of HFCs in the atmosphere (specifically HFC-134a and HFC-23). In 2005, in response to a request from the United Nations Framework Convention on Climate Change (UNFCCC) and the Parties to the Montreal Protocol, a Special Report *"Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons"* **[S4]** was produced jointly by TEAP and the Intergovernmental Panel on Climate Change (IPCC). This included our updated data on HFC-134a and HFC-23 along with new data on HFC-125. This report was then cited in the 2006 SAP Assessment and IPCC 2007 Report. In 2010 we published a paper showing the existence of another HFC (227ea) in the atmosphere and its rising abundance **[R1]**. This paper was cited in the 2010 and 2014 **[S1]** SAP Assessments.

Having been informed of the threat of HFCs through these reports, the Parties subsequently adopted the Kigali Amendment to the Montreal Protocol in 2016 that aims to reduce the use of HFCs by 80% over the next 30 years. This Amendment is designed to avoid 0.5°C of global warming by 2100, which is substantial in the context of the 2015 UNFCCC Paris Agreement that aims to limit global temperature rise to well below 2.0°C above pre-industrial levels, and to pursue efforts to limit the increase to 1.5°C.

We have continued to update the Parties on this issue via the latest 2018 SAP Assessment **[S2]** which cited our most recent paper on HFCs **[R4]**. The letter from the SAP Co-chair states,

"This [Kigali Amendment] *is a major policy change as it aims to reduce HFC usage, not to protect the ozone layer, but rather to avoid 0.5°C of global warming by 2100, because many HFCs are powerful greenhouse gases. UEA research underpinned this Amendment as it first alerted the world to the presence of these substances in the atmosphere and has continued to track their growth in abundance, identify new HFCs in the atmosphere and determine their atmospheric budgets."* **[S3]**.

2) Evidencing sources of non-compliant emissions of CFC-11:

In July 2018, Dr. Stephen Montzka (NOAA) published a paper that suggested unreported new production of CFC-11, which was inconsistent with the Montreal Protocol agreement to completely phase out global CFC production by 2010. The Open-Ended Working Group requested the SAP provide a report on this issue and to this end an International Symposium on the *Unexpected Increase in Emissions of Ozone-Depleting CFC-11* was held in March 2019. At this symposium we presented our research which highlighted substantial emissions of CFC-11 from China **[**subsequently published in **R6]** and demonstrated that measurements of other ozone depleting substances related to CFC-11 production did not have comparable trends **[**subsequently published in **R5]**.

The report from this symposium **[S5]**, citing our results, was presented at the meeting of the 41st Open-Ended Working Group in July 2019 and was a background document for the 31st Meeting of the Parties in November 2019. It was subsequently referred to in the published Decisions of this meeting under "*Decision XXXI/3: Unexpected emissions of CFC-11 and institutional processes to be enhanced to strengthen the effective implementation and enforcement of the Montreal Protocol"* **[S6]**.

The testimonial from the SAP Co-chair states, *"UEA research contributed to the international effort to address the urgent need to identify the source of the unexpected emissions of CFC-11, in particular by estimating emissions from China. This research is driving new decisions by the Parties for strengthening ODS* [ozone depleting substances] *tracking, and implementation and enforcement policies of the Protocol."* **[S3]**.

3) Informing the Parties of the source of increased concentrations of dichloromethane:

In 2017, the 39th Open-Ended Working Group expressed concern regarding the potential significant negative impact of dichloromethane on ozone recovery and in particular where the associated emissions were coming from **[S7]**. In response, an update on this science was provided in the 2018 SAP Assessment **[S2]** which was presented to the 30th Meeting of the Parties (November 2018). The Executive Summary contains the following *"Dichloromethane (CH_2Cl_2) is the main component of VSLS chlorine and accounts for the majority of the rise in total chlorine from VSLSs between 2012 and 2016. A substantial fraction of the global CH_2Cl_2 emissions has been attributed to southern and eastern Asia."* In the main body of the report this latter statement was substantiated solely by reference to our research **[R7**; **R3]**.

The SAP Co-chair states, *"In 2017, a particular concern to the Parties was the potentially large negative impact on stratospheric ozone of dichloromethane (CH_2Cl_2), a short-lived (180 days) anthropogenically chlorinated gas that is not controlled under the Protocol. The spatial distribution of dichloromethane emissions are critical to its impact on stratospheric ozone. … Based on UEA* *research, the Parties were informed, through the 2018 Assessment, of a significant dichloromethane source region in Asia."* **[S3]**.

4) Alerting the Parties to the presence of newly detected ozone-depleting substances in the atmosphere:

Given our unique instrumental capabilities we have been able to alert the Parties to the presence of newly detected halogenated compounds in the atmosphere, their concentrations, and rates of emissions **[**e.g. **R1**; **R2]**. Our discovery of 3 CFCs and 1 HCFC in the atmosphere **[R2]** was specifically discussed at the 34th Open-Ended Working Group in July 2014 **[S8]**. Moreover, all concentration data for Halon-1202 and the separate CFC isomers 112, 112a, 113, 113a, 114, 114a, 216ba and 216ca, along with the emission estimates for the CFC isomers 112, 112a and 113a reported in the 2018 SAP Assessment are based on our measurements alone.

The SAP Co-chair states, *"UEA has the unique capability to measure concentrations of atmospheric halocarbons that cannot be monitored using the major NOAA and NASA measurement networks. This has enabled early detection of potential new threats to the recovery of the ozone layer. Moreover, it allows the determination of emissions of separate isomers, which often follow quite different trends."* **[S3]**.

As summarised by the SAP Co-chair "***UEA's research therefore makes a distinctive contribution to the Assessments and to international policy on ozone depleting substances and greenhouse gases.***" **[S3]**.

5. Sources to corroborate the impact

[S1] WMO (World Meteorological Organisation), *Scientific Assessment of Ozone Depletion:* 2014, co-chairs A-L. N. Ajavon, P.A. Newman, J.A. Pyle, A.R. Ravishankara, *Global Ozone Research and Monitoring Project Report No. 55*, WMO, Switzerland, Geneva, 2015. Accessed on 20.01.2021

[S2] WMO (World Meteorological Organisation), Scientific Assessment of Ozone Depletion: 2018, co-chairs D.W. Fahey, P.A. Newman, J.A. Pyle, B, Safari, Global Ozone Research and Monitoring Project Report No. 58, WMO, Switzerland, Geneva, 2019. Accessed on 20.01.2021

[S3] Testimonial from Chief Scientist for Earth Sciences Division, NASA Goddard Space Flight Center and Co-Chair of the Scientific Assessment Panel for the Montreal Protocol Ozone Secretariat, United Nations Environmental Programme, 14.12.2021.

[S4] IPCC/TEAP Special Report on Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons. Prepared by the Working Group I and III of the IPCC, and the TEAP [Metz, B., L. Kuijpers, S. Solomon, S.O. Andersen, O. Davidson, J. Pons, D. de Jager, T. Kestin, M. Manning, and L.A. Meyers (eds.)] Cambridge University Press, 2015. Accessed on 20.01.2021

[S5] The final report from the International Symposium on the Unexpected Increase in Emissions of Ozone-Depleting CFC-11 was held in March 2019. Accessed on 20.01.2021

[S6] Decisions adopted by the Thirty-First Meeting of the Parties to the Montreal Protocol. Accessed on 20.01.2021

[S7] Report of the 39th Open-Ended Working Group in July 2017. Accessed on 20.01.2021.

[S8] Report of the 34th Open-Ended Working Group in July 2014. Accessed on 20.01.2021.