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| **Institution:** University of Cambridge | | |
| **Unit of Assessment:** 8 | | |
| **Title of case study:** Supporting, contributing to and validating the Montreal Protocol | | |
| **Period when the underpinning research was undertaken:** 01/01/2000 - present | | |
| **Details of staff conducting the underpinning research from the submitting unit:** | | |
| **Name(s):** Professor John Pyle | **Role(s) (e.g. job title):** Professor and Director of Research | **Period(s) employed by submitting HEI:** 1/10/1985-present |
| **Period when the claimed impact occurred:** 01/08/2013-31/07/2020 | | |
| **Is this case study continued from a case study submitted in 2014?** Y | | |

## 1. Summary of the impact

Atmospheric science research in the Department of Chemistry, University of Cambridge has played a leading role in demonstrating the depletion of the ozone layer following anthropogenic emissions of halogenated compounds and other Ozone Depleting Substances (ODS). This research has been a key input into the series of assessment reports that have made the case to policy makers for strengthening the phase-out schedules for these compounds under the Montreal Protocol. The research underpinning these reports has made a vital contribution to a number of changes to the Protocol that have ensured a more rapid phase-out of a wider range of ODS and their replacements, leading to significant global health and climate benefits during the REF period. Researchers at Cambridge have helped to raise global awareness of these benefits, helping to maintain support for the Protocol among policy makers, and supporting the development of legislation to limit the environmental impact of ODS and their replacements.

## 2. Underpinning research

Professor John Pyle was a founder and co-director of the Centre for Atmospheric Science, an interdisciplinary research centre involving scientists from the Departments of Chemistry, Applied Mathematics and Theoretical Physics and Geography, and subsequently of Cambridge Centre for Climate Science at the University of Cambridge. Pyle has made a world-leading contribution to the work of these centres. His major contribution has been the development of integrated chemistry–climate numerical models for the stratosphere, which have been successfully evaluated against atmospheric observations. These include the UM_UKCA model developed in collaboration with the Met Office, which is now established as a gold standard in climate prediction. This model is widely used internationally and is a key component of the UK Earth System Model (UKESM1).[R1,R2] UM_UKCA and its predecessors have been used to explain the role of ozone depleting substances (ODS) in past changes in atmospheric composition and to make projections about future changes. Since 2000, Pyle and his colleagues in the Centre for Atmospheric Science have published over 60 original scientific papers that have greatly increased our understanding of the extent and causes of ozone depletion in the stratosphere, the factors that determine the rate of recovery of the ozone layer, the relationship between climate and chemical reactions of ODS with ozone, and the threat of anthropogenic, short-lived ODS that are currently outside the remit of the Montreal Protocol.

**Understanding ozone depletion in the stratosphere.** In 2000, calculations performed by the Pyle group demonstrated that chlorofluorocarbons (CFC) and other halogenated compounds had led to depletion of ozone in the Arctic. Their model calculations also showed that the severe Arctic ozone loss that occurs in some winters follows the same chemical mechanism as found in Antarctica.[R3] The Pyle group have also been pioneers in studying the relationship between stratospheric ozone levels and climate, which is now a major concern of the Montreal Protocol. Many global warming projection models use simplified estimates of atmospheric composition changes, often setting stratospheric ozone at constant

pre-industrial levels. Calculations by the Pyle group on the complex feedback effects between atmosphere, land surface, ocean and sea ice have demonstrated that chemistry-climate feedbacks exert a significantly more important influence on global warming projections than previously realised.[R1,R2]

**Demonstrating the Effect of the Montreal Protocol.** Pyle's calculations project the future evolution of ozone, explaining how atmospheric ozone concentrations are responding to regulation, with slow recovery this century.[R4] These chemistry–climate model projections show that, had the Montreal Protocol not been enacted, ozone depletion would have been even more severe, an Arctic ozone hole would have developed, and that consequently large changes in surface temperature and UV radiation would have occurred.[R5] In collaboration with epidemiologists, Pyle has extended these studies to demonstrate the very significant benefit of the Montreal Protocol in human health by reducing future increases in skin cancer.[R6]

**Short-lived ozone depleting substances.** The Pyle group has shown that the scientific framework for regulation of short-lived ozone depleting substances must be different to that for regulation of the longer-lived gases, like the CFCs. For short-lived gases, the ozone depletion potential (a concept enshrined in legislation) varies with region and season of emission, whereas for long-lived gases it is a constant.[R7] Pyle has also demonstrated the threat posed to the environment by the very short-lived substance dichloromethane, an ODS that is not controlled by the Montreal Protocol. Very short-lived ODS were previously thought to play a minor role in ozone depletion due to their short atmospheric lifetimes. Pyle showed that atmospheric concentrations of dichloromethane have risen recently and are continuing to increase rapidly, which will delay the recovery of the Earth's ozone layer.[R8] The issue of dichloromethane and other short-lived ODS is now at the forefront of discussions of future regulation by the Montreal Protocol.

## 3. References to the research


R1. Nowack, P. J.; Abraham, N. L.; Maycock, A. C.; Braesicke, P.; Gregory, J. M.; Joshi, M. M.; Osprey, A.; Pyle, J. A. A Large Ozone-Circulation Feedback and its Implications for Global Warming Assessments. *Nat. Clim. Change* **2015**, *5*, 41–45.

R2. Banerjee, A.; Maycock, A. C.; Archibald, A. T.; Abraham, N. L.; Telford, P.; Braesicke, P.; Pyle, J. A. Drivers of changes in stratospheric and tropospheric ozone between year 2000 and 2100. *Atmos. Chem. Phys.* **2016**, *16*, 2727–2746.

R3. Sinnhuber, B.-M.; Chipperfield, M. P.; Davies, S.; Burrows, J. P.; Eichmann, K.-U.; Weber, M.; von der Gathen, P.; Guirlet, M.; Cahill, G. A.; Lee, A. M.; Pyle, J. A. Large loss of total ozone during the Arctic winter of 1999/2000. *Geophys. Res. Lett.* **2000**, *27*, 3473-3476.

R4. Keeble, J.; Brown, H.; Abraham, N. L.; Harris, N. R. P.; Pyle, J. A. On Ozone Trend Detection: Using Coupled Chemistry–Climate Simulations to Investigate Early Signs of Total Column Ozone Recovery. *Atmos. Chem. Phys.* **2018**, *18*, 7625-7637.

R5. Chipperfield, M. P.; Dhomse, S. S.; Feng, W.; McKenzie, R. L.; Velders, G. J. M.; Pyle, J. A. Quantifying the Ozone and Ultraviolet Benefits Already Achieved by the Montreal Protocol. *Nat. Commun.* **2015**, *6*, 7233.

R6. Van Dijk, A.; Slaper, H.; den Outer, P. N.; Morgenstern, O.; Braesicke, P.; Pyle, J. A.; Garny, H.; Stenke, A.; Dameris, M.; Kazantzidis, A.; Tourpali, K.; Bais, A. F. Skin Cancer Risks Avoided by the Montreal Protocol – Worldwide Modelling Integrating Coupled Chemistry-Climate Models with a Risk Model for UV. *Photochemistry and Photobiology* **2013**, *89*, 234-246.

R7. Bridgeman, C. H.; Pyle, J. A.; Shallcross, D. E. A Three-Dimensional Model Calculation of the Ozone Depletion Potential of 1-Bromopropane (1-C3H7Br). *J. Geophys. Res.* **2000**, *105*, 26493-26502.

R8. Hossaini, R.; Chipperfield, M. P.; Montzka, S. A.; Leeson, A. A.; Dhomse, S. S.; Pyle, J. A. The Increasing Threat to Stratospheric Ozone from Dichloromethane. *Nat. Commun.* **2017**, *8*, 186–190.

All research outputs have been published in peer-reviewed journals.

## 4. Details of the impact

**The Montreal Protocol.** To quote Kofi Annan's address to the United Nations, "*It is impossible to devise effective environmental policy unless it is based on sound scientific information*". Annan went on to point out "*Perhaps the single most successful international environmental agreement to date has been the Montreal Protocol, in which states accepted the need to phase-out the use of ozone-depleting substances*." Over the last seven years, Pyle's work has continued to have a major impact on measures to strengthen the Montreal Protocol. As the Executive Secretary of the UNEP Ozone Secretariat said: "*His [Professor Pyle's] scientific research, analysis and observations have made significant contributions to further the understanding of the effects of ozone-depleting substances on the ozone layer and have been providing the basis for policy actions*".[E1] Pyle's work has contributed directly to national and international discussions and agreements on the phase-out of ODS, and, most recently, on the additional phase-out or phase-down of some of their replacements.

The Montreal Protocol on Substances that Deplete the Ozone Layer came into force in response to the scientific evidence that human-induced depletion of the ozone layer was indeed occurring. Every country in the world has signed up to the Protocol. Initially, the Protocol regulated only a handful of CFCs and set a schedule to phase-down their use. However, it is an agreement which is continually evolving as new scientific evidence comes to light, so changes to the Protocol have led to more rapid phase-out of CFCs and the addition of new controls for many more ODS (e.g. the HCFCs). The most recent 2016 amendment to the Protocol added hydrofluorocarbons (HFCs), which are potent climate gases, to the list of controlled substances with an agreement to phase-down their use over the next 30 years.[E2,E3]

**Scientific Assessment of Ozone Depletion.** Every four years, the measures introduced by the Protocol are assessed on the basis of available scientific, environmental, technical, and economic information. An international panel of experts, the Scientific Assessment Panel to the Montreal Protocol (SAP), carries out the scientific assessments by preparing reports to guide policymakers in their decisions regarding the Protocol, and these reports are published by the World Meteorological Organisation (WMO). Pyle has contributed scientific evidence to all the WMO Assessments to date, and for the most recent Assessments in 2014 and 2018, he was one of the four international co-chairs of the SAP.[E4,E5] The 2018 WMO Assessment contains over 45 citations to original research authored by Pyle, including the publications listed above.[E5] All of the WMO Assessments feed into the on-going Montreal Protocol regulation process and hence have continuing and wide-reaching impact.

**Addressing Short-lived Ozone Depleting Substances.** At least twice a year, there are meetings of the representatives of the governments of all 197 signatories of the Protocol, which are called the Conference of the Parties, Meetings of the Parties, and Open Ended Working Groups. The WMO Assessments produced by the SAP feed directly into these meetings, advising and supporting decision makers in modifying the Protocol. Pyle attends these meetings to present the scientific evidence on which the decisions taken are based. Pyle's work on short-lived ODS led to a specific plenary discussion of this problem at the Meetings of the Parties at MOP29 in 2017, and is discussed in the Executive Summary of the 2018 Assessment.[E5, E6] These discussions have placed short-lived ODS firmly on the agenda for regulation under the Protocol.

**Impact of the Montreal Protocol.** The controls put in place by the Montreal Protocol have had a significant impact on the sustainability of the planet and have averted long-term threats to future health. In 2018, definitive evidence was obtained to show that the hole in the ozone layer over Antarctica has begun to shrink.[E5] The models that originally pointed

out the problems with the levels of CFCs in the stratosphere and the consequences for ozone depletion were confirmed by the experimental observation of the Antarctic ozone hole. These models can therefore be used with confidence to project what would have happened to the ozone layer in the absence of the Protocol. For example, Pyle's prediction studies showed that, without the Montreal Protocol, an Arctic ozone hole, similar to that seen in the south, would have occurred during the last decade with consequently large increases in UV. There are also important additional indirect impacts of the Protocol, for example on human health. The predictions show that many millions of skin cancers are avoided annually as a direct result of the reduction in UV dosage due to the measures put in place by the Protocol.[E7] There can be no doubt that the Protocol has had a major impact in avoiding further ozone depletion, in avoiding climate change thanks to the phase-out of those ODS which are also greenhouse gases, and in preventing UV-related health issues. Ensuring that the Protocol is continually adjusted and amended according to the latest scientific developments is essential to their continuing impact, and the chemistry-climate models developed by Pyle are vital for reminding the public and the governments of the world that the consequences of non-compliance would be catastrophic.

In conclusion, Pyle's research has not only provided valuable scientific input into the Montreal Protocol, which continues to have major long-term impact on the habitability of the planet, but also provided Pyle with a platform to directly influence government policy in every single country in the world through his role as co-chair of the Scientific Assessment Panel. In 2018 the Executive Secretary of the United Nations Ozone Secretariat, said "*We, in the ozone community, are so proud to have Professor John Pyle guiding the decision making of the parties to the Montreal Protocol ... His work has vastly contributed to our global efforts to protect the ozone layer*".[E8]

**5. Sources to corroborate the impact**

E1. Letter from Executive Secretary of the Ozone Secretariat, UN Environment Programme

E2. United Nations Environment Programme – Kigali 15.11.2016. "Report of the Twenty-Eighth Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer".

E3. UN Environment OzonAction – About Montreal Protocol 29.07.2019. "Phase down of HFCs – The Kigali Amendment".

E4. World Meteorological Organization – 2014 Report by the Scientific Assessment Panel (SAP) 19.12.2014. "Scientific Assessment of Ozone Depletion: 2014".

E5. World Meteorological Organization – 2018 Report by the Scientific Assessment Panel (SAP) 01.2019. "Scientific Assessment of Ozone Depletion: 2018".

E6. United Nations Environment Programme – Quito 15.11.2018. "Report of the Thirtieth Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer".

E7. Our World in Data – Impacts on Skin Cancer Risk 06.2018. "Ozone Layer"

E8. United Nations Environment Programme – Ozone Secretariat 14.07.2018. "SAP Co-Chair John Pyle Awarded for Scientific Leadership".