Institution: Manchester Metropolitan University		
Unit of Assessment: B7 Earth Systems and Environmental Sciences		
Title of case study: Evidence-based international standards and regulation to mitigate the environmental effects of aviation emissions		
Period when the underpinning research was undertaken: 2005 - 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:**
David Lee	Professor	2003 - present
Bethan Owen	Lecturer to Reader	1995 - present
Ling Lim	Research Fellow	2002 - 2020
Simon Christie	Research Fellow	2007 - 2020
Agnieszka Skowron	Research Assistant/Associate	2012 - present
Sarah Freeman	Research Associate	2014 - 2019
Ruben Rodriguez De León	Research Associate	2005 - present
Period when the claimed impact occurred: 1 August 2013 – 31 December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Manchester Metropolitan University researchers' modelling of aircraft emissions and their climate effects has directly informed the technical development of international standards and agreements to reduce CO_2 emissions from aviation. The research underpinned the design of the EU Emissions Trading Scheme for aviation, which delivered net savings of 193MtCO_2 between 2013 and 2020. Modelling and emissions analyses for the UK Government within the International Civil Aviation Organization (ICAO) have directly informed technical specifications across ICAO's so-called "basket of measures" which are now in place to mitigate climate change effects from the global aviation sector over the next 15 years. The research shaped two new international regulatory standards for aircraft engine particulate and CO_2 emissions; the latter will reduce CO_2 emissions by 5% annually (785MtCO_2 to 2035). Evidence also contributed to the design of ICAO's CORSIA, the flagship aviation CO_2 offsetting scheme agreed by 191 countries.

2. Underpinning research

Aviation is a major emitter of CO_2, but while most industry sectors are decarbonising, emissions from global aviation in 2019 were around 70% greater than in 2005. If the sector was a country, it would be among the top 10 emitters worldwide, therefore making a significant contribution to climate change. The sector has been a clear target for emissions regulation, which has generally involved the development and adoption of international regulatory mechanisms by Member States of the European Union and/or the nation states of the United Nations specialised agency, the International Civil Aviation Organization (ICAO).

To support such initiatives, researchers in Manchester Metropolitan University's Centre for Aviation, Transport and the Environment (CATE) have conducted world-leading studies to model and forecast the impacts of aviation on climate. Since 2005, the group has published approximately 50 peer-reviewed scientific papers in this field. Team members have contributed to five major climate assessments as lead authors and also made distinct research contributions to confidential internal technical papers within ICAO (see Section 4).

Key studies led by Lee have shown that aircraft have significant effects on climate from non-CO_2 emissions; NO_x and contrail cirrus cloud formation from soot emissions have associated effects on the atmosphere and hence climate. The research found that about half of the total climate impact from aviation is derived from non-CO_2 effects **[1,2]**. The 2009 study **[1]** has become a seminal, highly cited paper in the field (see Section 3), while the updated computations for the period 2000 to 2018 provide the most comprehensive analysis to date of aviation's contribution to climate forcing **[2]**. This recent analysis found that aviation contributed around 3.5% to the global warming effect in 2018 – a similar proportion to 2000, but only because the contribution to warming from other sectors has also increased over this period. Most worryingly, the modelling found the actual contribution to warming doubled between 2000 and 2018 and thus significantly outpaced efforts to reduce the sector's climate effects. The work emphasises the urgency and primary importance of addressing CO_2 emissions to aviation's climate impact in the long term (see Section 4).

Studies commissioned by the European Commission provided key evidence that the EU Emissions Trade Scheme for aviation should focus on CO_2 emissions; our modelling of aviation NO_x emissions indicated that while NO_x has significant climate effects, the science was still insufficiently understood to integrate into the scheme **[3]**. Subsequent research has confirmed that mitigation of non-CO_2 impacts is challenging. If NO_x emissions are reduced, even by large amounts (e.g. 50%) at the expense of small increases in CO_2 (e.g. 2%) arising from the inherent technological tradeoffs in designing combustors, perverse outcomes can result, making the overall climate impact worse **[4]**. This strand of our research shows that the impacts of climate on background atmospheric chemistry can result in the cooling component of aircraft net-NO_x climate impact to increase over longer time-periods.

In terms of contrail cirrus, our updated modelling shows that it has half the impact previously calculated **[2]**. However, we show that contrail cirrus, formed on soot particles from aircraft engines, is currently the largest climate forcing agent from aviation. With researchers at MIT, industry partners and the US and Swiss aviation authorities, Owen developed a new method (SCOPE11) to estimate soot emissions – known as non-volatile particulate matter (nvPM) or black carbon mass and number – from aircraft engines **[5]**. The researchers used real-world data to develop a new relationship between smoke number and black carbon mass concentration. The research also developed methods to estimate particle geometric mean diameters, permitting estimation of engine black carbon number emissions. The method has been developed as part of a new ICAO certification emission standards for nvPM (see Section 4).

Collectively, our findings provide robust evidence regarding aviation's CO_2 and non-CO_2 impacts on climate. Our NO_x emission impact modelling suggests caution against focusing on the uncertain outcomes of NO_x mitigation (with long-term economic costs to industry) rather than the clear and undisputed benefits of CO_2 reductions. The results also show the clear benefits of alternative fuel formulation, which reduces CO_2 and as a co-benefit, soot emissions, which will have a beneficial effect on reducing contrail cirrus. Drawing on this body of underpinning work, we provided original analyses and scenario modelling on behalf of the UK Government and European delegation to ICAO that confirmed both technological and market-based approaches are effective measures in reducing CO_2 emissions and climate impacts **[6]**. These studies underpin the UK position and technical specifications in ICAO on international aviation policy, regulation and standards to mitigate the sector's climate impacts as described in Section 4.

3. References to the research

1. **Lee** DS, Fahey DW, Forster PM, Newton PJ, Wit RCN, **Lim** LL, **Owen** B, Sausen R, (2009). Aviation and global climate change in the 21st century. *Atmos. Environ.* 43:3520-3537. DOI: 10.1016/j.atmosenv.2009.04.024.
2. **Lee** DS, Fahey DW, **Skowron** A, Allen MR, Burkhardt U, Chen Q, Doherty SJ, **Freeman** S, Forster PM, Fuglestvedt J, Gettelman A, **De León** RR, **Lim** LL, Lund MT, Millar RJ, **Owen** B, Penner JE, Pitari G, Prather MJ, Sausen R, Wilcox LJ, (2020) The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmos. Environ.* 244:117834. DOI: 10.1016/j.atmosenv.2020.117834.
3. Wit RCN, Boon BH, van Velzen A, Cames M, Deuber O, **Lee** DS, (2005). Giving wings to emission trading. Inclusion of aviation under the European emission trading system (ETS): design and impacts. CE-Delft, No. ENC.C.2/ETU/2004/0074r, The Netherlands.
4. **Freeman** SJ, **Lee** D, **Lim** L, **Skowron** A, Rodriguez **De Leon** R, (2018). Trading off aircraft fuel burn and NO_x emissions for optimal climate policy. *Environ. Sci. Technol.* 52(5):2498-2505. DOI: 10.1021/acs.est.7b05719.
5. Agarwal A, Speth R, Fritz T, Jacob D, Rindlisbacher T, Iovinelli R, **Owen B**, Miake-Lye R, Sabnis J, Barrett S, (2018). The SCOPE11 method for estimating aircraft black carbon mass and particle number emissions. *Environ. Sci. Technol.* 53:1364-1373. DOI: 10.1021/acs.est.8b04060.
6. **Owen** B**, Lee** DS**,** (2020) A technical assessment of the reduction of CO_2 emissions from aviation by in-sector regulatory measures and out-of-sector market-based measures. Confidential report to the Department for Transport, November 2020. Available on request.

Funding

Since 2000, Manchester Metropolitan has attracted approximately GBP12,000,000 of direct income from research grants and contracts related to this body of work. This includes funding

from EPSRC (GBP1,500,000), UK Government (DFT, DEFRA, DECC; GBP4,500,000), and the European Union (GBP2,000,000). Key grants supporting referenced research include:

G1. Opportunities for Meeting the Environmental challenge of Growth in Aviation (OMEGA). 2007-2009. Competitive Department for Trade and Industry funding delivered through HEIF. Total award: GBP5,000,000. PI: Raper. *Manchester Metropolitan led the cross-sector collaborative programme to study sustainable growth in the aviation industry.*

G2. Department of Transport, 2016-2020. Environmental and Aviation and Atmospheric Technical Advice 2016-2020. Award value: GBP3,100,000. PI: Lee.

G3. European Commission, FP7, 2013-2017. FORUM-AE (Grant ID: 605506). Total award: EUR1,199,331 (07-2013). Award to Manchester Metropolitan: EUR78,206 (07-2013). Lead: Owen.

G4. European Commission, Horizon 2020, 2016-2018. Air Traffic Management for environment, ATM4E (Grant ID: 699395). Total award: EUR599,625 (05-2016). Award to Manchester Metropolitan: EUR75,500 (05-2016). Lead: Owen.

Additional indicators of research quality

- Reference [1] is an enduring 'landmark' paper. It has gathered 452 citations (Journal Expected Citations: 43.10; WoS, Dec 2020) suggesting substantial contribution to the discipline. Altmetric places it in the 99^{th} percentile for all research outputs ever tracked.
- Staff are repeatedly invited to participate in prestigious assessments as Lead Authors, including UK Committee on Climate Change and IPCC reports. In 2018, Lee was selected for a Lead Author role for the IPCC Sixth Assessment Report (Working Group III).
- Repeated appointments by ICAO: Lee co-leads the Impacts and Science Group and Owen co-leads the Technical Working Group 3 (emissions) alongside US representatives. These bodies assess research evidence (including Manchester Metropolitan contributions) and make evidence-based policy recommendations and technical specifications to the ICAO Committee on Environmental Protection (CAEP).

4. Details of the impact

Our body of research directly underpinned the design of the EU Emissions Trading Scheme (EU-ETS), launched for aviation in 2012. More recently, our work shaped technical elements across ICAO's so-called "basket of measures" to address aviation emissions and climate effects. Aviation is not explicitly mentioned in the current Paris Agreement so ICAO was tasked to address emissions from this sector, hence the "basket of measures" described below. Together, this suite of regulations provides the first ever internationally agreed industry sector framework to move global aviation towards climate sustainability.

Pathway to impact: commissioned research and positions on ICAO technical groups

Our research influenced the design of these measures through two pathways. First, the group has provided commissioned research for the UK Government and the European Commission (e.g. references [3] and [6]). These studies directly underpin policy development and technical specifications (e.g. EU-ETS and ICAO standards). Second, as co-leads on ICAO technical groups (see Section 3), both Lee and Owen have drawn on their research methodologies and referenced findings as part of ICAO technical discussions and papers that provided the scientific basis, scenario modelling and specifications for CORSIA and the new standards detailed below.

Commenting on the overall contribution of Manchester Metropolitan research in these processes, the Senior Director, Technology, at the International Coordinating Council of Aerospace Industries Associations (ICCAIA), formerly at Airbus, states: *"As the only academic institution in Europe trusted to work closely with European States and industry on both CO_2 and local air quality issues, Dr Owen and Professor Lee remain in a unique position of global influence"* **[A]**. The Head of International Aviation and Climate Change at the Department of Transport agrees: *"Prof Lee, Dr Bethan Owen and Dr Ling Lim provide scientific advice to inform policymaking and represent the UK at the UN International Civil Aviation Organisation (ICAO) in technical negotiations on aviation emissions. This is supported by cutting-edge research by the whole team back at MMU... In recent years, the MMU team have provided essential advice, analysis, research and scientific leadership that has led to the agreement in ICAO of the first carbon dioxide emissions standard for international aviation, the first scientifically-based non-volatile particulate matter standards for the sector, and the first global market-based measure to address carbon dioxide emissions in any single sector"* **[A]**.

EU-ETS for aviation: singular focus on CO_2 delivers emissions reductions

In 2004, the European Commission commissioned Lee and collaborators to analyse and scope out the EU-ETS for aviation in terms of pollutants and geographical scope. The European Parliament wanted to include non-CO_2 emissions from aviation, but Lee's research (ref. [3]) showed that the science of non-CO_2 climate impacts was immature and should not be included; the research team argued that only CO_2 emissions should be accounted in the cap-and-trade scheme. Launched for aviation in January 2012, EU-ETS mandates all intra-European flights to monitor, report and verify their emissions and trade against set allowances. The singular focus on CO_2, which avoided the complex tradeoffs outlined in reference [4], helped make the scheme highly successful. Since 2013, the EU-ETS for aviation has saved 193MtCO_2 and limited CO_2 emissions growth to just 3% since 2014 compared with 10% without EU-ETS **[B].** The impact of the scheme on a single airline operator also illustrates its significance: British Airways says its participation in EU-ETS has reduced CO_2 emissions by 40% per flight (8MtCO_2 in total) **[C]**.

As a part of the EU-ETS legislation, the Commission was obliged to assess by 2020 whether non-CO_2 impacts could be incorporated into the scheme. Lee led the science team and Owen, the technology team, for the European Aviation Safety Agency. Their findings, communicated to the European Parliament in November 2020, sets out future mitigation options for non-CO_2 impacts and their relative maturities. The report is evidence of the researchers' on-going contribution to the design of international aviation policy and regulation, by providing policymakers with evidence to shape future decisions on mitigating non-CO_2 climate effects **[D]**.

CORSIA: the international market-based measure to offset CO_2 emissions growth

ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is the new global market-based measure designed to keep global aviation CO_2 emissions at 2019/20 levels. In 2014, Lee introduced an objective, scientific metric of cumulative CO_2 from the IPCC as the appropriate metric to determine CORSIA's efficacy **[E]**, which was lacking in earlier design. Owen and Lee modelled cumulative emissions (reference [6]) under various CORSIA design scenarios. This output was the sole European input to the technical design and negotiations of CORSIA **[A]**.

ICAO's 191 nation states adopted CORSIA in 2016 **[F]**; it will offset approximately 73% of international aviation CO_2 emissions above 2019 levels (approximately 3,250MtCO_2 over the period 2021 to 2035, see reference [6]). The significance of the agreement is highlighted by Violeta Bulc, European Commissioner for Transport, who said: *"This unprecedented [CORSIA] agreement opens a new chapter in international aviation, where sustainability finally becomes part of the way we fly. We have now set a process in motion, which will not be reversed"* **[F]**.

The significance of CORSIA is evident in the scale of preparatory activity and investment made by ICAO, nation states and airline operators between 2017 and 2020. ICAO created the CORSIA Central Registry to collect emissions reports; it also set up the Assistance, Capacity-building and Training programme (ACT CORSIA) to help countries set up mandatory monitoring and reporting infrastructure and systems. During 2019/20, airline operators compiled their baseline emissions data, ready for the voluntary pilot implementation stage, beginning 1 January 2021 **[G].** 88 countries representing 77% of international aviation activity will voluntarily offset 80% of CO_2 emissions growth from this date compared to their 2019 baseline **[G]**.

ICAO aeroplane CO_2 emissions standard

Owen is the co-lead of ICAO/CAEP's Working Group 3 (emissions) and provided the key UK technical and scientific contributions to the ICAO team that developed the new aeroplane CO_2 emissions standard (see reference [6]). The Senior Director, Technology at ICCAIA confirms that Owen and Lee *"developed a trusted relationship with Airbus that permitted the sharing of commercially confidential, sensitive data to inform the UK and European negotiating position... We met regularly to discuss numerous technical and political issues and ensure the successful delivery in the Standard over a period of around seven years"* **[A]**.

The 36-state ICAO Council adopted the CO_2 standard in 2017 **[H]** since adopted in law in all 191 ICAO nation states. Compliance was required for all new aircraft type designs from 1 Jan 2020, and for all in-production aircraft type designs from 2023. By 2028, manufacturers will be unable to produce any non-compliant aircraft unless they sufficiently modify their designs. The standard is thus a technological measure to reduce absolute aircraft emissions to complement CORSIA's market based measures. Remarks by the ICAO Council President indicate the significance of the standard: *"International civil aviation has once again taken pioneering action* *to address the impact of aviation CO_2 emissions on the global climate, making air transport the first industry sector globally to adopt a CO_2 emissions design certification standard"* **[H]**. It is estimated that this standard will save around 785MtCO_2 (larger than Germany's emissions for one year) between 2020 and 2040 (reference [6]), representing an approximate 5% annual reduction in emissions over this period.

ICAO nvPM emissions standard: first steps to reduce non-CO_2 climate impacts

The underpinning research (e.g. references [1-2]) provides the most robust evidence that contrail cirrus, formed on soot particulate emissions, is a major component of aviation's climate warming. This evidence supported ICAO's drive to introduce an nvPM emissions standard for aircraft engines. Owen co-led a team of approximately 50 specialists for ICAO on its technical development **[A]**. Technical work to develop the standard produced the SCOPE11 method (see reference [5]) which has been incorporated into the ICAO Doc9889, the Airport Air Quality Manual. This international guidance document assists nation states to implement best practices with respect to airport-related air quality **[I]**.

ICAO CAEP endorsed the nvPM standard in February 2019, with adoption by ICAO Council in March 2020. The nvPM standard comes into effect globally for new and in-production engines from 2023 **[I]** and is expected to reduce landing and take off emissions of particulate matter by about 20 to 30% from 2025 to 2040 with concomitant reductions in cruise emissions expected. Reducing nvPM will help to reduce contrail cirrus **[I]**.

Influencing debate: policy and public discourse

Beyond its contribution to these international instruments, our research evidence underpins on-going policy discourse. As part of the UK Government's *Aviation 2050* consultation, Lee authored two key evidence papers that draw on his research to analyse the extent to which the aviation sector might meet UK CO_2 and non-CO_2 emissions thresholds. He argued that non-CO_2 emissions were still too uncertain to be targeted, but that CO_2 reductions be vigorously pursued **[J]**. Lee co-authored the chapter on aviation and shipping emission in the latest UN Environment Program (UNEP) Emissions Gap Report 2020, a science-based assessment of the gap between countries' pledges and performance on greenhouse gas emissions reductions. The report cites our data and forecasts (references [1-2]); it highlights the growing contribution of aviation and shipping to allowable CO_2 emissions and will inform high level debate and negotiations on emissions reductions such as at COP26 in Glasgow and in organisations such as ICAO **[J]**.

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

A. Statements from Head of International Aviation and Climate Change, Department for Transport and Senior Director, Technology ICCAIA (formerly at Airbus) *on the contribution of our research and expertise to the ICAO emissions standards and regulations*.

B. European Aviation Environmental Report 2019 (EASA, EEA, EUROCONTROL) *reports on the significant impact of EU-ETS on net CO_2 emissions. The report cites reference [1] as its primary source on current understanding of climate effects from emissions.*

C. Sustainability at British Airways (Feb 2020) *states impact of EU-ETS on CO_2 reductions*.

D. 'Updated analysis of the non-CO_2 climate impacts of aviation and potential policy measures pursuant to the EU Emissions Trading System Directive Article 30(4)' COM(2020) 747 final: Report from The Commission to the European Parliament and The Council (Nov 2020) *is evidence of the research underpinning EU-ETS monitoring and on-going policy development*.

E. 'Quantifying impacts of the effects of various emissions reductions scenarios from a GMBM using a cumulative CO_2 emissions approach' (Information Paper CAEP-SG/20142-IP/10).

F. Press releases from ICAO and the European Commission *give evidence on the global reach and significance of CORSIA to tackle aviation-associated CO_2 emissions growth*.

G. The Aviation Benefits Beyond Borders website pages and ICAO Implementation Plan brochure *provide details of offset benefits and the reach and scale of preparatory activities for CORSIA by ICAO, nation states and aviation operators 2016-2020*.

H. ICAO press release *describes adoption and implementation of the CO_2 Standard*.

I. ICAO press release and Environmental Report 2019 *describe the adoption and implementation for the nvPM emissions standard and official use of SCOPE11 methodology*.

J. Aviation 2050 reports and the UNEP Emissions Gap Report 2020 *show that our research provides evidence in UK policy consultation and international emissions monitoring*.