Institution: University of Reading		
Unit of Assessment: 7 - Earth Systems and Environmental Sciences		
Title of case study: Improved turbulence forecasts for the aviation sector		
Period when the underpinning research was undertaken: Between 2003 and 31 December 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:**
Professor Paul D. Williams	Professor of Atmospheric Science	October 2003 to Present
Period when the claimed impact occurred: Between 2014 and 31 December 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Atmospheric turbulence is the leading cause of weather-related aircraft accidents and incidents. It injures hundreds of passengers and flight attendants annually, costs the aviation sector hundreds of millions of dollars, and increases aircraft fuel consumption and emissions. To help reduce turbulence encounters, the University of Reading has co-developed an improved clear-air turbulence forecasting algorithm, which is now being used operationally by the US National Weather Service as well as private weather companies, and which will soon be rolled out globally. The algorithm has helped improve the comfort, safety, and environmental impact of air travel on 4.9 billion passenger journeys, growing by 2.6 million every day (pre-COVID). In addition, an extension of the maximum lead time for turbulence forecasts from 12 to 18 hours means that smooth flight routes can now be planned six hours earlier than before. The University of Reading's discovery that climate change is increasing clear-air turbulence has prompted the world's largest manufacturer of aircraft to develop an automated turbulence-reporting function and has prompted airlines worldwide to share real-time turbulence data for the first time.

2. Underpinning research

Clear-air turbulence is a common and hazardous form of turbulence for aircraft to encounter. It is invisible from the cockpit and undetectable by satellites and on-board weather radar. Clear-air turbulence is generated by Kelvin–Helmholtz shear instabilities, which may be initiated by gravity waves in an otherwise stable shear flow. The spontaneous emission of gravity waves from balanced flow had historically been regarded as an unimportant source of atmospheric gravity waves. However, research led by Paul Williams at the University of Reading between 2003 and 2008 [R1] showed that balanced flow spontaneously generates gravity waves at a much larger rate than previously thought – decaying to zero slowly (linearly) with the Rossby number, rather than quickly (exponentially). This evidence was obtained by analysing a novel laboratory experiment using a sophisticated flow visualisation technique, which allowed the spontaneous-emission process to be studied in unprecedented detail.

These findings suggested that the spontaneous emission of atmospheric gravity waves could be an important – but previously unrecognised – source of clear-air turbulence. Williams harnessed this new knowledge to co-develop an improved turbulence forecasting algorithm. Funded by a NERC Fellowship (between 2006 and 2009), he collaborated with John Knox (Professor of Atmospheric Sciences at the University of Georgia specialising in clear-air turbulence) and Don McCann (aviation meteorologist with 36 years of practical forecasting experience at the US National Weather Service). Williams' contribution was mainly on the theoretical aspects, providing technical expertise on how to diagnose the locations and amplitudes of spontaneously emitted gravity waves from a given balanced flow. The new clear-air turbulence forecasting algorithm was named the Lighthill–Ford method, after two early pioneers of the underpinning theory.

The collaborators developed the Lighthill–Ford algorithm between 2005 and 2008, and verified its skill using a large database of pilot reports of turbulence encounters. Receiver Operating Characteristic (ROC) curves were used to compare the Lighthill–Ford algorithm with the US National Center for Atmospheric Research (NCAR) Graphical Turbulence Guidance (GTG1) system, which was the best available turbulence forecasting method at the time. When the false-alarm rate was fixed at 20% for both algorithms, the probability of detection of moderate-or-greater turbulence was found to be 83% for the Lighthill–Ford method but only 56% for GTG1. Therefore, the world's (then) leading algorithm was correctly identifying 56 out of every 100 patches of turbulence but missing 44, whereas the Lighthill–Ford algorithm was correctly identifying 83 patches but missing 17. This equates to a 61% drop in unforecastable clear-air turbulence. The collaborators published these findings, concluding that "*major improvements in clear-air turbulence forecasting could result if the methods presented herein become operational*" [R2].

The collaborators then developed an improved version of the Lighthill–Ford algorithm between 2008 and 2012, with three major modifications. First, the altitude range was extended, providing a forecasting capability not just above 20,000 feet (as with the original version) but all the way down to the top of the planetary boundary layer. (Note that all altitudes are given in feet, as this is the convention in aviation meteorology.) Second, turbulent kinetic energy production from the background environment was included, alongside that from the gravity waves. Finally, the forecast product was converted into an eddy dissipation rate, which is the worldwide standard for measuring aircraft turbulence strength, as mandated by the International Civil Aviation Organization (ICAO). These modifications led to further improvements in the forecast skill, with the probability of detection (for a false-alarm rate of 20%) reaching nearly 90% for severe turbulence [R3].

In a separate, but related, body of work performed between 2013 and the present, Williams has pioneered research into how anthropogenic climate change is increasing clear-air turbulence. He and co-authors showed, in a landmark paper published in *Nature* [R4], that climate change has already caused the jet stream at aircraft cruising altitudes to become 15% more sheared since satellites began observing it in 1979. The shear is expected to continue to strengthen in the coming decades, as the thermal wind balance in the jet stream responds to future temperature changes. Given that shear generates clear-air turbulence, it follows that climate change is causing clear-air turbulence to increase.

Williams has led a series of studies using climate model simulations to quantify the projected future turbulence increase. First, the prevalence of moderate-or-greater turbulence at 39,000 feet over the North Atlantic in winter was found to increase by 40–170%, in response to the atmospheric CO_2 concentration reaching twice its preindustrial value [R5]. Then, in a more detailed analysis of how the different turbulence strength categories individually respond to climate change, the calculations projected an average of 59% more light turbulence, 94% more moderate turbulence, and 149% more severe turbulence [R6]. Finally, these studies were extended by analysing global (not just North Atlantic) projections, in all seasons (not just winter), and at multiple flight levels (not just 39,000 feet), finding hundreds of per cent more turbulence by 2050–2080 under the Representative Concentration Pathway 8.5 (RCP8.5) climate change scenario [R7].

In summary, research performed at the University of Reading since 2003 has identified an important but previously unrecognised source of clear-air turbulence. That knowledge has been applied to develop a new turbulence forecasting algorithm with unrivalled skill. Related research performed since 2013 has shown that climate change is increasing clear-air turbulence, in a manner consistent with observed large-scale changes in the jet stream.

Therefore, climate change threatens to exacerbate the operational impacts of turbulence on aircraft in future.

3. References to the research

Research Quality Statement: All references were published in the peer-reviewed literature and meet or exceed the two-star quality criteria ("provides useful knowledge and influences the field"; "involves incremental advances"). Evidence of influence is indicated by Web of Science Citations in square brackets, as of December 2020.

[R1] Williams, P. D., Haine, T. W. N. and Read, P. L. (2008). 'Inertia–gravity waves emitted from balanced flow: observations, properties, and consequences'. *Journal of the Atmospheric Sciences*, **65**(11), 3543–3556. DOI: 10.1175/2008JAS2480.1 [52]

[R2] Knox, J. A., McCann, D. W. and Williams, P. D. (2008). 'Application of the Lighthill–Ford theory of spontaneous imbalance to clear-air turbulence forecasting'. *Journal of the Atmospheric Sciences*, **65**(10), 3292–3304. DOI: 10.1175/2008JAS2477.1 [41]

[R3] McCann, D. W., Knox, J. A. and Williams, P. D. (2012). 'An improvement in clear-air turbulence forecasting based on spontaneous imbalance theory: the ULTURB algorithm'. *Meteorological Applications*, **19**(1), 71–78. DOI: 10.1002/met.260 [12]

[R4] Lee, S. H., Williams, P. D. and Frame, T. H. A. (2019). 'Increased shear in the North Atlantic upper-level jet stream over the past four decades'. *Nature*, **572**(7771), 639–642. DOI: 10.1038/s41586-019-1465-z [10]

[R5] Williams, P. D. and Joshi, M. M. (2013). 'Intensification of winter transatlantic aviation turbulence in response to climate change'. *Nature Climate Change*, **3**(7), 644–648. DOI: 10.1038/nclimate1866 [47]

[R6] Williams, P. D. (2017). 'Increased light, moderate, and severe clear-air turbulence in response to climate change'. *Advances in Atmospheric Sciences*, **34**(5), 576–586. DOI: 10.1007/s00376-017-6268-2 [28]

[R7] Storer, L. N., Williams, P. D. and Joshi, M. M. (2017). 'Global response of clear-air turbulence to climate change'. *Geophysical Research Letters*, **44**(19), 9,976–9,984. DOI: 10.1002/2017GL074618 [18]

4. Details of the impact

The National Center for Atmospheric Research (NCAR) states that atmospheric turbulence is the leading cause of weather-related aircraft accidents and incidents. It is possible that clear-air turbulence is the leading cause of turbulence encounters, although the exact breakdown is uncertain [R6]. In the US, where the effects of turbulence have been documented in detail, turbulence has several ramifications. According to NCAR, approximately 5,500 aircraft encounter severe turbulence annually, injuring around 1,000 flight attendants and passengers. In addition, for general (non-commercial) aviation, NCAR estimates that turbulence accounts for approximately 40 fatalities each year. The total economic cost of turbulence is estimated to be in the range USD150–500M per year. Turbulence also has consequences for the environment, by increasing aircraft fuel consumption and emissions of CO_2, NO_x, and other pollutants. According to Delta Air Lines and NASA, up to two-thirds of flights deviate from the most fuel-efficient altitude due to turbulence, for an average of 41 minutes per deviation. These deviations waste fuel – up to 160 million gallons annually – and they also contribute to climate change through 1.5 million tonnes of unnecessary CO_2 emissions annually, equivalent to the annual emissions of 324,000 cars.

Because an aircraft's fuel burn rate varies strongly with altitude, the optimum strategy for avoiding turbulence is generally to remain at the most fuel-efficient altitude and fly around it, rather than above or below it. However, historically this strategy has been hindered by poor turbulence forecasts because it requires accurate prior knowledge of the locations of the turbulence. Improved turbulence forecasts allow flight planners to generate smoother flight routes, leading to fewer injuries, cost savings, and less pollution.

The US Federal Government publishes targets for the accuracy of aviation turbulence forecasts, including a goal for the probability of detection of moderate-or-greater turbulence to exceed 80% [R2]. Previous forecasting algorithms were failing to achieve this goal, but the Lighthill–Ford algorithm succeeded [R2]. The US government-sponsored National Center for Atmospheric Research (NCAR) therefore implemented the Lighthill–Ford algorithm into their Graphical Turbulence Guidance (GTG) system [S1]. The US Federal Aviation Administration (FAA) commissioned an independent assessment of the quality of the GTG turbulence forecasts, from the Quality Assessment Product Development Team (QAPDT) at the National Oceanic and Atmospheric Administration (NOAA). Their published report found that the version using the Lighthill–Ford algorithm (and other upgrades; GTG3) was "*consistently better at discriminating [turbulence] events from non-events*" than the previous version (GTG2.5) [S2]. It was on this basis that GTG3 (including the Lighthill–Ford algorithm) entered into operational usage at the US National Weather Service (NWS) Aviation Weather Center (AWC) on 20 October 2015 [S1]. According to the lead developer of GTG, "*Out of the 70 or so diagnostics available in GTG, only the most reliable 5-10 are actually used in the output ensemble mean, and the Lighthill–Ford algorithm is included in both the continental US and global versions*" [S1]. The forecasts are published on an official US Federal Government website at: www.aviationweather.gov. They are freely available and fully open access. The forecasts cover all 48 contiguous US states, plus much of Canada and Mexico and parts of the Pacific and Atlantic Oceans. They forecast turbulence up to 18 hours ahead and are updated hourly. Given that the previous maximum forecast lead time for the GTG system had been 12 hours [S3], the extension to 18 hours (enabled partly by the skill of the Lighthill–Ford algorithm) means that smooth flight routes can now be planned six hours earlier than before.

Every day since 20 October 2015, federal turbulence forecasts made with GTG3 (including the Lighthill–Ford algorithm) have been used in flight planning by commercial and private pilots, flight dispatchers, and air-traffic controllers. On an average day in the USA alone (pre-COVID, 2016), 2.6 million people fly on a scheduled passenger service, and 66,000 general aviation flight hours are flown [S4]. Therefore, by the end of 2020, the Lighthill–Ford algorithm had helped improve the comfort, safety, and environmental impact of air travel on approximately 4.9 billion passenger journeys and 120 million general aviation flight hours. On average, every 10 minutes a further 20,000 airline passengers take to the skies and benefit from the algorithm. In addition to these federally produced forecasts, a Minneapolis-based private weather company, DTN, which serves more than 90 airlines and business jet operations, also uses the Lighthill–Ford algorithm [S5]. Furthermore, a version of GTG that includes the Lighthill–Ford algorithm will be rolled out globally in early 2021, as part of the World Area Forecast System (WAFS) supported by the International Civil Aviation Organization (ICAO) [S1].

Williams' discovery that climate change is increasing clear-air turbulence has motivated Airbus – the world's largest manufacturer of aircraft – to develop an automated turbulence-reporting function. Williams has been collaborating with Airbus since 2017 to explore the various aviation-relevant impacts of climate change. The Airbus Project Manager leading this work said: "*Professor Williams' research has been a true motivation for Airbus to work on an automated turbulence-reporting function. We consider that his assessment of the evolution of turbulence phenomena in the future is a key point to demonstrate the interest of such a function. The research has contributed to increasing Airbus's understanding of the impacts that climate change may have on aircraft operations*" [S6].

Williams' discovery has also motivated the International Air Transport Association (IATA) – which represents 290 airlines worldwide and 82% of global air traffic [S7] – to develop their *Turbulence Aware* platform, allowing airlines to share automated real-time turbulence data for the first time. The Head of Flight Operations Efficiency at IATA said: "*Since its inception in 2017, Turbulence Aware has gained rapid and significant momentum in the industry due to the research of Professor Paul Williams indicating that turbulence will increase in frequency and severity in the coming decades. The latter was a significant motivation not only for IATA to develop the program, but also for many airlines to join IATA's initiative and invest in turbulence-reporting capabilities*" [S7].

He continued: "*Professor Williams has made a significant contribution to aviation safety by educating the airline industry about the impact of climate change on turbulence and the need for the industry to take better action in managing this phenomenon. His research is included in IATA's Industry Turbulence Reporting Guidelines, published in 2018 and used by many airlines to improve turbulence mitigation. Professor Williams also presented his latest research and participated in a panel discussion at the 2019 Safety and Flight Operations Conference in Barcelona, attended by senior aviation management from over 60 airlines*" [S7].

In summary, atmospheric turbulence is now being forecast with unprecedented skill on billions of passenger journeys, thanks to research performed at the University of Reading. The lead developer of GTG said: "*I believe the Lighthill–Ford algorithm to be a shining example of the value of fundamental university research transition to practical operations, one which has contributed to societal benefits of enhanced safety for the flying public*" [S1]. Commenting on the algorithm's prize-winning entry in the 2018 Natural Environment Research Council (NERC) Impact Awards, NERC's Associate Director of Research said: "*Professor Williams met a challenge that was thought to be intractable - predicting air turbulence - and tackled it head on, coming up with a theory, proving it and having it adopted as an industry standard*" [S6]. The algorithm is now being used by UK Research and Innovation (UKRI) as a case study to demonstrate the high impact of UK–US research collaboration [S5]. Finally, Williams' discovery that climate change is increasing clear-air turbulence has prompted a fundamental sector-wide shift in turbulence data collection and sharing. IATA's Head of Flight Operations Efficiency concluded: "*Professor Williams' research has been a critical facilitator of the industry-wide paradigm shift to objective-based turbulence reporting and how it is ultimately managed by airlines globally*" [S7].

5. Sources to corroborate the impact

[S1] Written testimonial from Graphical Turbulence Guidance (GTG) lead developer, US National Center for Atmospheric Research (NCAR), 29 September 2020.

[S2] 'Assessment of the Graphical Turbulence Guidance, Version 3 (GTG3)', National Oceanic and Atmospheric Administration, 5 September 2014. https://esrl.noaa.gov/fiqas/publications/articles/gtg3-assessment-results-trp-102914.pdf

[S3] 'Turbulence help: tutorial on GTG', US National Weather Service Aviation Weather Center. www.aviationweather.gov/turbulence/help?page=tutorial

[S4] 'Air traffic by the numbers', US Federal Aviation Administration, October 2017 – see Passenger Statistics Table on Page 6 (2016), and GA Flight Hours on Page 2 (2016) divided by 365 days for 66,000 daily flight hours.

[S5] 'The impact of UK–US research collaboration', UK Research and Innovation (UKRI), February 2019. https://www.ukri.org/files/international/usa/uk-us-impact-brochure

[S6] 'NERC Impact Awards 2018: 2.5 billion passengers enjoy safer air travel', Natural Environment Research Council (NERC) press release, 22 November 2018. http://webarchive.nationalarchives.gov.uk/20200930000000/http://nerc.ukri.org/press/releases/2018/54-air-travel

[S7] Written testimonial from the Head of Flight Operations Efficiency at the International Air Transport Association (IATA), 29 September 2020.