scores at the start of the first year, a gender gap emerges. Moreover, at the start of the second year, boys were much more likely to reach the highest levels of academic achievement than were girls. They were also twice as likely to be in the top 5%. These early gaps among high achievers have implications for who will persist in STEM fields[3].

Martinot and colleagues find that these gender gaps in maths are ubiquitous. The gaps coincide with the first year of education in all types of school – for example, private and public schools (those with and without tuition fees) – and for students from all socio-economic backgrounds (Fig. 1). Furthermore, the gender gaps can be found in all regions of France and even when the students' parents are both scientists or engineers. Surprisingly, the size of the gap varies only minimally between different student groups – for example, when comparing students from two-parent and single-parent families.

The key advances of this clever work come from the large-scale data, which enable richer insights into the scope of the problem than have previously been possible. The data provide an opportunity to estimate the evolution of the gender gap across all student groups, types of school and regions of the country. Crucially, moving from using a single average difference for all students documented by survey data[4] to measuring differences in specific groups improves researchers' understanding of the nature and extent of the phenomenon. This follows from the authors' carefulness in showing the universality of the gaps and exploring the variables that might moderate the effect[5].

The granularity of the data also enables Martinot and colleagues to pin the emergence of the maths gender gap to school entry. Most children in France start school in September of the year of their sixth birthday. The authors compared the gap between children who had just turned seven and were starting their second year of school with those who were just shy of turning seven and starting their first year. These students were born almost at the same time, but the former had already completed one year of school whereas the latter had only just started. Because the gap exists only in the slightly older group, it is linked directly to being in school rather than to age itself. This analysis relies on a small part of the data set – the students who were born shortly before or shortly after the school-entry cut-off – and is therefore feasible only with large-scale data.

We applaud this work. However, as is the case with any work of science, it does call for further research. For example, although the evidence presented by Martinot *et al.* points to a clear policy issue, addressing these disparities will require an improved understanding of the underlying mechanisms. If the gender gap in the first year of schooling is caused by teachers' differing attitudes towards boys and girls, then the policy solutions will be distinct from those needed if the gap is due to changes in parents' investment in their child's education, for example.

Large-scale data sets are essential for documenting differences in student achievement, but fall short of capturing specific educational inputs and behaviours that can pinpoint the causes. Although the richness of their data set enabled the authors to consider some potentially important moderating variables, the finding that these gender gaps arise ubiquitously across all the variables does not provide clear evidence of any specific drivers.

A crucial next step is to establish the causal mechanisms to help policymakers to design interventions that can reduce the gaps. Given the importance of academic achievement for long-term economic opportunity and the implications for social and wealth inequalities, future work should follow students over time, to study the dynamics and persistence of the gaps. To improve researchers' understanding of the causes and dynamics, further documentation is needed in contexts beyond this work in France and in studies in the United States[6]. Such investigations should clarify the scope of the problem and could shed light on its causes.

John A. List is in the Department of Economics, University of Chicago, Chicago, Illinois 60637, USA. **Andrew Simon** is in the Frank Batten School of Leadership and Public Policy, University of Virginia, Charlottesville, Virginia 22903, USA.
e-mails: jlist@uchicago.edu; arsimon@virginia.edu

1. Fryer, R. G. Jr & Levitt, S. D. *Am. Econ. J. Appl. Econ.* **2**, 210–240 (2010).
2. Martinot, P. *et al. Nature* **643**, 1020–1029 (2025).
3. Karna, U., Lee, M. S., List, J. A., Simon, A. & Uchida, H. *Nature* **639**, 976–984 (2025).
4. Fischer, J.-P. & Thierry, X. *Br. J. Dev. Psychol.* **40**, 504–519 (2022).
5. List, J. A. *Experimental Economics: Theory and Practice* (Univ. Chicago Press, in the press).
6. Dhuey, E., Figlio, D., Karbownik, K. & Roth, J. *J. Policy Anal. Mgmt* **38**, 538–578 (2019).

The authors declare no competing interests.
This article was published online on 24 June 2025.

Climate science

Solving aviation's climate-action conundrum

Christiane Voigt

A decision-making tool for the aviation sector helps to assess the likelihood of a net positive outcome from climate actions that can have competing effects on warming. **See p.988**

Like road and maritime transport, aviation produces carbon dioxide emissions that contribute to climate warming. However, aviation also drives warming through shorter-lived effects mainly related to the formation of trails of condensed water vapour (contrails) and the emission of nitrogen oxide compounds (NO_x). This warming is substantial – the energy added to the atmosphere by aviation's non-CO_2 effects over periods of a few years is estimated[1] to be comparable to the cumulative energy input from all aircraft CO_2 emissions since the start of commercial air traffic in the 1940s. However, uncertainties associated with these estimates have made it hard to decide on the best approach for mitigating warming caused by non-CO_2 effects when the actions taken could cause an increase in CO_2 emissions. On page 988, Prather *et al.*[2] report a risk-assessment tool that cuts through the uncertainties.

Regulators and industry are strongly committed to decreasing aircraft CO_2 emissions to achieve climate neutrality in the aviation sector[3,4], but much less attention is paid to reducing non-CO_2 effects – even though efforts to quantify these effects[5] began before 1999. Several issues account for the lack of progress, such as the complexity of the processes that govern contrail formation. Another problem is that CO_2 cycles between the atmosphere, oceans and continents and is gradually removed from the atmosphere over centuries[6], whereas NO_x-induced increases in ozone and reductions in methane (both of which affect climate) manifest over timescales of months to decades[7,8]. Contrails, meanwhile, persist for only hours at aircraft cruise altitudes[9]. The huge range of timescales involved has complicated efforts to compare the climate effects of aircraft CO_2 emissions with the non-CO_2 effects.

Further challenges stem from the fact that global climate models use simplified representations of the complex processes underlying non-CO_2 effects, and from the lack of observational data. For instance, it is not possible to measure the radiative forcing – the

From the archive

Questions raised by a fission reaction billions of years ago, and making silver compounds lighter with light.

50 years ago

Nature, it would seem, had anticipated man by something like 1,800 million years in bringing about the first self-sustained nuclear chain reaction on the Earth. And, contrary to common belief, it was not in the squash court of the University of Chicago in December 1942, but in the wilds of what is today the Republic of Gabon at a place called Oklo that this fantastic phenomenon took place ... One of the questions discussed ... was whether the Oklo phenomenon was unique. The general feeling was that such propitious circumstances must have occurred elsewhere on the Earth ... The fact that most of the fission products seem to have stayed put over ~ 1,800 Myr has great relevance to present-day waste disposal problems in the field of nuclear reactors (and nuclear explosions).
From *Nature* 24 July 1975

100 years ago

Messrs. P. P. Koch and B. Kreis describe ... measurements made on particles of silver bromide and silver chloride, the mass of which was about 10^{-11} gr. The particles were made to float in air in the electrostatic field of a condenser, in which they were observed by means of a microscope. The particles were strongly illuminated by means of an arc lamp and a powerful condenser; the mass being determined before and after illumination by means of measurements of the condenser voltage and of the charge of the suspended particle. The intensity of illumination employed was so high as 67×10^6 metre candles; and it was found that in a short time the loss of mass was so great as 25 per cent. This loss appears to be due to separation of the halogens. The apparatus may be regarded as a very sensitive microbalance, in which particles of the same order of size as those in a photographic plate can be weighed, and the theory of photographic action can be directly tested.
From *Nature* 25 July 1925

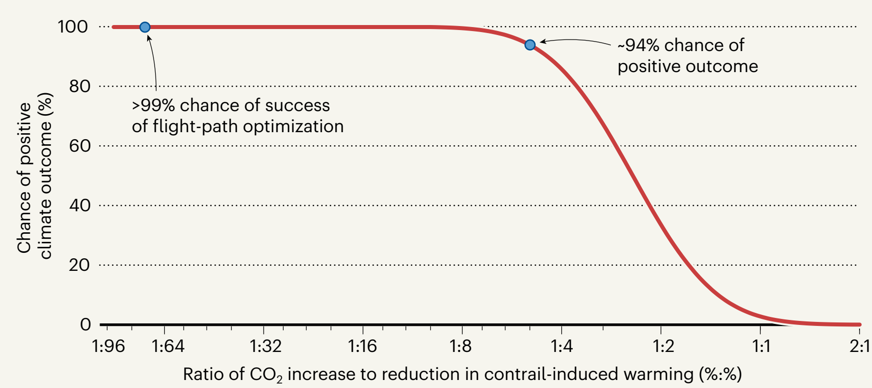

Figure 1 | A decision-making tool to guide climate action in the aviation sector. Global warming caused by aircraft results both from carbon dioxide emissions and from non-CO_2 effects – comprising mainly trails of condensed water vapour (known as contrails) and emission of nitrogen oxides. Strategies for reducing non-CO_2 effects can increase CO_2 emissions, making it hard to assess the overall impact on global warming. Prather *et al.*[2] have developed 'risk curves' that plot the likelihood of a net positive climate outcome when a 1% increase in CO_2 emissions is offset by an N% reduction of a non-CO_2 effect. For instance, a strategy that increases CO_2 emissions by 1% but lowers contrail-induced warming by 5% (a 1:5 ratio on the x axis) has an approximately 94% chance of mitigating global warming (taking into account the effects of one year of global flights over a 100-year period). To give a specific example, optimization of flight paths could reduce contrail-induced warming by 73% while increasing CO_2 emissions by less than 1% (ref. 11). The risk curve shows that this strategy has a greater than 99% chance of mitigating global warming. (Adapted from Fig. 3a of ref. 2.)

change in Earth's energy balance caused by a perturbation – of aircraft CO_2, NO_x or contrails.

Taken together, the substantial difficulties in assessing non-CO_2 effects have long hindered the ability of policymakers and the aircraft industry to decide on mitigation strategies. Yet the need for rapid decision-making is more urgent than ever, because reducing the non-CO_2 effects of aircraft is essential for achieving the targets of the 2015 Paris climate agreement. This aims to limit global warming to less than 1.5 °C above pre-industrial levels.

Some progress on understanding non-CO_2 effects was made in a 2021 study[1] that used a combination of modelling and statistical analysis to evaluate the climate effects of aviation. It assessed the individual impacts of various factors (CO_2 emissions, contrails, NO_x and so on) and helped to define the uncertainties involved in making these estimates. However, the study was unable to offer clear recommendations on specific mitigation measures that involve trade-offs – such as whether there would be an overall climate benefit to reducing contrails or NO_x emissions if the measure taken increased CO_2 emissions.

Prather *et al.* now cut this Gordian knot and take the field a step forwards. The authors introduce a risk-based trade-off assessment – a type of decision-making process widely used in other fields – that explicitly accounts for the scientific uncertainties. Specifically, their method determines the probability that a mitigation measure that could have either a positive or a negative effect on climate will have a net positive outcome.

The authors start by proposing an alternative to the global warming potential (GWP), a standard metric that measures the energy input to the atmosphere per mass of an emission relative to that of CO_2. The GWP is not ideal for describing the atmospheric effects of NO_x and contrails, because their climate impacts are influenced by atmospheric conditions and cannot be described on the basis of the mass of emissions. The authors therefore define a new metric: global warming potential per activity (GWA), which quantifies the atmospheric energy input of an activity (such as emitting NO_x or producing contrails) per year.

Unlike temperature-based climate metrics that capture only the portion of energy input that alters surface temperatures, the GWA also accounts for the fraction of the energy input that dissipates in the atmosphere and that potentially affects atmospheric dynamics, weather systems, the hydrological cycle and extreme weather events. The GWA can be used to quantify warming over different time periods, typically 20, 50 or 100 years.

Using the GWA metric and the previously reported statistical uncertainty information[1], Prather *et al.* present strikingly simple, yet powerful, 'risk curves' that plot the probability of a net positive climate outcome against the 'trade-off ratio' (1:N, which describes the trade-off when an N% reduction in a non-CO_2 effect cancels a 1% increase in CO_2 emissions; see Fig. 1, for example). Hence, the risk curves enable such trade-offs to be quantitatively assessed by indicating the likelihood of a positive climate outcome (for probabilities greater than 50%) or of a negative outcome (for probabilities less than 50%).

Can Prather and colleagues' risk curves be used to quantify the likelihood of success of specific mitigation strategies reported in the literature? Consider climate-warming contrails, for example, which form only under specific cold and humid conditions encountered by a relatively small proportion of flights[10]. It has been proposed that formation of these contrails could be avoided by adjusting flight altitudes. However, because aircraft typically follow cost- or fuel-efficient routes, such altitude adjustments might lead to a slight increase in CO_2 emissions.

A statistical analysis[11] that simulated the effects of optimizing 85,000 flight tracks to avoid contrail formation suggests that the climate impact of contrails could be reduced by 73% with a less than 1% increase in CO_2 emissions. Prather and colleagues' risk curve shows that the probability of this mitigation strategy being successful is extremely high – greater than 99% (Fig. 1). However, the operational feasibility of contrail avoidance will need to be demonstrated in real-world trials.

New methodologies always come with inherent limitations. Further research is needed to narrow down the wide ranges of currently estimated values for contrail and NO_x effects, for example, by improving weather- and contrail-prediction capabilities. Also, the effects of CO_2 need to be estimated over a longer period than the 100 years currently considered by Prather *et al.*, because CO_2 emissions can linger in the atmosphere for more than a century[6].

Moreover, the statistical uncertainties for some climate impacts remain unknown. For instance, the adoption of low-sulfur aviation fuels can benefit climate by altering contrail formation, but can also have an adverse outcome by reducing the cooling effect of low clouds[12]. The lack of knowledge about these processes currently prevents the risk curves from being used reliably to assess the net climate effects of low-sulfur fuels.

Improved observational capabilities will be essential to improving the accuracy of the trade-off assessments – for example, using ground-based and in-flight experiments and on-board contrail cameras, as well as high-resolution data collected by satellites. Future research should also explore how the climate impacts of aviation vary over time and location. Refinements of the risk curves might be necessary to include uncertainties that are related to individual flights, to explore low trade-off ratios or to integrate risk concepts that have been developed in other disciplines.

Nevertheless, Prather and colleagues' approach provides a compelling framework for making trade-off decisions that consistently favour mitigation of the non-CO_2 effects of aviation. It is now up to industry, policymakers and researchers to develop and implement mitigation strategies that offer a high likelihood of success – and substantial climate benefits.

Christiane Voigt is in the Institute of Atmospheric Physics at the German Aerospace Centre (DLR), Wessling 82234, Germany, and at the Institute for Atmospheric Physics, University of Mainz, Mainz, Germany.
e-mail: christiane.voigt@dlr.de

1. Lee, D. S. *et al. Atmos. Environ*. **244**, 117834 (2021).
2. Prather, M. J., Gettelman, A. & Penner, J. E. *Nature* **643**, 988–993 (2025).
3. Air Transport Action Group homepage; available at https://atag.org (accessed 18 July 2025).
4. Destination 2050 homepage; available at https://www.destination2050.eu (accessed 18 July 2025).
5. Intergovernmental Panel on Climate Change. *IPCC Special Report: Aviation and the Global Atmosphere* (eds Penner, J. E. *et al.*) (Cambridge Univ. Press, 1999).
6. Joos, F. *et al. Atmos. Chem. Phys*. **13**, 2793–2825 (2013).
7. Holmes, C. D., Tang, Q. & Prather, M. J. *Proc. Natl Acad. Sci. USA* **108**, 10997–11002 (2011).
8. Prather, M. J. & Zhu, X. *Elementa* **12**, 00112 (2024).
9. Vázquez-Navarro, M., Mannstein, H. & Kox, S. *Atmos. Chem. Phys*. **15**, 8739–8749 (2015).
10. Teoh, R. *et al. Atmos. Chem. Phys*. **24**, 6071–6093 (2024).
11. Martin Frias, A. *et al. Environ. Res. Infrastruct. Sustain*. **4**, 015013 (2024).
12. Righi, M., Hendricks, J. & Sausen, R. *Atmos. Chem. Phys*. **13**, 9939–9970 (2013).

The author declares no competing interests.