BAAN/W2/4

TOWN AND COUNTRY PLANNING ACT 1990

Appeal by Bristol Airport Limited concerning land at North Side Road, Felton, Bristol, BS48 3DY

DEVELOPMENT OF BRISTOL AIRPORT TO ACCOMMODATE 12 MILLION PASSENGERS PER ANNUM

Appeal Reference APP/D0121/W/20/3259234

REBUTTAL PROOF OF EVIDENCE

of

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06 JULY 2021

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Appendices to BAAN/W2/4

R1. Extract from UK Department of Business Energy and Industrial Strategy (DBEIS) "*2021 Government Greenhouse Gas Conversion Factors for Company Reporting, Methodology Paper for Conversion factors, Final Report*". See for full report: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/990675/2021-ghg-conversion-factors-methodology.pdf

R2. M. Klöwer et al., 2021: "*Quantifying aviation's contribution to global warming*". See: https://www.essoar.org/pdfjs/10.1002/essoar.10507359.1

1. Introduction

1.1. In this rebuttal evidence I respond to six aspects of the proof of evidence of Matt Ösund-Ireland [BAL/6/2 – Proof of Evidence: Carbon and Climate Change]. This rebuttal evidence should be read together with my proof of evidence [BAAN/W2/1].

2. Optimistic Assumptions in BAL's Environmental Statement

2.1. In paragraph 7.1.2 (a.), Matt Ösund-Ireland concludes that "*BAL has properly assessed the carbon emissions from additional flights that will arise as a result of the Appeal Proposal. The assessment of aircraft related emissions is robust and can be considered reasonably worst case in terms of future technology impacts on emissions*." He expands on this in paragraphs 2.2.1 (5.), 4.2.2, and paragraphs 4.3.9 – 4.3.13. He asserts that the assumptions made in BAL's ES / ESA about future reductions in emissions from aviation can be described as a 'reasonable worst case' when compared to the Committee on Climate Change (CCC) scenario assumptions which themselves he does not consider to be optimistic.

2.2. However, I do not agree that the CCC assumptions are a sensible yardstick by which to judge a reasonable worst case scenario, given that the CCC was setting out scenarios designed to bring about the changes needed for the UK to achieve Net Zero by 2050, making "moderate" assumptions about innovation [**CD 9.34** page 24].

2.3. The CCC obtained fleet fuel tCO2/passenger values from DfT modelling, assumes the introduction of hybrid electric aircraft, and extensive use of alternative fuels (biofuel and synthetic fuel) by 2050 [**CD 9.66** page 9-12].

2.4. The baseline DfT modelling assumes efficiency improvements of 0.7%/year [**CD 9.66** page 10]. However, the CCC assumes efficiency improvement from 1.4%/year (in-line with historical averages) to 2.1% a year – which is very optimistic, given that improvements in aircraft efficiency become more difficult to achieve every year as I explain in paragraphs 4.6 – 4.8 of my main proof of evidence. BAL's ES / ESA assumes an "upper" worst case emissions scenario of 0.8%/year (Matt Ösund-Ireland's Table

4.1), meaning that it assumes greater efficiency improvements than the DfT modelling.

2.5. It should also be clarified that these efficiency improvements are not compound year-on-year gains as is often assumed. Rather, they are usually compared vs. a year 2000 baseline. Meanwhile air traffic has historically grown about 4%/year compound, so has doubled in size roughly every 15 years. This means that whilst aircraft may be 15-20% more fuel efficient in 2021 than they were in the year 2000, global air traffic has more than doubled in this time period, causing total emissions to increase, not decrease. I explain this in paragraphs 4.1 to 4.6 of my main proof of evidence.

2.6. Furthermore, there is no step-change in aircraft or engine architecture planned by any of the major aviation manufacturers over the next 10-15 years, so the current plan (illustrated by the aircraft orderbooks of Airbus and Boeing) is for a roll-out of existing aircraft such as Airbus A320neo and A350, and Boeing 737Max and 787 over the next 15 years. Due to the 20-30 year lifetime of aircraft, these will be the aircraft configurations predominantly in-service even by 2050. I therefore judge an assumed aircraft efficiency improvement of 1%/year to be overly optimistic.

2.7. In addition, it is a misconception to assert that a fleet fuel efficiency improvement of any magnitude will lead to reduced emissions. As I demonstrate in paragraphs 4.1 to 4.6 of my main proof of evidence – historic trends show total global aviation emissions increasing rapidly over the past decades, despite known efficiency gains. This is because passenger numbers have increased, and airlines have also simply used the efficiency improvements to fly passengers further, which has led to total fuel burn increasing. It is therefore not credible to rely on efficiency improvements to reduce emissions, without effective policy to increase the cost of emissions or to limit air traffic. This is likely one of the reasons that, even with the optimistic assumed efficiency gains used in the Sixth Carbon Budget reports, the CCC emphasises that the main way in which aviation emissions must be reduced in order to achieve Net

Zero is through demand reduction and no net expansion of UK airports – something Matt Ösund-Ireland never directly acknowledges.

2.8. I also consider the CCC's quantities of alternative jet fuel (biofuel and synthetic fuel) to be optimistic. There is currently no policy roadmap for use of alternative jet fuels by UK airlines and there are currently no mandates that would ensure a certain quantity of these fuels being used by a certain date. In Lord Deben's letter [**CD 9.93**] he states on page 9 that "*Our scenario has a 10% uptake of sustainable fuels in 2050. It is not appropriate to plan for higher levels of uptake at this stage, given the range of competing potential uses for biomass across the economy (Figure A8) and uncertainty over which use will be most cost-effective. Our scenarios are based around supply of sustainable biomass with strong governance to ensure they reflect genuine emissions savings. We therefore assume high emissions saving from these biofuels.*" Yet all of the CCC's pathways have greater than 10% biofuel use. This shows that the CCC's pathways are ambitious, reflecting the significant rapid changes needed to address the climate crisis. However, this means they are not a proper comparator against which to judge a reasonable worst case for the purposes of an environmental impact assessment.

2.9. I cover the numerous issues with biofuels in Section 7.3 of my main proof of evidence, showing why aviation biofuel use will simply divert biofuels from other sectors, and that any biomass used for aviation fuel will be competing with other vast global requirements. Combining additional biofuel requirements to this demand will therefore inevitably lead to increased bioenergy impacts: biodiversity loss, food and water scarcity, and land-use change emissions meaning that 'high emissions savings' from biofuels are unlikely. As Lord Deben points out, the CCC's approach assumes a "*sustainable biomass with strong governance to ensure they reflect genuine emissions savings*" which is another ambitious aspect of the CCC's net zero pathways.

2.10. Finally, there is also no consideration given to non-CO2 emissions in the ES/ESA. I address this issue in Section 5 below.

2.11. In summary, the CCC's emission reduction pathway is optimistic, and hence sets ambitious aims for decarbonization. It is not a good yardstick against which to judge a reasonable worst-case scenario.

2.12. The emissions reduction pathway in BAL's ES, which should be based on a worst-case scenario, is instead very optimistic. It relies on efficiency improvements and alternative jet fuel quantities which have a low likelihood of occurring. In addition, any efficiency improvements and increases in alternative jet fuel consumption that do occur are likely to be cancelled out by an increase in air traffic and air miles flown from Bristol Airport. Furthermore, any reduction in CO2 emissions per passenger-km from these strategies may be cancelled out from a global warming perspective by an increase in land-use change emissions from biofuels, or by non-CO2 emissions from the aircraft (I expand on this below).

3. Significance of Increase in Emissions from the Appeal Proposal

3.1. In paragraph 7.1.2 b., Matt Ösund-Ireland concludes that "*BAL has examined the carbon emissions from expansion within the context of the 'planning assumption' that has been used in setting the First to Fifth Carbon Budgets and has also explained the legislative and policy context for the treatment of domestic and international aviation within the Sixth Carbon Budget*." He expands on this is in paragraphs 2.2.1 (6.) where he concludes that "*the incremental increase in emissions from the Appeal Proposal is not significant when compared with the planning assumption of 37.5 MtCO2 or, indeed, when compared with the lower figure of 23 MtCO2 considered by the CCC*." He also continues in paragraph 2.2.2 that "*bearing in mind that there are a range of wider options that the Government might employ to meet these new obligations and that aviation is just one sector contributing to greenhouse gas emissions to be considered, there is also good reason to conclude that the Appeal Proposal would not jeopardise UK obligations to reach net zero by 2050 or to achieve the planned 2035 intermediate target*."

3.2. However, the line "*incremental increase in emissions from the Appeal Proposal is not significant*" is vague and subjective. It demonstrates a lack of awareness about the issue of climate change and how we need to deal with it. Viewed independently, any single infrastructure project or activity can be made to look like a tiny % contribution of a national or global total. However, it is the sum of all contributions which is the issue, and this requires collective action to reduce emissions cross-sector and cross-society. It is important to understand that there is a finite carbon (and other emissions) budget for maintaining the planet well below 2°C of global warming and even more limited to limit global warming to 1.5°C. Therefore, any additional budget taken by aviation activities will result in a reduction in available budget elsewhere.

3.3. As I note in paragraph 3.6 of my main proof of evidence: "*a single return flight from Lisbon to New York generates roughly the same level of emissions required to heat the average EU home for an entire year*". This highlights the emissions-intensity of flying, and demonstrates why it is a mischaracterisation to suggest that a small increase in flying will not jeopardise decarbonisation attempts: if a single international return flight uses up the same carbon budget as a year of heating your home, that shows how much other emissions must decrease to offset even a small increase in the number of international flights. This also shows the need for demand-management to address aviation emissions, given that very little to no weight can safely be put on claims of delivering significant emissions reductions through "sustainable aviation" technologies.

3.4. Whilst aviation is one of the most energy-, carbon- and emissions-intensive activities that exists, it is also one of the most difficult to decarbonise, due to its reliance on liquid hydrocarbon fuels. Therefore, if we expand aviation, we lock-in higher emissions levels, which will jeopardise our ability to meet our emissions reduction obligations. This is addressed in detail in Professor Anderson's proof of evidence.

3.5. Furthermore, as stated in the National Planning Policy Framework, quoted by Matt Ösund-Ireland in paragraph 3.5.2: "*The planning system should support the transition to a low carbon future in a changing climate, taking full account of flood risk and* *coastal change. It should help to: shape places in ways that contribute to radical reductions in greenhouse gas emissions*". As I lay out in my main proof of evidence, given the physics of flying and of fuel production and consumption, and in light of the limited possibilities offered by "sustainable aviation" technologies, the only way to contribute to radical reductions in greenhouse gas emissions from aviation is to reduce total aviation fuel consumption, by limiting air traffic growth. The need for these radical reductions therefore undermines the ability for any large increase in passenger numbers based on airport expansion to receive planning permission, unless <u>reductions</u> in capacity elsewhere are also secured. This is in line with the CCC's advice that the Balanced Pathway allows for 25% growth in passenger demand by 2050 compared to 2018 levels, but with <u>no net expansion</u> of UK airport capacity (my emphasis) [**CD 9.66** page 21]. Matt Ösund-Ireland never engages with this aspect of the CCC's advice.

3.6. Finally, in paragraph 3.6.2 of Matt Ösund-Ireland's proof, Figure 3.2 shows a key principle of North Somerset Council is to "*reduce emissions from transport*", this principle will be far more difficult to achieve if passenger demand in the region is permitted to expand at Bristol Airport in a way that is directly contrary to the CCC's advice in the Sixth Carbon Budget.

3.7. In summary, in light of the climate crisis and the need to rapidly reduce emissions across industry and society, my view is that the increase in emissions which will be caused by the Appeal Proposal should be judged as significant.

4. Use of Carbon Offset Schemes

4.1. In paragraph 7.1.2 b., Matt Ösund-Ireland concludes that BAL has "*explained the legislative and policy context for the treatment of domestic and international aviation within the Sixth Carbon Budget and the UK ETS and CORSIA*." He expands on this in paragraph 2.2.1 (7.) where he states that: "*Emissions from aircraft can only be influenced by BAL and are controlled at the national level, with UK Government providing clear mechanisms for capping aviation emissions within UK carbon budgets and encouraging the industry to drive emission reductions through innovation to* *make best use of existing runways. Those mechanisms include the Sixth Carbon Budget and the UK ETS / CORSIA*".

4.2. However, as I outline in Section 8 of my main proof of evidence, it is not likely that the EU or UK ETS and CORSIA mechanisms will cap aviation emissions. The EU ETS (to be replaced with UK ETS) currently features many exemptions for airline emissions and has hardly impacted on growth, whilst the CORSIA scheme has numerous weaknesses which make it very unlikely to be effective in reducing emissions. The CCC has also advised that CORSIA is not currently compatible with the UK's Net Zero commitment and has thus advised that "*CORSIA should not contribute to meeting the carbon budgets*". Both Professor Anderson and Sam Hunter-Jones also address CORSIA in their proofs of evidence.

4.3. Additionally, in paragraph 3.1.1 (z), Matt Ösund-Ireland details some aspects of a letter dated 24 September 2019 from Lord Deben on behalf of the CCC to the UK Secretary of State for Transport, for instance stating "*that the primary approach for reducing international aviation emissions should be international, principally through the International Civil Aviation Organisation (ICAO) which managed the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)*" [**CD 9.93**].

4.4. However, this neglects to mention that while Lord Deben advocates for an international approach, he also states on page 2 that "*the aim should be to meet the target without relying on use of international offset credits. The Government confirmed to Parliament that this is its approach.*" As I describe in paragraph 8.3.9 of my main proof of evidence: the CCC maintained and strengthened that position in the Sixth Carbon Budget Report (released over a year on from Lord Deben's letter), stating that "*The current level of ambition under CORSIA is an insufficient contribution to the goals of the Paris Agreement*" and that CORSIA "*should not contribute to meeting the carbon budgets*" [**CD 9.34** pg 425].

4.5. Additionally, as I explain in paragraph 8.3.6 of my main proof of evidence: the CORSIA offset credits are simply far too cheap to purchase per tonne of CO2 to be an effective form of control on emissions. For example, they cost less than $1 per tonne of CO2 (tCO2) today, and will only cost up to $12/tCO2 by 2035. This can be compared with the costs for industrial CO2 capture ("Direct Air Capture", or DAC) which is currently closer to $1000/tCO2 (one tCO2 = 1000kgs) and is projected to (best-case) reduce to $100/tCO2 over the next few decades. This is emphasised in Lord Deben's letter [**CD 9.93**] which states on page 10 that CO_2 captured industrially through DAC is likely to provide emissions reductions "*at lower cost when combined with CCS [carbon capture and storage] rather than it being inefficiently recycled into a fuel*". It also states that "*costs for DAC are expected to be high (e.g. in our net-zero advice we estimated that it might be around £300/tCO_2 by 2050)*" and that "*Once CO_2 has been captured, sequestering it geologically can provide abatement at a further cost of up to £20 per tonne of CO_2*". This implies £320/tCO2 by 2050 which demonstrates, in my opinion, the inadequacy of the cost of CORSIA offset credits compared with the current and projected costs for industrial CO2 capture.

4.6. Furthermore, in paragraph 4.2.6 Matt Ösund-Ireland notes that BAL's environmental assessment included a number of assumptions about the future of the aviation sector including "*Achieving net zero requires increased sustainable fuel use, greenhouse gas removals/offsets and operational improvements, which will be driven by international sector-based mechanisms (such as the EU ETS and CORSIA). Robust and CORSIA-eligible offsetting opportunities in the UK, including substantial investment in Carbon Capture and Storage (CCS), are required to increase the extent amount of carbon removal in the UK.*" and also assumes that "*National and international-level responses to reducing aviation GHG emissions that have been put in place (e.g. Aviation Strategy, CORSIA) will be effective.*"

4.7. However, I provide information that counters the efficacy of increased alternative jet fuel use in Section 7 of my main proof of evidence. I also provide information that counters the effectiveness and robustness of offsets under the CORSIA scheme and other carbon offsetting mechanisms in Section 8 of my main proof of evidence. In particular, I note that these offset schemes do not cover the majority of aviation emissions and are far too cheap versus the costs of greenhouse gas removal technologies, such as the CCS technology mentioned here. The CORSIA scheme is currently the only policy mechanism for alternative jet fuels, yet the sustainability criteria of the fuels eligible under the scheme are very weak and do not provide a credible mechanism for achieving significant reductions in emissions.

4.8. I have some direct experience of how the industry views CORSIA, as a result of my employment at Rolls-Royce. The inherent weaknesses in the CORSIA scheme and the use of carbon offsets in general to drive aviation emission reductions, set out above, were acknowledged to me internally by members of the Executive Leadership Team within Rolls-Royce (a major global aviation manufacturer, and one of the leading corporations behind the UK "Sustainable Aviation" industry lobby group) at various points during 2019 and 2020.

4.9. In summary, the fact that BAL's environmental assessment assumes that aviation emissions reductions will be driven by policy mechanisms such as ETS and CORSIA provides a low likelihood that the claimed emissions reductions will occur.

5. Neglect of CO2 Emissions

5.1. In paragraph 7.1.2 (d.), Matt Ösund-Ireland concludes: "*The non-CO2 effects of aviation are acknowledged so choices made in the technologies used to reduce aircraft CO2 emissions do not result in non-CO2 impacts increasing*." He expands on this in paragraphs 2.2.1 (13.), 3.2.1 (e.), 3.7.1-3.7.9, and 6.2.44. He states that BAL simply acknowledging non-CO2 emissions in its Carbon and Climate Change Action Plan (CCCAP) is an adequate position to prevent non-CO2 impacts from increasing. He also cites the Stansted Airport Appeal decision which highlighted that significant uncertainties remain over the effects of non-CO2 emissions and how they should be accounted for and mitigated as justification for ignoring the impact of non-CO2 emissions and concluded that "*the potential effects on climate change from non-carbon sources are not a reasonable basis to resist the Appeal Proposal*."

5.2. However, despite Matt Ösund-Ireland stating repeatedly for example, in paragraph 2.2.1 that "*Non-CO2 emissions cannot be ignored and need to be acknowledged* *today*", it is quite evident that non-CO2 emissions have been ignored by BAL. The Environmental Statement chose to highlight the uncertainties in the exact global warming effect of non-CO2 emissions, and does not give any consideration to the impact of non-CO2 emissions. Nor are these non-CO2 emissions accounted for in the assessment of the airport's contribution towards the UK aviation emissions budget.

5.3. As I describe in paragraph 3.4 of my main proof of evidence: the latest science estimates that "*the contribution of these non-CO2 effects mean that aviation is currently warming the climate at approximately three times the rate of that associated with its CO2 emissions alone*". As per paragraph 3.2.1 (e.) of Matt Ösund-Ireland's evidence: "*the aviation industry is encouraged to take account of, and where appropriate reduce, its contribution to global warming*" and it was identified (back in 2003) that there are additional non-CO2 contributors to climate change and that "*while further research is needed on these issues, the broad conclusion that emissions are significantly more damaging at altitude is clear*". So, while there is uncertainty over the exact global warming impact of non-CO2 emissions, there is consensus that non-CO2 emissions have a warming effect and it is clear that non-CO2 emissions have a relatively large impact. This is likely to be multiple times higher than the CO2 emissions.

5.4. The additional global warming impact of non-CO2 emissions is illustrated in paragraph 3.4 of my main proof of evidence by the UK Department of Business Energy and Industrial Strategy (DBEIS) recommending a multiplying factor of 1.9 be applied to the CO2 emissions from aviation to take into account non-CO2 emissions (see Appendix 6 to Professor Anderson's proof of evidence, BAL/W1/2]. Therefore, the effects <u>are</u> significant and should (whilst accounting for uncertainty) at least be included in a precautionary way in the estimation of total emissions, as per UK Government best practice.

5.5. It should be noted that in June 2021 DBEIS published an updated version of the document at Professor Anderson's Appendix 6. The 2021 version retains DBEIS' advice that a 1.9 times multiplier should be applied, "*based on the best available* *scientific evidence*" (paragraph 8.40) [extract attached as Appendix 1 to this Rebuttal proof].

5.6. In addition, the only place in his evidence that Matt Ösund-Ireland addresses the need for a precautionary approach is when he mentions Article 3 of the UNFCCC, which "*states, amongst other things, that: (3) The Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects*." He does not address the basic principle in UK law, which I am advised is applicable to assessing environmental impacts, that a precautionary approach should be taken. BAL should have taken a precautionary approach with respect to non-CO2 and the worst-case total climate impact, or at least best approximation of total climate impact assumed, for example by applying DBEIS's multiplier – rather than neglecting their impact completely. Contrary to what is implied by BAL and Matt Ösund-Ireland's evidence, there is a high confidence that reducing air traffic would reduce both CO2 and non-CO2 emissions and therefore aviation's total climate impact would be reduced.

5.7. The neglect of non-CO2 emissions effects may also mislead the Inquiry about the potential of aircraft efficiency improvements to reduce future airline emissions. As a recent paper makes clear "*Planning on fuel efficiency improvements does not significantly reduce aviation's contribution to warming, as past progress in efficiency was over compensated by air traffic growth and further efficiency potential is limited. More efficient jet engines tend to produce more contrails, such that savings in fuel could be overcompensated by the warming effect of contrails*" [Appendix 2, pgs 10-11].[1] The statement here that "*more efficient jet engines tend to produce more contrails*" is consistent with my understanding from an internal presentation on non-CO2 emissions by the Environmental Strategy team within Rolls-Royce, which I attended on 27 January 2020, where it was shown that aircraft engines with higher

[1] This is a very recent preprint by leading scientists, including Prof David Lee and Prof Myles Allen, who contributed to the 2020 paper on Anthropogenic Climate Forcing, published in 2021 [**CD 9.60**]. The recent paper references an earlier peer-reviewed paper which also came to the conclusion on which I rely.

overall efficiency produce contrails over a larger range of flight altitudes and therefore cause contrails more frequently.

5.8. The evidence that fuel efficiencies may be overcompensated by non-CO2 emissions shows why it was important to include the impact of non-CO2 emissions within the environmental impact assessment. That assessment should have considered whether, as airlines operating from Bristol Airport transition to more fuel-efficient aircraft, any fuel and CO2 emissions savings expected to reduce the global warming impact of the flights may be cancelled out by an increase in non-CO2 emissions. There is, in my view, credible evidence to this effect, which should inform the Inquiry's approach to BAL's claims resting on fuel efficiency.

5.9. Paragraph 3.7.6 of Matt Ösund-Ireland's evidence also presents options outlined by the CCC for reducing non-CO2 effects, such as alternative fuel and alternative flight routing. First, this again shows why a proper, rounded assessment of the impact of non-CO2 emissions should have been part of the Environmental Statement, as it would have allowed all relevant matters to be taken into account and a sensible assessment made. Second, it is worth noting that the ability of such options to reduce emissions will be made more viable by ensuring reduced air traffic (as this enables alternative flight routing) and reduced total fuel burn (as this allows for higher % quantities of limited alternative fuel supplies) – yet another reason why the CCC's approach is built on demand reduction. This undermines, rather than supports, BAL's proposal.

5.10. As I also explain in paragraph 7.5 of my main proof of evidence: non-CO2 emissions will not be eradicated by the use of alternative fuels, even if these are derived solely from green renewable energy. There are also no mandates in place for specific quantities of alternative jet fuel use by airlines in the UK. Therefore, there are currently no assurances that airlines operating from Bristol Airport will be mandated to use specific quantities of specific alternative fuels across a specific timeline. Therefore, this issue of accounting for and mitigating non-CO2 emissions is unresolved and undermines the case for airport expansion while this is the case.

5.11. In summary, Matt Ösund-Ireland's conclusion that BAL simply acknowledging in its CCAP that non-CO2 emissions will affect the choice of future technology was "*the most appropriate approach to address this issue*" is inadequate. Given that it is accepted that non-CO2 emissions exacerbate global warming and that the best estimate of the global warming impact of non-CO2 emissions is that they are significant, it is unacceptable to omit any estimation of these from BAL's environmental assessment. Furthermore, it distorts other aspects of the environmental assessment by potentially over-estimating the reduction in emissions made possible by, for example, more fuel-efficient aircraft technology. It is clear, as per CO2 emissions, that technology alone cannot be relied upon to reduce non-CO2 emissions, and that demand management is key.

6. Use of Novel Technology

6.1. In paragraphs 4.4.10-4.4.12, Matt Ösund-Ireland makes reference to various UK Government commitments to support various types of "*green technology*" for aviation such as "*zero-emission*" aircraft e.g., hydrogen or battery-electric propulsion that could "could enter service in 2030". A *"£15 million competition to support the production of Sustainable Aviation Fuels (SAF) in the UK*", a SAF "clearing house" and consulting on a SAF mandate is also mentioned. He concludes that the UK Government is "*encouraging the industry to drive emission reductions through innovation*".

6.2. However, regarding the UK Government encouraging the industry to drive emission reductions through innovation, see Sections 5, 6 and 7 of my main proof of evidence. We cannot rely on technology innovation alone to drive emissions reductions without more effective policies to limit air traffic growth, as outlined by the CCC. Any "*zero-emission aircraft that could enter service in 2030*" will either be very small electric or hydrogen aircraft that cannot contribute significantly to reducing UK aviation emissions (see Sections 5 and 6 of my main proof of evidence), or will involve alternative jet fuels, which will only be available in very small quantities by 2030 (see

Section 7 of my main proof of evidence). The £15 million competition announced is a very small amount of money relative to that necessary to stimulate production (the UK aviation industry have asked for £500m in government funding to support their alternative jet fuel roadmap) and will not significantly affect supply of alternative jet fuel. Whilst, the UK Government is consulting on an alternative jet fuel mandate, it has not yet announced one that we can interrogate, and evidence from other EU countries such as Germany is that this will at most contribute at most 5% of aviation fuel consumption by 2030 (see Section 7 of my evidence).

6.3. In Section 5.3, Matt Ösund-Ireland also makes reference to BAL's draft Carbon and Climate Change Action Plan (CCCAP) and in paragraph 7.1.2 (f.), he concludes that: "*BAL's proposed Carbon and Climate Change Action Plan is robust*."

6.4. However, I have provided various comments on BAL's CCAP report in Section 9 of my main proof of evidence where I conclude that little or no weight can be placed on any of these measures providing a significant reduction in aviation emissions. Of note, BAL's first step "*utilises offsetting schemes*" which I deal with in Section 8 of my main proof of evidence. It also claims that growth of Bristol Airport "*will enable BAL to invest in the future of sustainable aviation*" and "*an even greater opportunity to reduce emissions. This includes delivering a zero-emission fleet across the airport where practicable, an extended Aviation Carbon Transition (ACT) Programme.*" It goes on to say that the ACT Programme may provide "*funding of £250k available in 2021 for enabling sustainable aviation fuel (SAF) and other sustainable flight solutions*." The claim that airport/airline growth can facilitate the purchase of more efficient aircraft technology which will enable reduced emissions is demonstrably false – I detail in Section 4 of my main proof of evidence how more efficient aircraft have historically led to increased total aviation emissions, without measures to constrain air traffic growth. In Section 5 and 6 of my main proof of evidence, I also show that there is limited scope for "zero-emissions" electric or hydrogen aircraft to decarbonise aviation emissions before 2050 – a conclusion shared by the CCC. The ACT Programme for Bristol Airport also has no specific commitments associated with it, apart from towards research which may not achieve any results. The £250k of funding proposed is insignificant compared to that required to stimulate alternative jet fuel production, and in any case, I highlight issues with such fuels in Section 7 of my main proof of evidence.

6.5. In summary, both UK Government commitments and BAL commitments made in the draft CCAP, provide a low likelihood that the reductions in aviation emissions from Bristol Airport will occur.

7. Lack of Quantified, Enforceable Commitments

7.1. A recurring theme throughout Matt Ösund-Ireland's main proof of evidence is the acceptance of a lack of quantified, enforceable commitments to reduce aviation emissions. However, without such quantified, enforceable commitments, little weight can be placed on emissions reductions actually happening.

7.2. For example, Matt Ösund-Ireland's evidence assumes that the most efficient aircraft will be used as these become available, but no commitment exists to ensure this happens. As such, airlines operating from Bristol Airport may continue to use existing or older generations of aircraft into the future.

7.3. Matt Ösund-Ireland mentions electric and hydrogen aircraft, but no commitment exists to use a specific number of these aircraft, for a specific quantity of flights operating from the airport, by any specific dates. Infrastructure for such aircraft is also mentioned, but no commitment exists to quantify the extent of this infrastructure or to install it by a certain date.

7.4. Alternative jet fuel is mentioned and relied upon within the environmental assessment, but no commitment exists for airlines operating from Bristol Airport to use specific quantities, of specific types of alternative jet fuel, by any specific dates.

7.5. The detailed evidence in my main proof of evidence demonstrates why little weight can be placed on "sustainable aviation" measures. Matt Ösund-Ireland's evidence only engages in a superficial way these measures and places very significant reliance on assumptions or promises that lack any quantified, enforceable commitment. That approach is not robust, given the reality of “sustainable aviation”, demonstrated in my evidence.

Finlay Asher

6 July 2021

Department for
Business, Energy
& Industrial Strategy

APPENDIX R1

2021 Government Greenhouse Gas Conversion Factors for Company Reporting

Methodology Paper for Conversion factors Final Report

June 2021

Notes: Totals may vary from the sums of the components due to rounding in the more detailed dataset.

Indirect/WTT Conversion factors from Air Transport

8.33. Indirect/WTT emissions factors for air passenger and air freight services include only emissions resulting from the fuel lifecycle (i.e. production and distribution of the relevant transport fuel). These indirect/WTT conversion factors were derived using simple ratios of the direct CO_2 conversion factors and the indirect/WTT conversion factors for aviation turbine fuel (kerosene) and the corresponding direct CO_2 conversion factors for air passenger and air freight transport in the "Business travel – air" and "Freighting goods" worksheets.

Other Factors for the Calculation of GHG Emissions

Great Circle Flight Distances

8.34. We wish to see standardisation in the way that emissions from flights are calculated in terms of the distance travelled and any uplift factors applied to account for circling and delay. However, we acknowledge that a number of methods are currently used.

8.35. An 8% uplift factor is used in the UK Greenhouse Gas Inventory to scale up Great Circle distances (GCD) for flights between airports to account for indirect flight paths and delays, etc. This is lower than the 9-10% suggested by IPCC Aviation and the global atmosphere, but has been agreed with DfT based on recent analysis as more appropriate for flights arriving and departing from the UK. This factor has been used since the 2014 update of both the GHGI, and the GHG Conversion factors set.

8.36. It is not practical to provide a database of origin and destination airports to calculate flight distances in the GHG Conversion factors. However, the principal of adding a factor of 8% to distances calculated on a Great Circle is recommended (for consistency with the existing approach) to take account of indirect flight paths and delays/congestion/circling. This is the methodology recommended to be used with the GHG Conversion factors and is applied already to the conversion factors presented in the 2021 GHG Conversion factors set.

Indirect effects of non-CO_2 emissions

8.37. The conversion factors provided in the 2021 GHG Conversion factors "Business travel – air" and "Freighting goods" worksheets refer to aviation's direct CO_2, CH_4 and N_2O emissions only. There is currently uncertainty over the other non-CO_2 climate change effects of aviation (including water vapour, contrails, NO_X, etc.) which have been indicatively accounted for by applying a multiplier in some cases.

8.38. Currently there is no suitable climate metric to express the relationship between emissions and climate warming effects from aviation, but this is an active area of research. Nonetheless, aviation imposes other effects on the climate which are greater than that implied from simply considering its CO_2 emissions alone.

8.39. The application of a ‘multiplier’ to take account of non-CO_2 effects is a possible way of illustratively taking account of the full climate impact of aviation. A multiplier is not a straightforward instrument, in particular it implies that other emissions and effects are directly linked to production of CO_2, which is not the case. Nor does it reflect accurately the different relative contribution of emissions to climate change over time or reflect the potential trade-offs between the warming and cooling effects of different emissions.

8.40. On the other hand, consideration of the non-CO_2 climate change effects of aviation can be important in some cases, and there is currently no better way of taking these effects into account. A multiplier of 1.9 is recommended as a central estimate, based on the best available scientific evidence, as summarised in Table 46 and the GWP_{100} figure (consistent with UNFCCC reporting convention) from the ATTICA research presented in Table 47 below (Sausen , et al., 2005) and in analysis by Lee et al (2009) reported on by (CCC, 2009).

From CCC (2009): “The recent European Assessment of Transport Impacts on Climate Change and Ozone Depletion (ATTICA, http://ssa-attica.eu) was a series of integrated studies investigating atmospheric effects and applicable climate metrics for aviation, shipping and land traffic. Results have been published which provide metrics to compare the different effects across these sectors in an objective way, including estimates of Global Warming Potentials (GWPs) and Global Temperature Potentials (GTPs) over different time horizons (20, 50 and 100 years). Table 47 shows the 20-year and 100-year GWPs, plus 100-year GTPs, for each forcing agent from aviation. Based on estimates of fuel usage and emission indices for 2005, the emission equivalent of each agent for these metrics is given on the right, and on the bottom right is the overall ratio of total CO_2-equivalent emissions to CO_2 emissions for aviation in 2005.”

8.41. It is important to note that **the value of this 1.9 multiplier is subject to significant uncertainty** and should only be applied to the CO_2 component of direct emissions (i.e. not also to the CH_4 and N_2O emissions components). The 2021 GHG Conversion factors provide separate conversion factors including this uplift for indirect effects of non-CO_2 emissions in separate tables in the “Business travel – air” and “Freighting goods” worksheets.

Table 46: Indirect effects of non-CO_2 emissions according to Sausen et al. (2005)

		RF [mW/m^2]							
Year	**Study**	**CO_2**	**O_3**	**CH_4**	**H_2O**	**Direct Sulphate**	**Direct Soot**	**Contrails**	**Total (w/o) Cirrus**
1992	IPCC (1999)	18.0	23.0	-14.0	1.5	-3.0	3.0	20.0	48.5
2000	IPCC (1999) scaled to 2000	25.0	28.9	-18.5	2.0	-4.0	4.0	33.9	71.3
2000	TRADEOFF	25.3	21.9	-10.4	2.0	-3.5	2.5	10.0	47.8

Notes: Estimates for scaling CO_2 emissions to account for indirect effects of non-CO_2 emissions are not quoted directly in the table, but are derived as follows: IPCC (1999) = 48.5/18.0 = 2.69 ≈ 2.7; TRADEOFF = 47.8/25.3 = 1.89 ≈ 1.9

Table 47: Findings of ATTICA project

	Metric values			CO_2e emissions ($MtCO_2e$/yr.) for 2005			LOSU
	GWP_{20}	GWP_{100}	GTP_{100}	GWP_{20}	GWP_{100}	GTP_{100}	
CO_2	1	1	1	641	641	641	High
Low NO_x	120	-2.1	-9.5	106	-1.9	-8.4	Very low
High NO_x	470	71	7.6	415	63	6.7	Very low
Water vapour	0.49	0.14	0.02	123	35	5.0	–
Sulphate	-140	-40	-5.7	-25	-7	-1.0	–
Black carbon	1600	460	64	10	2.8	0.38	–
Contrail	0.74	0.21	0.03	474	135	19	Low
AIC	2.2	0.63	0.089	1410	404	57	Very low
				CO_2e/CO_2 emissions for 2005			
Low NO_x, inc. AIC				4.3	1.9	1.1	Very low
High NO_x, inc. AIC				4.8	2.0	1.1	Very low
Low NO_x, exc. AIC				2.1	1.3	1.0	Very low
High NO_x, exc. AIC				2.6	1.4	1.0	Very low

Source: Adapted by (CCC, 2009) from Lee et al. (2009) Transport impacts on atmosphere and climate; Aviation, Atmospheric Environment. The level of scientific understanding (LOSU) is given for each process in the right column. Values are presented for both high and low GWP values for NO_x reflecting the wide uncertainties in current estimates. The ratios on the bottom right are presented both including and excluding aviation induced cloudiness (AIC) because of uncertainties both in estimates of the magnitude of this effect and in the future incidence of AIC due to air traffic. The different time horizons illustrate how a unit emission of CO_2 increases in importance relative to shorter-lived effects as longer timescales are considered.

Notes: GWP = Global Warming Potential, GTP = Global Temperature Potential

Quantifying aviation's contribution to global warming

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Growth in aviation contributes more to global warming than is generally appreciated because of the mix of climate pollutants it generates: aviation contributed approximately 4% to observed human-induced global warming to date, despite being responsible for only 2.4% of global annual emissions of CO_2. Aviation is projected to have caused a total of about 0.1˚C of warming by 2050, half of it to date and the other half over the next three decades. Should aviation's pre-COVID growth resume, the industry will contribute a 6-17% share to the remaining 0.3-0.8˚C to not exceed 1.5-2˚C of global warming. Under this scenario, the reduction due to COVID-19 to date is small and is projected to only delay aviation's warming contribution by about 5 years. But the leveraging impact of growth also represents an opportunity: Aviation's contribution to further warming would be immediately halted by either a sustained annual 2.5% decrease in flights under the existing fuel mix, or a transition to a 90% carbon-neutral fuel mix by 2050.

Flying contributes to global warming. Through emissions and contrails, aircraft alter the radiative balance of the planet. Global aviation has increased dramatically in recent decades, from 310 million in 1970 to 4.3 billion passenger journeys in 2018 (International Air Transport Association 2020). The carbon footprint of top emitters in a society is usually dominated by air travel (Gore, Alestig, and Ratcliff 2020), indicating the inherent inequality in this emission sector.

Aviation is a large international industry, important for business, governments, tourism, and research. Flying often provides the only possibility to reach remote locations within an acceptable time frame. However, flying is also one of the most carbon-intensive ways to travel, emitting per hour up to 100 times more than train, bus or shared car rides (Creutzig et al. 2015). The public travels for a variety of reasons, essential journeys and leisure trips alike (Lenzen et al. 2018). Since the beginning of the COVID-19 pandemic, many of us have involuntarily reduced travel, forcing the global aviation industry into its biggest economic crisis (International Air Transport Association 2020; Gössling 2020). In most countries, the majority of flights were cancelled from March 2020, simultaneously causing a large reduction in carbon emission and other climate pollutants (Le Quéré et al. 2020).

Limiting global warming to well below 2˚C requires all emission sectors to decarbonise and to present pathways that reach net zero in the second half of the 21st century (Intergovernmental Panel on Climate Change 2018). International aviation is usually considered a "hard to abate" sector and often left out of reduction targets, as in the Paris Agreement (UK Climate Change Commitee 2020). Before the pandemic, aviation was responsible for about 2.4% of global annual carbon emissions (Intergovernmental Panel on Climate Change 2015). Additionally, aircraft mostly emit nitrogen oxides (NO_x) at altitudes of 8 - 12 km, causing complex chemical reactions in the atmosphere as well as causing cirrus cloud formation through condensation trails (David S. Lee et al. 2020). To estimate aviation's contribution to current and future anthropogenic global warming, we analyse the total climate forcing, taking both CO_2 and non-CO_2 effects into account. Different scenarios are presented that depict possible futures of aviation until 2050, resulting in a discussion how the aviation industry can act.

How aviation affects the climate

Aircraft engines have burned more than 1 billion litres of fuel per day in recent years(David S. Lee et al. 2020). In doing so, they emit, per kg of fuel, 3.16 kg of CO_2, 1.23 kg of water vapour (H_2O), up to 15.14 g of NO_x, 1.2 g of sulphur (SO_2) and 0.03 g of black carbon (soot), see Table S1. Nitrogen oxides react in the atmosphere altering the radiative balance of other gases, including methane (CH_4), ozone (O_3) and stratospheric water vapour (H_2O) and therefore indirectly impact the climate. These non-CO_2 emissions cause an additional net warming effect (David S. Lee et al. 2020).

Aircraft can also create condensation trails on their paths, and if persistent, forming cirrus clouds that act as another climate forcing through reflection and absorption of radiation, net warming the planet (Chen and Gettelman 2013). Cloudiness is increased with contrails that scale approximately with the total distance flown. Airliners, i.e. excluding private, military and cargo flights, covered about 50 billion km in 2018 (David S. Lee et al. 2020), equivalent to 350 times the distance between the Earth and the Sun.

The emissions and persistent contrail formations are converted to effective radiative forcings (Table S1), i.e. the additional energy that the Earth's surface receives on average through aircraft changing the atmospheric composition. The total climate forcing through all CO_2 and non-CO_2 effects is approximately their sum, assuming that the individual effects are independent of each other.

The contribution of any sector to global temperature change ΔT over period Δt is given, to a good approximation, by a combination of cumulative CO_2 emissions $\bar{E}\Delta t$ and cumulative non-CO_2 radiative forcing $\bar{F}\Delta t$ over that period (M. Smith, Cain, and Allen 2021; Intergovernmental Panel on Climate Change 2018):

$$\Delta T = \chi \left(\bar{E}\Delta t + L^{-1}\bar{F}\Delta t\right) \tag{1}$$

Where χ is the *transient climate response to emissions* (TCRE) of about 0.45˚C per trillion tonnes of CO_2. The linear operator L converts CO_2 emission to radiative forcing using values from the IPCC 5th Assessment Report (Intergovernmental Panel on Climate Change 2015). Its inverse L^{-1} is used to convert non-CO_2 radiative forcing to CO_2 warming-equivalent emissions over multi-year time scales. The quantity in brackets is the total cumulative CO_2-warming-equivalent emissions (Cain et al. 2019) over this period. Here we use up-to-date assessments of non-CO_2 radiative forcing (David S. Lee et al. 2020) expressed as warming-equivalent emissions using the above formula. For details see the supplementary information.

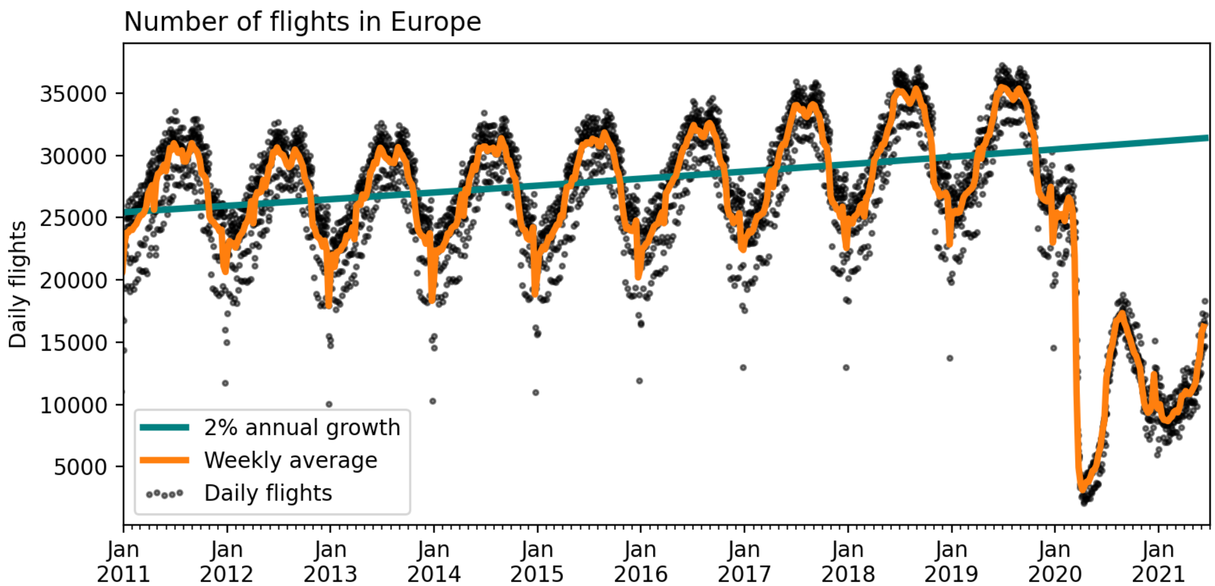

Figure 1. Daily flights over Europe between 2011 and present. The seasonal cycle shows more flights in summer and less in winter with a strong decrease associated with holidays at the end of the year. The number of flights increased by about 2% per year pre-COVID in Europe. The pandemic forced many airplanes to ground since March 2020 with only a partial recovery in summer 2020 and 2021.

Scenarios for 2050

Travel restrictions and national lockdowns due to the COVID-19 pandemic came into effect in 2020. Over Europe, many days in March and April 2020 saw fewer than 5,000 flights, which is an 80% decrease from pre-COVID typical air traffic (Fig. 1). For summer 2020, European aviation partially recovered with more than 15,000 flights a day, only to face another decrease due to regional or national lockdowns in autumn and winter. Globally, the number of flights dropped by about 45% on average in 2020 (Fig. 2b).

Following the deployment of COVID-19 vaccines in 2021, air traffic is expected to increase again. Whether pre-COVID levels are reached within the next few years or whether international travel will remain low is unclear. Pandemic-induced travel restrictions could remain in case vaccines are not fully effective against some virus variants, and the boom in virtual technology could lower the demand for travel to meetings or conferences. Since 1970, aviation has grown at approximately 3% per year (Fig. S1). We design four scenarios to capture possible futures of global aviation:

Scenario 1: No Pandemic assumes no COVID-19 pandemic and a continuous growth in air traffic CO_2 emissions of about 3% per year. Annual growth data are taken from the International Civil Aviation Organization (ICAO, see Fig. S1) assuming moderate efficiency improvements in technology and operation (Fleming and de Lépinay 2019).

Scenario 2: Back to Normal assumes a post-COVID recovery for 2021-2024 at 16% annual growth and 3% thereafter. The pre-COVID level is reached in 2024.

Scenario 3: Zero Long-Term Growth assumes a 13% annual growth for the recovery period 2021-2024 and zero growth thereafter. About 90% of the pre-COVID level is reached in 2024.

Scenario 4: Long-Term Decline assumes a 10% annual growth for the recovery period 2021-2024 but a 2.5% per year decline thereafter. Air traffic levels are about 50% lower in 2050 compared with 2019, similar to the first pandemic-year 2020.

Emissions indices are unchanged in scenarios, and non-CO_2 climate forcings continue to scale with annual CO_2 emissions.

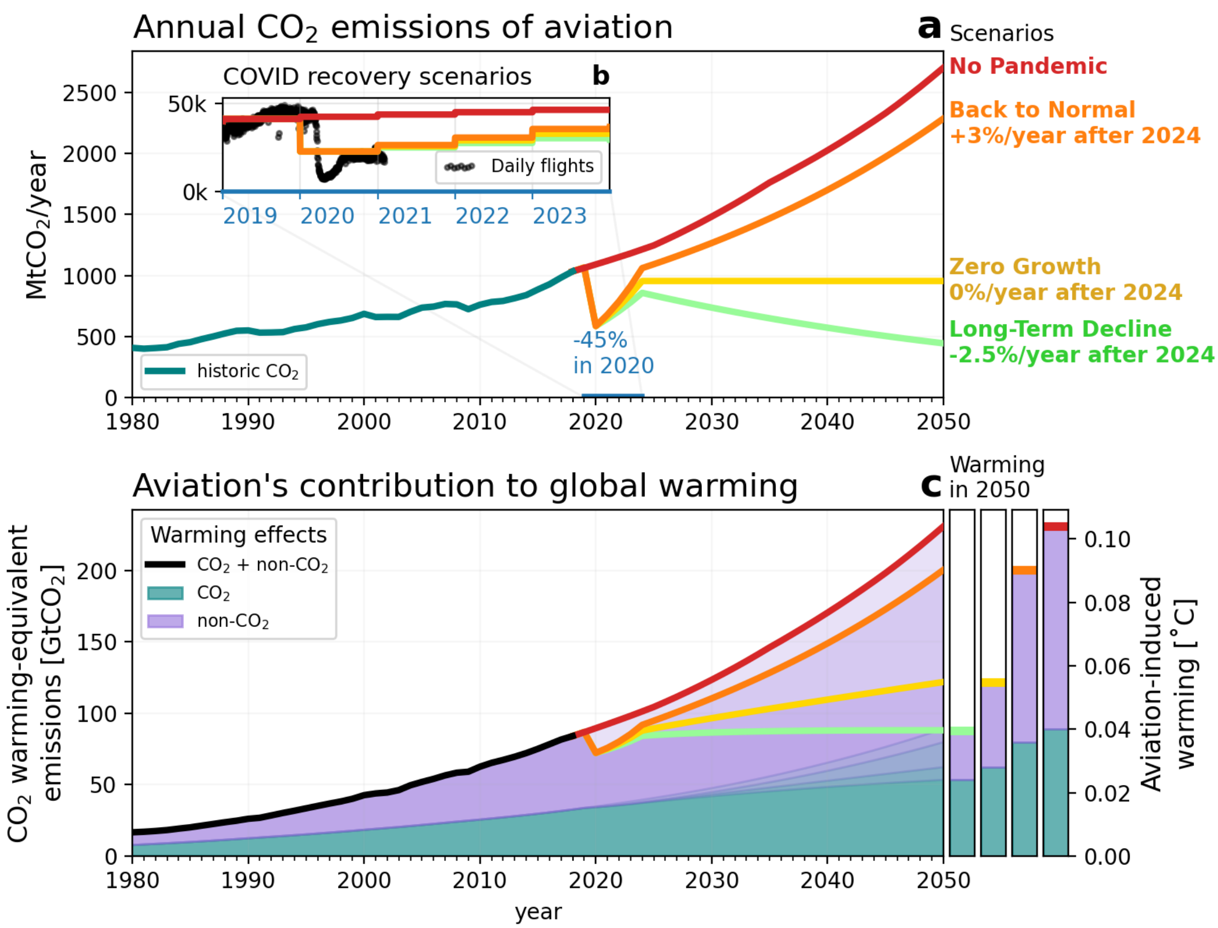

Figure 2. Aviation's contribution to global warming to 2050. **a** Annual historic and future annual carbon dioxide (CO_2) emissions of aviation following four scenarios: *No Pandemic, Back To Normal, Zero Long-Term Growth,* and *Long-Term Decline* as explained in the text. **b** Daily flights of selected airports globally between 2019 and Nov 2020 and annual averages for all scenarios. **c** Cumulative warming-equivalent emissions of CO_2 and non-CO_2 effects of aviation since 1940 and the corresponding aviation-induced global warming. Scenarios are colour-coded as in **a**.

Aviation's warming footprint

In 2019 the emissions of global aviation were about 1 billion tonnes of CO_2 ($GtCO_2$), more than 4 times the emissions of New York City (Moran et al. 2018). For the scenarios *No Pandemic* and *Back To Normal* with about 3% annual growth the emissions will more than double by 2050. In the other two scenarios the annual emissions peaked in 2019.

A large fraction of the increase in atmospheric CO_2 naturally stays for many 1,000s of years (Inman 2008). Therefore not the recent emissions of CO_2 alone drive global warming, but the cumulative historic emissions. The accumulated carbon emissions of aviation for the period 1940-2019 are 33 $GtCO_2$ (Fig. S2a), equivalent to the historic emissions of Canada and about 2% of the world's CO_2 cumulative emissions. Through the climate forcing of these CO_2 emissions (Fig. S2b) a warming of 0.015˚C is already caused today, which will reach 0.025-0.04˚C in 2050, depending on the scenario. COVID has a negligible impact on the CO_2-induced warming from aviation, since it is the cumulative emissions that matter. However, aircraft also affect the climate through other climate pollutants. Contrails and contrail cirrus alone exerted a greater effective radiative forcing pre-COVID than that due to historic aviation CO_2 emissions (Fig. S3). These non-CO_2 effects act mostly within days (e.g. contrail cirrus) to decades (CH_4 response to NO_x). The long-term impacts of aviation therefore result from accumulated past CO_2 emissions but from the recent non-CO_2 effects. Taking both into account, the total aviation-induced warming up to 2019 is about 0.04±0.02˚C, about 4% of the almost 1.2˚C that the planet has warmed so far (Haustein et al. 2017; Morice et al. 2021). This is in good agreement with the Effective Radiative Forcing fraction of 3.5% (David S. Lee et al. 2020). About 0.03°C of this aviation-induced warming is due to emissions since 1990, representing 5.3% of total human-induced warming in this period.

How much warming will aviation have caused in 2050? Following the 3% annual growth scenario *Back To Normal,* aviation will have contributed 0.09±0.04˚C to global warming by 2050 (Fig. 2). More than half of that warming will be caused in the next three decades, contributing a 6-17% share to the remaining 0.3-0.8˚C to stay within a 1.5-2˚C target. Without policy intervention, this contribution will continue to increase beyond 2050. The halt in air traffic due to COVID in 2020 will reduce this only slightly, by ~10%. The annual growth in air traffic in the coming years has a much greater impact than COVID itself. In that sense, COVID is projected to only delay the warming contribution of aviation by about 5 years, should the pre-COVID growth resume. In the *Zero Long-Term Growth* scenario aviation-induced warming will keep rising over the next decades, as the CO_2 emissions continue to accumulate and start to dominate over the non-CO_2 effects.

Interestingly, if global aviation were to decline by about 2.5% per year, even with no change in current fuel mix or flight practices, the impacts of the continued rise in accumulated CO_2 emissions and the fall of non-CO_2 climate forcers would balance each other, leading to no further increase in aviation-induced warming with immediate effect. As a comparison, ambitious climate targets require other sectors to reduce emissions by 3-8% per year[15], still implying a significant continuous contribution to further warming over the next decades. The short-lived climate forcers, which amplify the impact of any increase in aviation emissions, however, also act to amplify the impact of any decrease. Consequently, aviation would not actually need to cease immediately to end its contribution to further global warming — an optimistic message given the limited options of near-operational alternatives to carbon-intensive intercontinental flights.

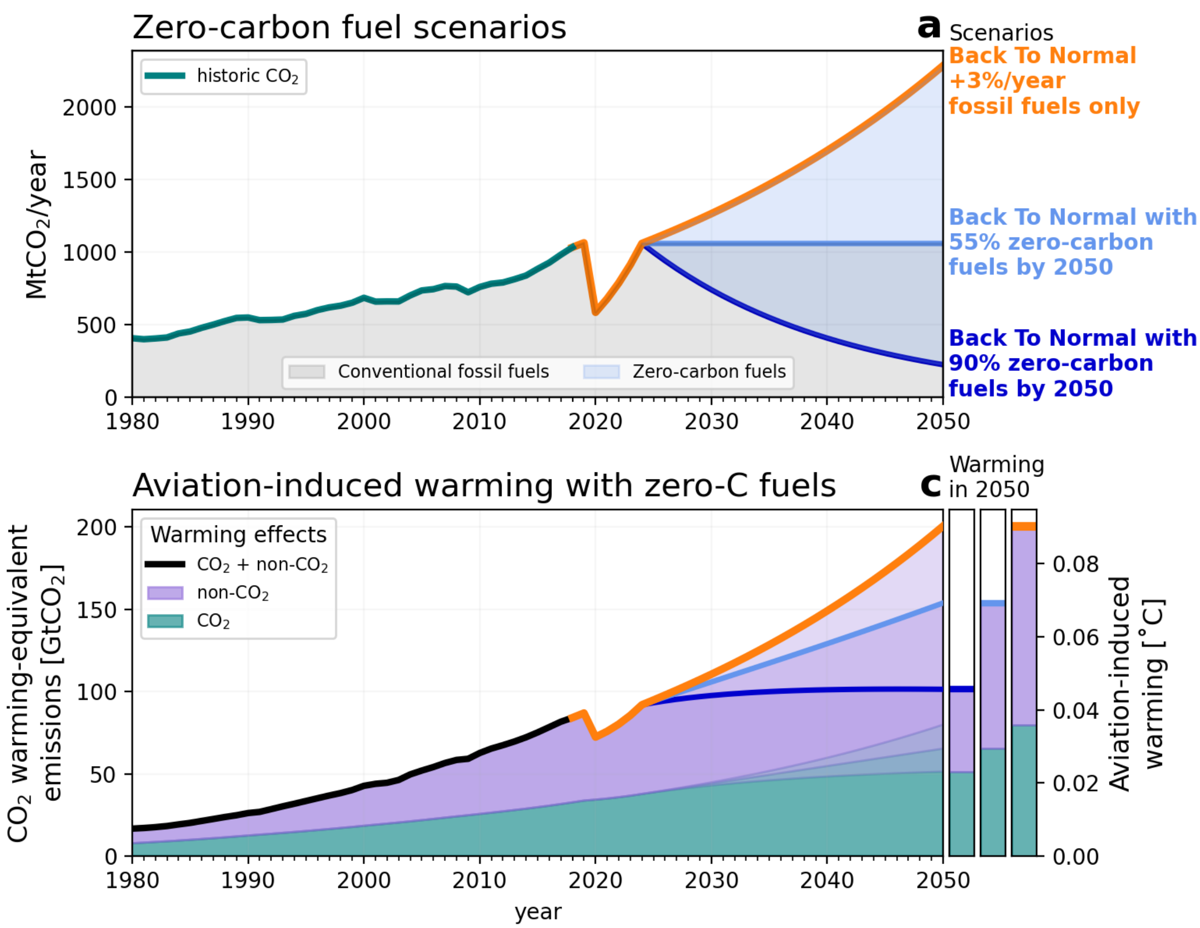

Figure 3. Zero-carbon fuels (bio or synthetic) can limit aviation-induced warming only when they replace fossil fuels by 2050. **a** CO_2 emissions of aviation following the 3% annual air traffic growth of the *Back To Normal* scenario (as in Figure 1) but with increasing use of zero-carbon fuels. **b** Aviation-induced warming in two scenarios: 55% zero-carbon fuels by 2050 will not limit the warming, only the highly ambitious scenario of 90% carbon neutrality reaches a maximum warming of about 0.04˚C. Scenarios are colour-coded as in **a**.

Potential of zero-carbon fuels

If 3% per year growth continues, the most obvious remaining option to reduce aviation's CO_2 emissions is rapid introduction of low-carbon fuel (bio or synthetic) as an alternative to conventional fossil-based jet fuel. Carbon emissions are compensated for (at least partially) during the growth-phase of respective plants, or in the extraction of CO_2 from the air for the production of synthetic fuels, if renewable energy is used (Yao et al. 2020). Although most non-CO_2 effects would continue to increase warming with increasing air traffic, contrail formation is predicted to be reduced by low-carbon fuels (Burkhardt, Bock, and Bier 2018; Voigt et al. 2021; Kärcher, Mahrt, and Marcolli 2021), see supplement. Changes in flight routes can also alter non-CO_2 effects. For example, adjusting aircraft cruise altitude can reduce the formation of contrails and hence the associated radiative forcing, by up to 60% (Teoh et al. 2020). However, additional CO_2 emissions may be incurred and persistent contrail formation cannot yet be predicted with sufficient accuracy. Hydrogen fuels are another possible alternative, but not considered here due to limited data on its non-CO_2 effects.

The *Back to Normal* scenario with an increasing use of low-carbon fuels, reaching 55% carbon-neutrality by 2050 (similar to IEA's *Sustainable Development Scenario*, (IEA 2020)), is investigated (Figure 3). Such a scenario will reduce aviation's contribution to global warming insufficiently to be sustainable, nor will it stop the non-CO_2 effects from increasing. Only a much more ambitious 90% carbon-neutral fuel-mix by 2050 will limit aviation-induced warming. Low-carbon fuels also need to compete with food crops to be sustainable, and emissions from land-use change need to be considered too.

Many carbon footprint calculators use a constant, so-called *multiplication factor* to include the non-CO_2 of aviation in a simplified way. For a 3% continuous annual growth in aviation the multiplication factor is approximately 2.6, such that the aviation-induced warming is 2.6 times greater than from its carbon emissions alone (Fig. 4). In general, multiplication factors are scenario and time-dependent and therefore should be used with caution in carbon footprint calculations. Nevertheless, for all scenarios the warming footprint of aviation is at least twice as large as its carbon footprint in the coming decade, clearly highlighting that non-CO_2 effects are non-negligible to assess the contribution of aviation to global warming.

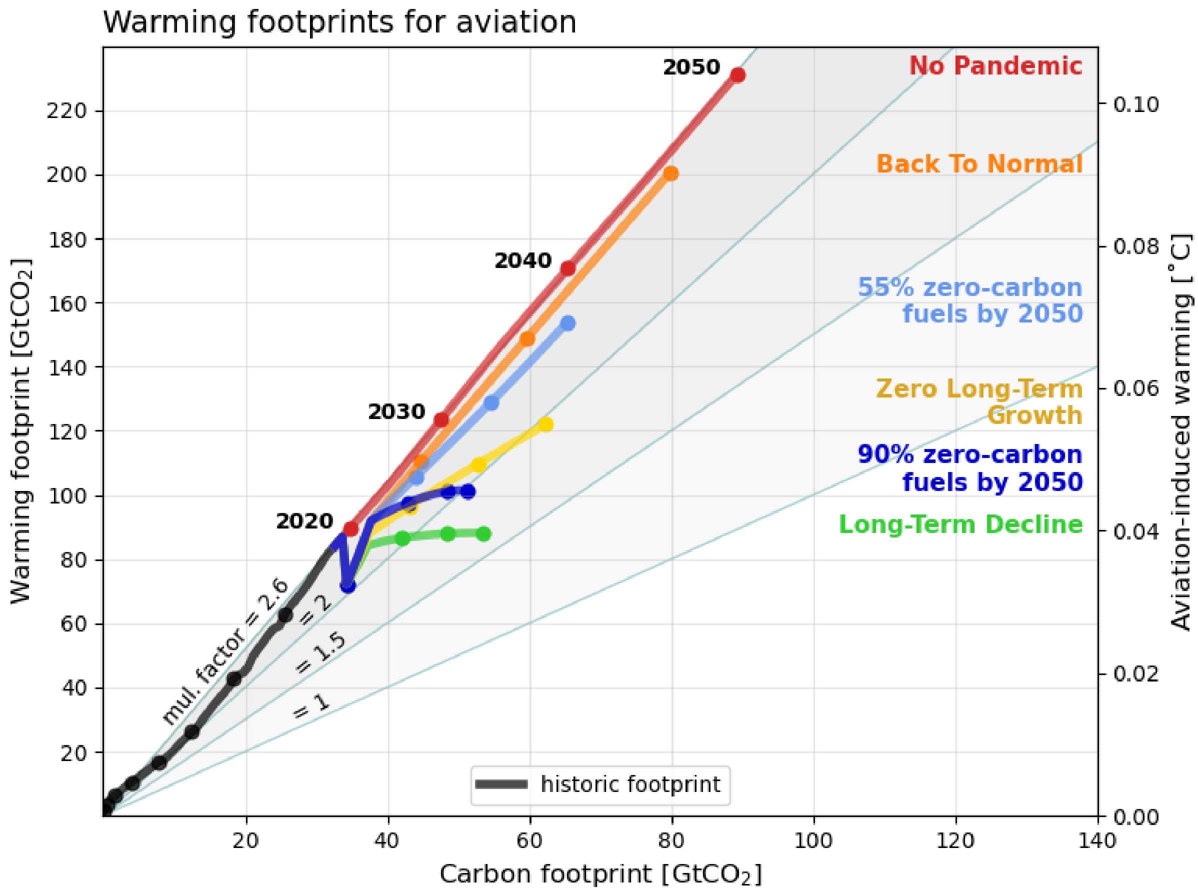

Figure 4. The warming footprint of aviation is a scenario and time-dependent multiplicative of its cumulative carbon footprint, about 2-2.6x larger in recent decades. Diagonal lines represent a constant *multiplication factor* often used in carbon footprint analyses to simplify the non-CO_2 effects of aviation. Dots represent decades for all scenarios and historic emissions. Warming footprints are the cumulative CO_2 warming-equivalent emissions, including both CO_2 and non-CO_2 effects.

Future of aviation

In conclusion, a significant on-going reduction of 2.5% per year in aviation CO_2 emissions limits the aviation sector's contribution to further global warming. Alternatively, or in combination, low-carbon fuels could replace fossil fuels over the next decades — a strategy that has to be treated with caution, as non-CO_2 climate impacts of alternative fuels are less well understood (Burkhardt, Bock, and Bier 2018). Planning on fuel efficiency improvements does not significantly reduce aviation's contribution to warming, as past progress in efficiency was overcompensated by air traffic growth and further efficiency potential is limited. More efficient jet engines tend to produce more contrails, such that savings in fuel could be overcompensated by the warming effect of contrails (Schumann 2000).

The pandemic has forced us to limit international travel — is this an opportunity to reevaluate the structures within aviation and to rethink its possible future? Such a reevaluation would benefit from greater clarity about how aviation actually contributes to changing global temperatures, a link that is currently obscured by conventional "carbon footprint" metrics. Expressing the impact of aviation in terms of warming-equivalent emissions makes this link clear, and also reveals that a decline of 2.5% per year would be consistent with no additional aviation-induced warming. Rapid introduction of low-carbon fuels, provided these are themselves sustainable, can support this.

The pandemic and a boom in virtual technology has led many to question the necessity of flying. Nevertheless, mobility is an essential aspect of a globalised society, which has to be decoupled from aviation's climate impact to mitigate the climate crisis. The powerful leveraging effect of non-CO_2 climate drivers means this could be achieved surprisingly rapidly through a 2.5% per year contraction over the coming decades, buying time to develop fully sustainable solutions.

Funding

MK gratefully acknowledges funding by the National Environmental Research Council under grant number NE/L002612/1. SRP's research was funded by the UK Research and Innovation COVID urgency grant scheme, grant number NE/V00946X/1. DSL and AS were supported by the UK Department for Transport and the European Union's Horizon 2020 Research and Innovation Action ACACIA under grant agreement number 875036.

Declaration of competing interest

The authors declare no competing financial interests to influence this work.

Data and materials availability

All data are available in https://github.com/milankl/FlyingClimate (will be converted to DOI upon acceptance) and described in the supplementary information. Only the No Pandemic scenario uses data from the International Energy Agency (IEA) which is subject to copyright and cannot be shared. Fig. S1 illustrates that data and shows how it can be well approximated for reproducibility. European flight history data are retrieved from the European Organisation for the Safety of Air Navigation (EUROCONTROL) STATFOR dashboard and is copyright by EUROCONTROL, 2020.

Appendix

1. Flight data

The European flight data shown in Fig. 1 were extracted from the EUROCONTROL STRATFOR system and includes all civilian aircraft required to file flight plans in European airspace each day. The daily flight data in Figure 2b were derived from the Opensky database (Strohmeier et al. 2021; Schäfer et al. 2014). Aircraft positions were downloaded and processed into individual flights by detecting take-off and landings (Proud 2020).

The annual fuel consumption of aviation and the data of total distance covered per year are from Lee et al. 2020 originally derived from International Energy Agency (IEA) data on JET-A fuel usage and aviation gasoline. Data on aviation's CO_2 emissions dating back to 1940 is taken from Sausen and Schumann, 2000 (Sausen and Schumann 2000).

2. Effective radiative forcings

Based on the annual fuel consumption of aviation, the emissions of CO_2 and other greenhouse gases and aerosols are calculated following the emission indices from Table 1, which are the best estimate from Lee et al. 2020.

	Emission index [per kg fuel]	Effective radiative forcing
Carbon dioxide CO_2	3.16kg	(from climate model)
Water vapour H_2O	1.231kg	0.0052 mW/m^2/(Tg (H_2O)/year)
Black carbon (BC)	0.03g	100.67 mW/m^2/(Tg (BC)/year)
Sulfate SO_2	1.2g	-19.91 mW/m^2/(Tg (SO_2)/year)
Nitrogen oxides NO_x	15.14g (in 2018)	(via CH_4, O_3 and strat. H_2O)
Methane CH_4 decrease	-	-18.69 mW/m^2/(Tg (N)/year)
Ozone O_3 short-term increase	-	34.44 mW/m^2/(Tg (N)/year)
Ozone O_3 long-term decrease	-	-9.35 mW/m^2/(Tg (N)/year)
Stratospheric H_2O (SWV) decrease	-	-2.8 mW/m^2/(Tg (N)/year)
Contrail cirrus	-	9.36 x 10^{-10} mW/m^2/km

Table 1: Best estimate emission indices and effective radiative forcing for aviation emissions and contrail formation from Lee et al. 2020. Effective radiative forcings from NO_X arise via reaction with CH_4, O_3 (short and long-term) and stratospheric water vapour and are noted therein. Consequently, the radiative forcings of these scale with the emission of NO_x.

The emissions indices for CO_2 and water vapour are fixed for fossil fuel. The emission index for NO_x has been increasing from 9.8g/kg fuel in 1980 over to a value of 15.14 g/kg fuel in 2018 and is not assumed to increase further. The emission index for S is dependent on the fuel S content, which is only poorly known but is assumed to have an average of 600 ppm by volume. Soot emission indices are only very poorly known. Further documentation on these emission indices and the data quality/sources of information can be found in Lee et al. (2020). The total non-CO_2 effective radiative forcing $F_{\text{non-CO}_2}$ is approximately the arithmetic sum of the individual components (David S. Lee et al. 2020)

$$F_{\text{non-CO}_2} = F_{\text{H}_2\text{O}} + F_{\text{BC}} + F_{\text{SO}_2} + F_{\text{CH}_4} + F_{\text{O}_3\text{short}} + F_{\text{O}_3\text{long}} + F_{\text{SWV}} + F_{\text{contrail}} \quad (2)$$

The annual effective radiative forcings $F(t)$ for non-CO_2 are extrapolated for time t in years into the future under a p -percent growth model as follows

$$F(t) = F_0(1 + \frac{p}{100})^{t-t_0} \quad (3)$$

with F_0 being the initial forcing at the start t_0 of the scenario.

3. Radiative forcing of CO_2

Using the Finite Amplitude Impulse Response (FaIR) climate model (C. J. Smith et al. 2018), the carbon emissions of aviation are converted to a radiative forcing, which amounts to 32.6 mW/m^2 in 2018 (Fig. S2b), about 2% of the total anthropogenic forcing from CO_2 (Intergovernmental Panel on Climate Change 2015). As a baseline we use RCP2.6, 4.5 and 6.0, and attribute the CO_2 radiative forcing from aviation by subtracting aviation emissions from the baseline CO_2 emissions. The effective radiative forcing for CO_2 is then taken as the average of the three scenarios RCP2.6, 4.5 and 6.0.

4. Warming-equivalent emissions

For F in equation (1) the sum of the effective radiative forcings of non-CO_2 effects (Fig. S2b) is used, assuming independence of the different effects (e.g. the aircraft impact of NO_x is sensitive to the chemistry of the background atmosphere (Skowron et al. 2021), here the future atmosphere is assumed to be the mean of the three Representative Concentration Pathways scenarios[8]).

The year 1940 is taken as the start of commercial aviation, such that the considered time period is $\Delta t = t - 1940$. The linear operator L is a lower triangular Toeplitz matrix integrating the CO_2 emissions since 1940 to effective radiative forcing in year t with exponentially decaying weights (*e*-folding time scale is about 200 years) for years further in the past. Applying its inverse to the time series of cumulative non-CO_2 radiative forcing $\bar{F}\Delta t$ therefore returns the cumulative CO_2 that would cause the same warming on a multi-year time scale. For further information see Smith et al. 2021 (M. Smith, Cain, and Allen 2021).

5. Zero-carbon fuels

Alternative fuels from bio- or power to liquid sources have a very small change in emission indices with a different overall C/H ratio to fossil kerosene, but are considered to be insignificant for the purposes of this work. Low-carbon fuels tend to reduce contrail formation through soot particles. We parametrize this effect based on Burkhardt et al. 2018 (Fig. 1f therein) to reduce the radiative forcing F_contrail by

$$F^*_\text{contrail} = \sqrt{m} F_\text{contrail} \quad (5)$$

where $1 - m$ is the effective share of zero-carbon fuels in the fuel mix. The average CO_2 emission index of 3.16kg/kg of fuel (Table 1) is effectively reduced to 3.16m kg/kg of fuel. Zero-carbon fuels are assumed to be fully carbon-neutral.

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Supplementary Information

Figures

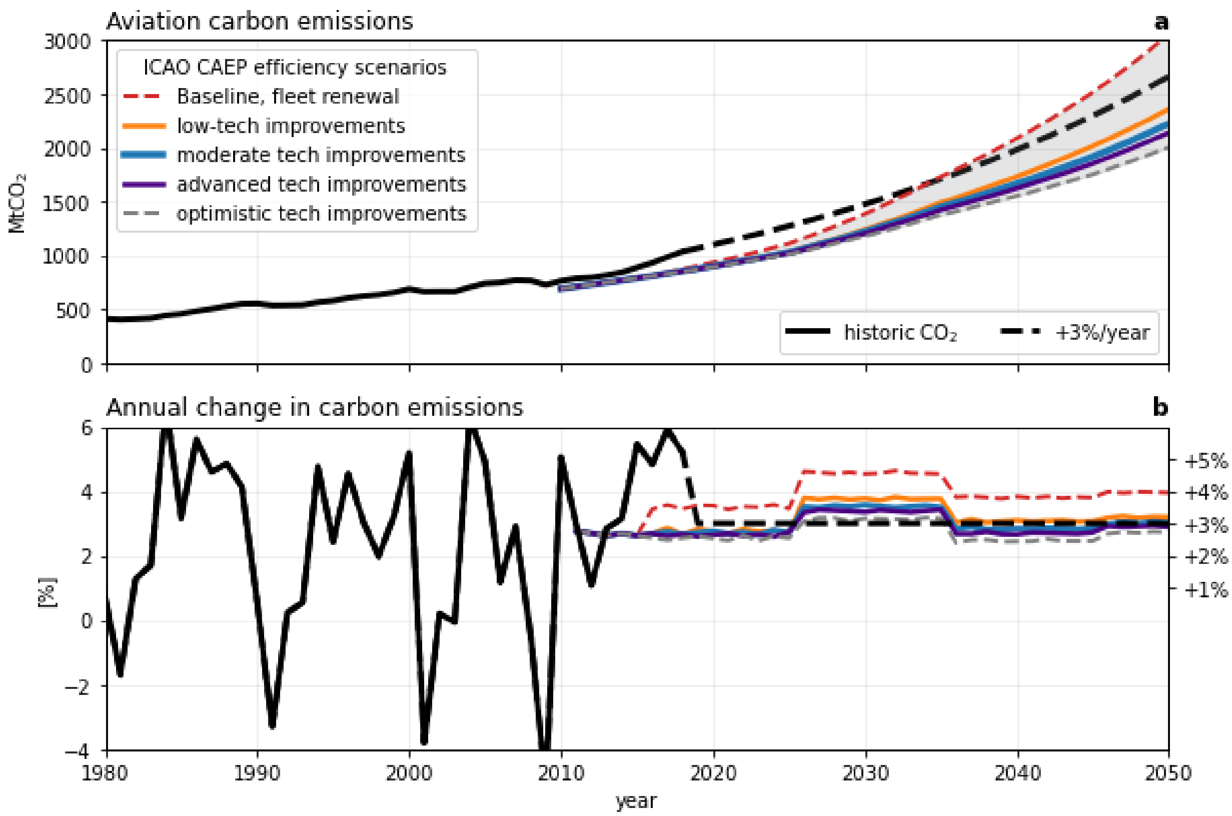

Figure S1. Annual increase in aviation CO_2 emissions for historic emissions and future projections. **a** Historical emissions (1970-2018) are taken from data of the International Energy Agency (IEA) as in Lee et al. (2020). The *No Pandemic* scenario here is taken from a mid-point growth scenario developed by the International Civil Aviation Organization (ICAO) which assumes moderate improvements in technology and operations (Fleming and de Lépinay 2019) and increases by about 3%/year. **b** Growth factors are utilized rather than the absolute data because of the well-known (~10-12%) mismatch between bottom-up idealized inventories and actual fuel usage recorded by the IEA (David S. Lee et al. 2009).

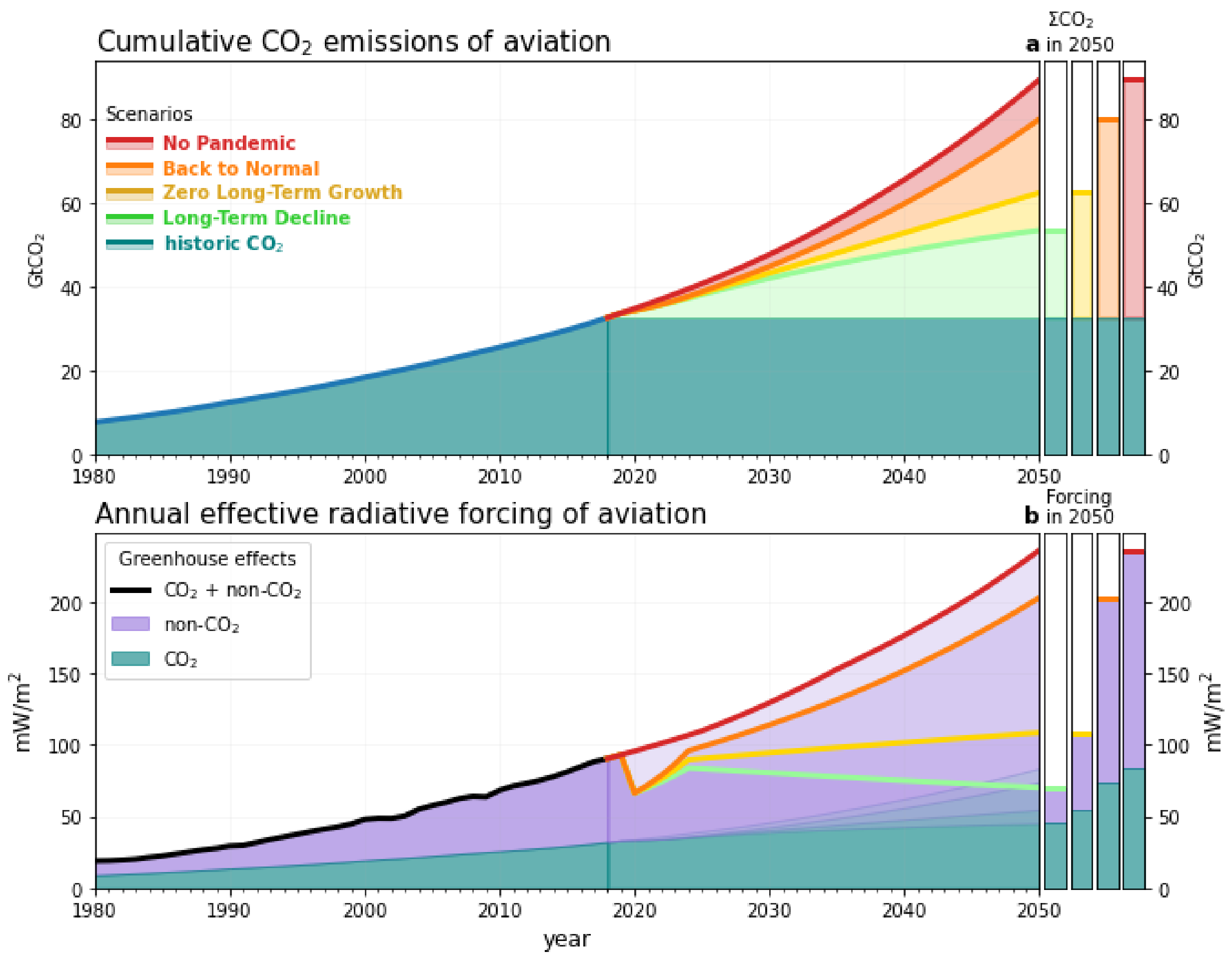

Figure S2. Non-CO_2 greenhouse effects dominate over CO_2 emission in the effective radiative forcing from aviation. **a** Aviation's cumulative CO_2 emissions from 1940 to 2018 for historic emissions and until 2050 following the four scenarios as in Fig. 1 (same colour-coding). **b** Annual effective radiative forcing resulting from CO_2 and non-CO_2 effects (see Fig. S3) until 2050 under the scenarios from **a**.

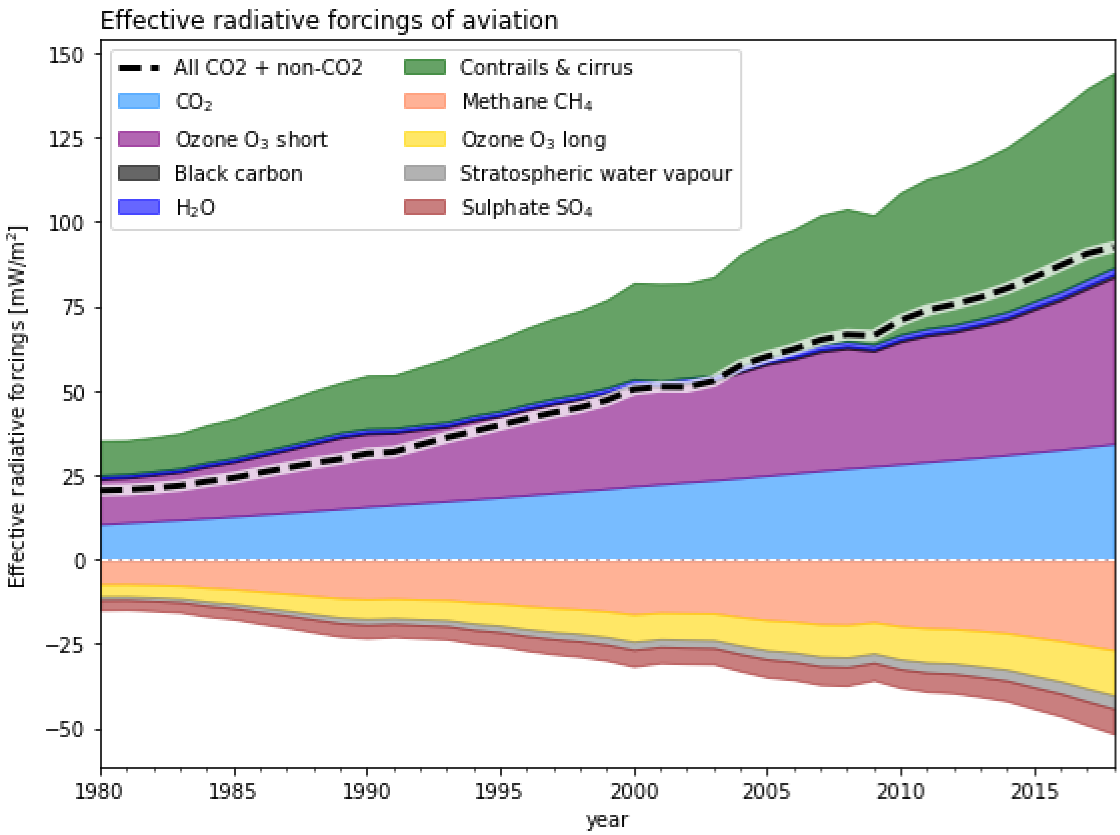

Figure S3. Contributions to CO_2 and non-CO_2 (all other) greenhouse effects from global aviation, based on historic fuel consumption and flight distances from 1980 to 2018. See Table S1 and Lee et al. (2020) for further information.