 doi:10.20944/preprints202012.0266.v1

Paper title: The potential climatic significance of the global reduction in aviation during the pandemic

Author: Dr Sally Cairns

Abstract: *This paper suggests that, in 2020, the beneficial atmospheric effect from the reduction in aviation could be at least 7-8 times as great as that occurring from the global reduction in fossil carbon dioxide emissions. Specifically, compared to potential atmospheric effects in 2020 without the pandemic, the decrease in effective radiative forcing from reduced contrail-cirrus formation may be in the order of 35mWm^{-2} in 2020, compared to a reduction of only 4-5mWm^{-2} from the drop in fossil CO_2 emissions. Over time, pursuing a low carbon pathway generates benefits that mount up to be much more significant than 2020 effects might imply, and is essential to stabilise the climate. However, this paper argues that a twin-track policy focus may be needed, with more emphasis on reducing short-term climate forcing, to minimise the impacts of climate change now, and to avoid detrimental feedback events. Future policy decisions about aviation should be made in this context.*

Keywords: Aviation, transport policy, climate change, pandemic, non-CO_2, contrail-cirrus

Email: S.Cairns2@leeds.ac.uk

Affiliation: Senior Research Fellow, Institute for Transport Studies, University of Leeds, Leeds, UK.

ORCID: 0000-0002-1174-991X

Acknowledgements: The author gratefully acknowledges support from UK Research and Innovation through the Centre for Research into Energy Demand Solutions, grant reference number EP/R 035288/1. This paper builds on the work of others – notably the papers by Lee et al (2020) and Forster et al (2020). Whilst there is no suggestion that these authors endorse the arguments made here, the importance of their work to this study is acknowledged. Also, grateful thanks to Piers Forster, Nick Eyre and Tim Johnson for their helpful advice.

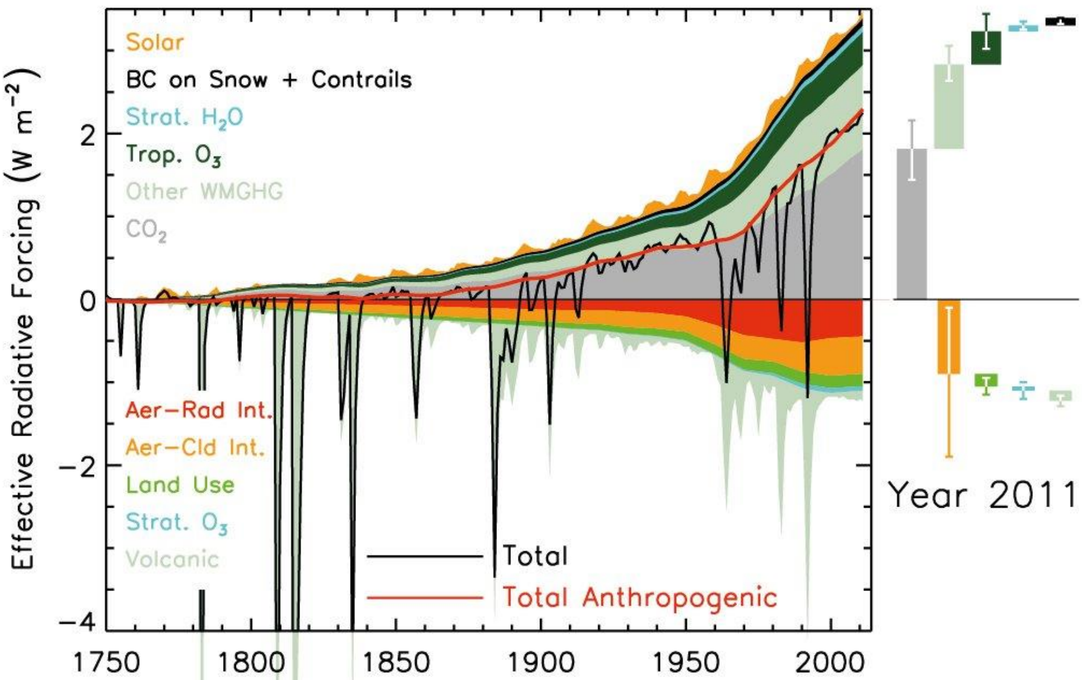
1. Introduction

It was disheartening to read the work by Le Quéré et al (2020) in May, estimating that the huge behavioural changes brought about by the pandemic might only reduce the world's annual carbon dioxide emissions by 7% in 2020; or the study by Forster et al (2020) suggesting that "*the direct [climatic] effect of the pandemic-driven response will be negligible*". Forster et al's central contention - that a green economic recovery is essential to stabilise climate impacts – is undoubtedly correct. However, estimations for one of the climate forcing agents generated by aviation suggests that the short-term climatic effect of the pandemic may have been considerably greater than some of this work implies. Specifically, according to first-order approximations, in 2020, reductions in contrail-cirrus formation may have had a beneficial atmospheric effect which is *7-8 times greater* than that resulting from the world reduction in fossil CO_2 emissions. Clarifying whether this has occurred in practice, and whether, therefore, cuts to sectors like aviation that have strong short-term effects can help to 'buy time' for solving the longer-term challenges of climate change, should be a priority for future policy thinking, and guide the extent to which governments encourage a return to the previous growth in aviation.

2. Background

A key IPCC approach to evaluating the importance of different elements of climate change is illustrated in Figure 1, reproduced from their Fifth Assessment Report (Myhre et al, 2013a).

Figure 1: *Time evolution of forcing for anthropogenic and natural forcing mechanisms, according to the IPCC Fifth Assessment Report. Reproduction of Figure 8.18 of Myhre et al (2013a), p699. Bars with the forcing and uncertainty ranges (5 to 95% confidence range) for 2011 vs 1750 are given in the right part of the figure*



'Effective radiative forcing' (ERF) – the measure used in the graph - gives a measure of the change that has occurred to the atmosphere's propensity to trap radiation over time. Specifically, Myhre et al (2013a) define it as "*the change in net top-of-the-atmosphere downward radiative flux after allowing for atmospheric temperatures, water vapour and clouds to adjust, but with surface temperature or a portion of surface conditions unchanged*", and it is measured in (m)Wm^{-2}. The values in each year reflect the effects of all the human activities (and natural changes) that have taken place since 1750, up to that point in time. So, for example, the carbon dioxide value in 2011 is determined by the long-term atmospheric accumulation of carbon dioxide, since it stays in the atmosphere for a relatively long time without dissipating. In effect, additional units of CO_2 are like adding semi-permanent insulation around the earth. As the graph shows, the effects are mounting up alarmingly. By 2011, the central estimate for the total ERF due to CO_2 was +1,816 mWm^{-2}, and from all anthropogenic activities was +2,294mWm^{-2}.

In contrast, some of the other effects shown in this figure do not mount up in the same way, but are, instead, continuously dissipating and being replaced. One of the most extreme examples is the contrail-cirrus effect from planes. When the environmental conditions are right, trailing clouds of ice crystals form in the wake of a plane flight, which, in turn, sometimes affect cirrus cloud formation. These cloud structures both reflect sunlight back into space and radiation back down to earth, with, *on average*, the net effect being that they trap more radiation than they deflect. However, they are not permanent structures. Effectively, they are like temporary insulation, which dissolves relatively quickly but (in normal circumstances) is being constantly replaced as a result of new flights. So, for this graph, the effect of contrail-cirrus in 2011 was estimated to be +50mWm^{-2}. However, most of this effect would have been generated *in* 2011 rather than representing an accumulated effect over many years.

Finding appropriate ways to consider the significance of different atmospheric forcing agents, given their differing timescales of impact, is one of the headaches that climate scientists face, and has led to a plethora of climate metrics depending on the question of interest (including both 'backward' looking metrics such as ERF, and 'forward' looking metrics such as GWP, GWP* and GTP). Forward looking metrics are usually most suitable for considering relatively stable growth trends, and for looking a long way into the future, with 100 years typically used as the standard.

However, there are two problems with this approach. The first is that use of longer-term metrics tends to devalue those solutions which could lead to short term cuts in climate warming *without* a detrimental growth in longer term impacts. The second is that such metrics may not be particularly suitable for considering major disruption to trends, as has occurred with the pandemic. This paper focuses on a simple comparison of potential changes in ERF values to illustrate this.

3. How contrail-cirrus effects may have changed in 2020

A paper published by Lee et al (2020) reflects the latest understanding of the climate impacts of aviation (up to 2018). Specifically, their data (c.f. their Table 2) suggests that, in 2018, a central estimate of the ERF due to aviation was +100.9mWm^{-2} (55, 145), with 34.3mWm^{-2} (28, 40) being due to the CO_2 from aviation, and 57.4mWm^{-2} (17, 98) coming from contrail-cirrus. (Figures in brackets give the 5% and 95% confidence intervals.) The remaining 9.2mWm^{-2} was comprised of a mixture of positive and negative climate forcing caused by NOx, water vapour, soot and sulphate aerosols. Between 2011 and 2018, using central estimates, their figures suggest that the total ERF due to aviation grew by 25%, from 80.4mWm^{-2}, whilst the ERF due to contrail-cirrus grew by 30%, from 44.1mWm^{-2}. (This 2011 figure updates the IPCC estimate of 50mWm^{-2} in 2011).

Lee et al compare their calculations with the IPCC estimates to suggest that, in 2011, aviation was responsible for 3.5% of all anthropogenic ERF. On this basis, it appears to be a relatively small contributor to the climate impacts generated by all human activities. However, its contribution looks very different if evaluating how the atmosphere in 2020 is different to what it might have been without the pandemic.

To the author's knowledge, although there are practical investigations taking place, (see Doyle 2020), there is no available modelling work that has yet answered this question, and correspondence with one of the leading experts on contrails suggests that a substantial amount of data on meteorology and flight patterns for the year would be required to estimate this accurately. (Although Forster et al (2020) do consider contrails, according to personal correspondence, the modelling results produced for this element are considered unreliable at present.) Instead, therefore, this paper attempts some first-order approximations, based on an extrapolation of available information.

Without the pandemic, the recent growth in aviation was expected to continue (IATA 2018, Bock & Burkhardt 2019). Suppose that, without the pandemic, the average annual growth in aviation contrails between 2018 and 2020 was equivalent to that which occurred between 2011 and 2018 (see Section 7 for justification). This might have led to a 2020 contrail-cirrus effect of about 61.2mWm^{-2}.

Then suppose that, as a first order approximation, the annual reduction in contrail-cirrus effects has been proportionate to the reduction in aviation activity. As explained in Section 7, IATA estimates suggest that 2020 plane miles may be less than 45% of those operating in 2019. If, as a result, contrail-cirrus also reduced by this amount, the ERF from this component of aviation in 2020 might be 26.7mWm^{-2}. The implied difference is a reduction of 34.5mWm^{-2} across the year as a whole.

This is inevitably inaccurate – contrail-cirrus effects from aviation are hugely dependent on when and where flights take place, including geographical region, altitude, time of day and season (see, for example, Lund et al, 2017, Dahlmann et al 2016, Stuber & Forster 2007). According to IATA data about passenger traffic (Pearce, 2020), whilst all markets have taken a hit, the effects vary across time and space. Domestic flying has generally recovered more than international flying; Chinese/Russian domestic flights, and international European flights show a greater recovery than other domestic and international flights respectively; and the biggest reductions in flights occurred during April-July. Assuming that the same pattern is true for plane miles, on the one hand, the figure given above could be an overestimate – since the greatest reduction in flights in the northern hemisphere has coincided with spring/summer, when contrails are less likely to form. On the other hand, it could be an underestimate – since the reduction in longer flights – with a greater proportion of mileage undertaken at altitudes likely to generate contrail-cirrus effects – may have been greater than the reduction in shorter flights. There are also many other factors which might affect calculations. However, from the readily available evidence, this calculation gives a first-order indication of potential magnitude.

Looking further ahead, the outlook for the aviation sector is very unclear. For simplicity of comparison with Forster et al (2020)'s 'two year blip' scenario, suppose that aviation returns to 2019 levels by 2023, and then assumes previous growth rates (i.e. the average annual rate of growth seen between 2011 and 2018). This might imply a contrail-cirrus effect of +63.1mWm^{-2} in 2025 and 72.6mWm^{-2} in 2030.

The data from this section is compared with data on CO_2 impacts in Section 5 of this paper.

4. How CO_2 effects may have changed in 2020

The 2019 Global Carbon Budget, produced by the Global Carbon Project (Friedlingstein et al, 2019) provides evidence about global trends in 'fossil' carbon emissions (i.e. emissions generated from fossil fuel use and industry). Specifically, its central estimates suggest that these emissions increased from 35.4 $GtCO_2$ in 2016; to 35.8 $GtCO_2$ in 2017; 36.6 $GtCO_2$ in 2018; and an estimated 36.8 $GtCO_2$ in 2019. These have fed into changing atmospheric concentrations of CO_2, which, as a result of all carbon cycle elements, were estimated to be 402.85 in 2016, 405.00 in 2017, 407.38 in 2018 and predicted to be 409.85 in 2019.

The formula given in Myhre et al (2013b) indicate that these atmospheric concentrations of CO_2 would correspond to ERF values of +1985mWm^{-2} (2016); +2013mWm^{-2} (2017); +2044mWm^{-2} (2018) and +2077mWm^{-2} (2019). The difference between the years comprises +28mWm^{-2} (2016-17); +31mWm^{-2} (2017-18); and +33mWm^{-2} (2018-19).

In May 2020, Le Quéré et al provided an estimate of the impacts of the behaviour changes brought about by the pandemic on global fossil carbon emissions. Their central estimate was that, at most, daily global carbon dioxide emissions decreased by 17% by early April 2020 compared with mean 2019 levels, and that annual emissions in 2020 could be -4% to -7% lower than in 2019. In July, Forster et al (2020) updated their work, using mobility data from Apple and Google. Their figures suggest that global fossil CO_2 emissions were potentially as much as 30% below 2019 levels during April 2020, and that, for 2020 as a whole, they may be 12-15% lower than 2019 emissions, partly depending on the economic stimulus recovery packages that governments adopt (see Section 7 for calculations).

The Forster et al study also suggests that, in terms of the impacts of changes in fossil CO_2 emissions on ERF in 2020, compared to what would have happened if countries had followed an expected 'baseline' pathway, the difference will be only -4.3 to -5.0mWm^{-2}.

However, their work also looks forward, and highlights the difference in ERF values from fossil CO_2 that could arise, depending on government decisions following the pandemic. Their 'strong green stimulus' pathway assumes a change in CO_2 levels which is equivalent to only a 6-7% drop in emissions each year, from 2019 levels. By 2025, given the cumulative effects of CO_2, the difference between adopting this pathway, and a 'two-year blip' scenario, where countries return to their previous pathway by 2023, would have generated to an ERF difference of 51.5mWm^{-2}. By 2030, this

ERF difference would have increased to 174.6mWm^{-2}. Even a 'moderate green stimulus' pathway, equivalent to a 3-4% annual drop in CO_2 emissions from 2019, would make a difference of 119.1mWm^{-2} by 2030.

5. Comparing the ERF estimations for contrail-cirrus and CO_2 changes

The calculations from the sections above are illustrated in Figures 2 and 3.

Figure 2: *Potential additional ERF contribution from fossil CO_2 and contrail-cirrus in 2020, compared to 2019, with and without the pandemic (first order approximations)*

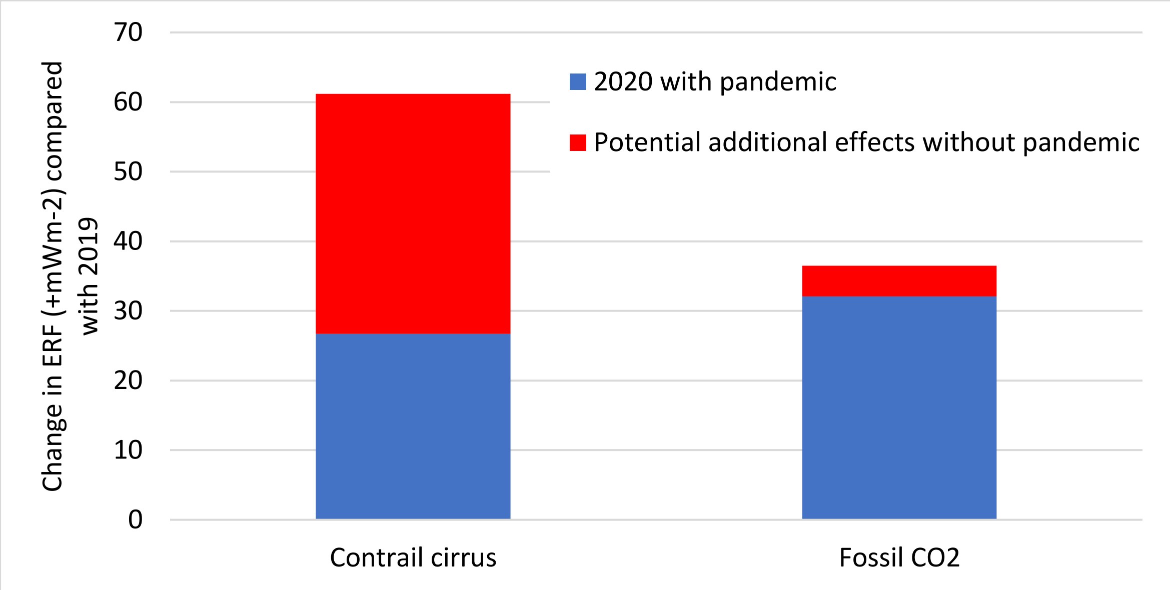


Figure 3: *Difference in ERF values in 2025 and 2030 from choosing different pathways for aviation and fossil CO_2 (first order approximations)*

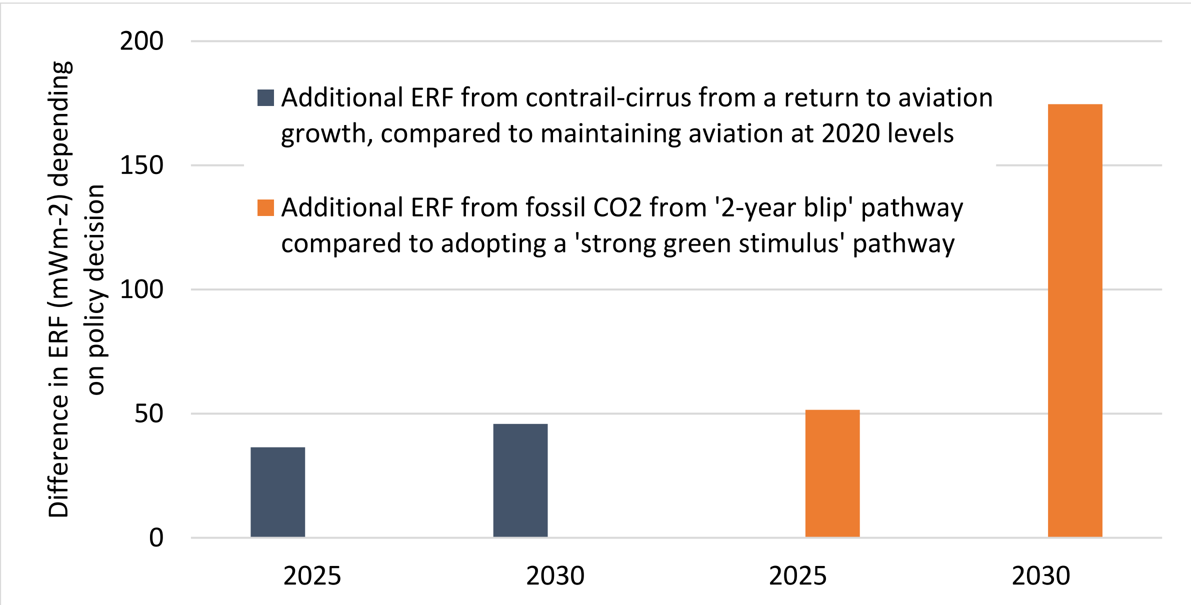


Figure 2 illustrates the first-order estimations for 2020, and suggests that the decrease in atmospheric effects caused by the reduction in contrail-cirrus is potentially 7-8 times greater than that caused by the reduction in global fossil CO_2 emissions.

Figure 3 then looks at the effects of choosing different policy scenarios over a longer time period. Specifically, it compares:

- The effects of aviation returning to 2019 levels in 2023, and then continuing on its previous growth trajectory *compared to* limiting aviation to 2020 levels; and
- Returning to previous fossil CO_2 trajectories by 2023 *compared to* adopting a 'strong green' pathway.

Because the aviation contrail-cirrus effect is only temporary, the potential reduction in ERF in 2025 or 2030 from constraining aviation is not that different to the reduction realised in 2020. In contrast, because the effects of fossil CO_2 are cumulative, the potential reduction in ERF increases over time, so that, by 2030, the effect on ERF of choosing a low carbon pathway from 2020 clearly outweighs the effect of only limiting aviation contrail-cirrus from 2020. At the same time, even in 2030, the potential additional atmospheric effect from allowing aviation to return to previous growth trajectories is not trivial.

There are many caveats relating to these calculations, as already outlined above. It should also be noted that calculating ERF values for contrail cirrus has a considerably greater uncertainty range than calculating the ERF values associated with carbon dioxide emissions, as shown by the $5^{th}/95^{th}$ values quoted from Lee et al (2020) for these two effects from aviation (see Section 3).

The other issue is that aviation is, of course, a contributor to fossil carbon, responsible, in 2018, for 2.4% of anthropogenic emissions of CO_2 (if including those from land use change), according to Lee et al (2020). Inclusion of aviation's CO_2 effects, and other non-CO_2 effects, would increase the ERF values for the effects of aviation overall. Equally, any low carbon pathway would logically lead to some constraint of aviation anyway, such that the scenarios discussed above are not, in practice, mutually exclusive.

6. Discussion

The calculations given above suggest that, in 2020, as a result of the pandemic, the beneficial short-term atmospheric effects from the reduction in aviation contrail-cirrus could be considerably greater than those occurring from the global reduction in carbon dioxide emissions from fossil fuel use and industry. Longer-term, the cumulative effects of adopting a low carbon pathway outweigh the effects of only limiting aviation, although even by 2030, the effects of simply limiting aviation contrail-cirrus formation are not negligible in comparison to the potential benefits from reducing global carbon dioxide emissions.

The first key point to make is that the aviation component of these calculations is neither the result of climate models nor of observed atmospheric changes. As such, it does not provide conclusive evidence. However, the figures serve to highlight a contention which seems of sufficient importance that it merits discussion.

Second, altering the magnitude of short-term forcing agents – like contrail-cirrus – cannot 'solve' climate change. As the ominous grey area in Figure 1 indicates, the effects of CO_2 are mounting up continuously. Reducing short-term effects may result in a dip in the overall trend, but it will continue upwards, unless CO_2 emissions are addressed. Put another way – reducing the short-term 'insulation' around the planet may be beneficial, but it cannot counteract the effects of increasing semi-permanent 'insulation'. As Lee et al (2020) highlight "*some combination of reductions in* CO_2 *emissions and non-*CO_2 *forcings might halt further warming temporarily, but only for a few years" … "neither condition is sufficient alone".* Instead, as Forster et al (2020) highlight *"economic investment choices for the recovery will strongly affect the warming trajectory by the mid-century. Pursuing a green stimulus recovery out of the post COVID-19 economic crisis can set the world on track for keeping the long-term temperature goal of the Paris Agreement within sight".* This is also relevant in relation to specific aviation solutions, where adopting solutions that would reduce non-CO_2 effects, but increase CO_2, is unlikely to be wise.

Whilst this point is critical, at the same time, it is important to recognise that certain behavioural change can result in relatively large atmospheric effects. Some commentary on the Le Quéré et al (2020) paper implied that, if the pandemic-engendered changes to behaviour had made such little difference to CO_2 emissions, the world was truly doomed. Hopefully, these calculations provide a little more hope for optimism. Specifically, Figure 2 aims to show that some short-term effects can be very large, whilst Figure 3 shows how relatively modest annual changes to long-lived pollutants can make a relatively large difference over time.

The calculations also highlight that, given its large short-term effects, aviation may be a particularly important area of activity to target. It is critical to consider its non-CO_2 effects in future policies – including those that relate to the desirable scale of the sector as a whole, and those that might be used to address its non-CO_2 impacts *without* increasing its CO_2 emissions.

Finally, this paper aims to highlight the general importance of considering short-term climatic effects. Forster et al (2020) highlight several other short-term effects from the pandemic that are also dramatically greater than the immediate effects from the reduction in carbon dioxide emissions (or, indeed, from aviation). Of these, the largest comprise a cooling effect from a reduction in tropospheric ozone, estimated to be a ERF change in 2020 of -46.3 to -51.8mWm^{-2} compared to 'baseline pathway' predictions, largely as a result of a reduction in NOx emissions from surface transport; and a warming effect from a reduction in aerosol emissions, estimated to be an ERF change in 2020 of +70.8 to +85.3mWm^{-2} compared to 'baseline pathway' predictions, reported to primarily result from changes in the power and industry sectors. Forster et al highlight the risks that may result from the short-term changes to aerosol emissions, which could contribute to increasing regional likelihood of extreme weather.

The IPCC (see IPCC 2018) already has a substantial strand of work focused on short-term climate forcing agents, with various studies showing that strategies which address them could affect both global and regional climate patterns over different timescales (e.g. Zhang et al 2018, Hanaoka & Masui 2020, Lund et al 2020, Harmsen et al 2019), including via indirect impacts on the carbon cycle (Fu et al, 2020). However, the changes wrought by the pandemic serve to highlight the scale and speed with which they might make a change to the atmosphere's propensity to trap radiation in the next few years, and therefore potentially 'buy us time'. Reducing CO_2 needs to be a priority now – but it is unclear whether it will be enough to avoid some of the irreversible changes that may occur – such as species extinction or ice cap loss. Lenton et al (2019), commenting in Nature, highlighted nine potentially irreversible 'climate tipping points', which are "*too close for comfort*".

Instead, a twin-track strategy seems key. *As well as* the current focus on carbon dioxide and other long-lived greenhouse gases, perhaps there should be increased political focus on short-term forcing agents? Whilst this might only be a delaying tactic, perhaps it could provide enough time to generate solutions to ensure that some irreversible changes never occur? Conversely, without a focus on short-term agents, presumably the likelihood of higher temperatures in individual years – and calamitous feedback from events like the fires in Australia, the Amazon, Siberia and California this year – becomes ever more likely?

This paper cannot answer these questions. However, by illustrating the potential scale of the different effects, it aims to highlight why they are important to ask.

 doi:10.20944/preprints202012.0266.v1

7. Supplementary details of data:

Estimations of aviation statistics:

Data from https://www.airlines.org/dataset/world-airlines-traffic-and-capacity/# suggests that, between 2011 and 2018, aircraft miles increased each year, equivalent to an average compound annual growth rate (CAGR) of +4.3%.

IATA (the International Air Transport Association) produces regular estimates of available seat kilometres (ASK) on planes. Whilst not the same as plane miles, in the absence of a better measure, ASK is used here as a proxy for air miles.

In terms of pre-pandemic expectations of growth, in December 2019, IATA (2019) were predicting that ASK had increased by 3.5% in 2019 and would increase by 4.7% in 2020, which, averaged over the two years, is reasonably similar to the CAGR of 4.3% that occurred between 2011 and 2018, justifying the linear extrapolation of the increase in contrail-cirrus ERF values between 2018 and 2020 (though implying the 2019 value used may be slightly high).

In terms of pandemic impacts, in June 2020, IATA (2020a) provided an assessment of the aviation market in 2020, suggesting that ASK were expected to reduce by 40.7%, and that revenue passenger kilometres (RPK), a measure of passenger traffic, was expected to reduce by 54.7%. In August, IATA (2020b) figures suggested that, for 2020 year-to-date, ASK were 55.3% lower than 2019, and RPK were 63.7% lower than 2019. In September, IATA (Pearce 2020) revised their annual 2020 estimate of RPK to suggest that it might be 66% lower than 2019 (but did not provide an equivalent figure for ASK). Given the August data, and the close links between RPK and ASK, it seems reasonable to assume that ASK will be at least 55% below 2019 levels.

Estimations from Forster et al's 2020 paper:

Various figures used in this paper are not quoted directly from Forster et al's 2020 paper, but have been calculated from the pathway spreadsheets given in the GitHub repository for the paper's data, http://github.com/Priestley-Centre/COVID19_emissions

Specifically, the two year blip pathway suggests an increase in ERF from fossil carbon, from 2019, of +203.9mWm^{-2} by 2025 and +387.2mWm^{-2} by 2030. In contrast, following a 'moderate green stimulus' pathway would mean an increase in ERF from fossil carbon of +168.7mWm^{-2} by 2025 and +268.1mWm^{-2} by 2030; whilst a 'strong green stimulus' pathway would mean an increase in in ERF from fossil carbon of +152.4mWm^{-2} by 2025 and +212.6mWm^{-2} by 2030.

Equivalent average annual reduction rates in CO_2 from 2019, for the moderate and strong green pathways, have been calculated by assuming a constant trend between 2019 values and 2030 values. The actual pathways used by Forster et al for calculations follow a more complex path. However, it is difficult to calculate meaningful annual rates that take these changes into account, given the substantial dip in 2020 figures.

8. References

Bock, L. and Burkhardt, U. Contrail cirrus radiative forcing for future air traffic, *Atmos. Chem. Phys.* ***19***, 8163–8174. (2019)

Dahlmann, K, Grewe, V., Frömming, C. & Burkhardt, U. Can we reliably assess climate mitigation options for air traffic scenarios despite large uncertainties in atmospheric processes? *Transportation Research Part D* ***46***, 40-55, (2016).

Doyle, A. Coronavirus: plane-free skies spur research into warming impact of aviation. Climate Home News (9/4/20)

Forster, P.M., Forster, H.I., Evans, M.J. *et al.* Current and future global climate impacts resulting from COVID-19. *Nature Climate Change* **10,** 913–919 (2020)

Friedlingstein, P. et al Global Carbon Budget 2019, *Earth Syst. Sci. Data*, 11, 1783–1838; and powerpoint/pdf summaries on the Global Carbon Project website (2019).

Fu, B., Gasser, T., Li, B. et al. Short-lived climate forcers have long-term climate impacts via the carbon–climate feedback. *Nature Climate Change* ***10***, 851–855, (2020).

Hanaoka, T. & Masui, T. Exploring effective short-lived climate pollutant mitigation scenarios by considering synergies and trade-offs of combinations of air pollutant measures and low carbon measures towards the level of the 2C target in Asia. *Environmental Pollution* ***261***, (2020).

Harmsen, M., Fricko, O., Hilaire, J. et al. Taking some heat off the NDCs? The limited potential of additional short-lived climate forcers' mitigation. *Climatic Change* (2019).

IATA IATA Forecast Predicts 8.2 billion Air Travelers in 2037. Press release about the IATA 20-year Passenger Forecast (24/10/18).

IATA Economics Economic Performance of the Airline Industry. End of year report including 2020 forecasts, (11/12/19).

IATA Economics Economic Performance of the Airline Industry. 2020 Mid-year report, (9/6/20).

IATA Economics Air passenger market analysis – August 2020. Monthly report, (29/9/20).

IPCC Task Force on National Greenhouse Gas Inventories Expert Meeting on Short-Lived Climate Forcers Meeting Report, 28-31 May 2018, Geneva, Switzerland, (2018).

Le Quéré, C., Jackson, R.B., Jones, M.W. *et al.* Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement. *Nature Climate Change* **10,** 647–653 (2020).

Lee, D.S. et al The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment* (2020)

Lenton, T.M. et al Climate tipping points — too risky to bet against. *Nature* ***575***, 592-595, (2019).

Lund, M. T., Aamaas, B., Stjern, C. W., Klimont, Z., Berntsen, T. K., and Samset, B. H. A continued role of Short-Lived Climate Forcers under the Shared Socioeconomic Pathways, *Earth Syst. Dynam. Discuss.* (2020).

Lund, M.T. el al Emission metrics for quantifying regional climate impacts of aviation. *Earth System Dynamics* ***8***, 547-563 (2017).

Myhre, G. et al Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (2013a)

Myhre, G. et al Anthropogenic and Natural Radiative Forcing Supplementary Material. Section 8.SM.3. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. (2013b)

Pearce, B. COVID-19: Downgrade for global air travel outlook. IATA Economics briefing, (29/9/20).

Stuber, N. & Forster, P. The impact of diurnal variations of air traffic on contrail radiative forcing. *Atmospheric Chemistry and Physics* ***7***, 3153-3162 (2007).

Zhang, H., Xie, B., & Wang, Z. Effective radiative forcing and climate response to short-lived climate pollutants under different scenarios. *Earth's Future* ***6***, 857– 866 (2018).