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

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Abstract: *This paper argues that, in 2020, the beneficial atmospheric effect from the reduction in aviation may have been at least 7-8 times greater than that occurring from the reduction in fossil carbon dioxide emissions from all sectors. Specifically, compared to potential atmospheric effects in 2020 without the pandemic, the decrease in effective radiative forcing from reduced contrail-cirrus formation may have been 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, 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

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Key points:

- Various sectors – notably aviation – have significant climatic impacts, over and above those due to CO_2 emissions.
- Comparing CO_2 and non-CO_2 climate impacts is often challenging, not least because they often operate over different timescales.
- The dramatic changes in trends wrought by the pandemic can provide new insights on the potential significance of CO_2 and non-CO_2 impacts.
- Initial estimations suggest that, in 2020, the immediate climatic benefit from reduced plane contrails may have been many times greater than that resulting from the global reduction in fossil CO_2 emissions from all sectors.
- The findings highlight the importance of considering aviation's non-CO_2 impacts when considering the future of the sector, and of considering short-lived climate forcing agents in climate policy more generally.

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1. Introduction

For those interested in avoiding climate change, it has been disheartening to read that the huge behavioural changes brought about by the pandemic have only reduced the world's annual carbon dioxide emissions by a small amount (Le Quéré et al 2020, Forster et al 2020, Friedlingstein et al 2020, Liu et al 2020, Tollefson 2021). However, some activities have climate impacts over and above any carbon dioxide emissions that they produce, with different timescales and magnitudes of effect, and where the impacts of the pandemic are likely to have been substantially different in character. This is particularly the case for aviation.

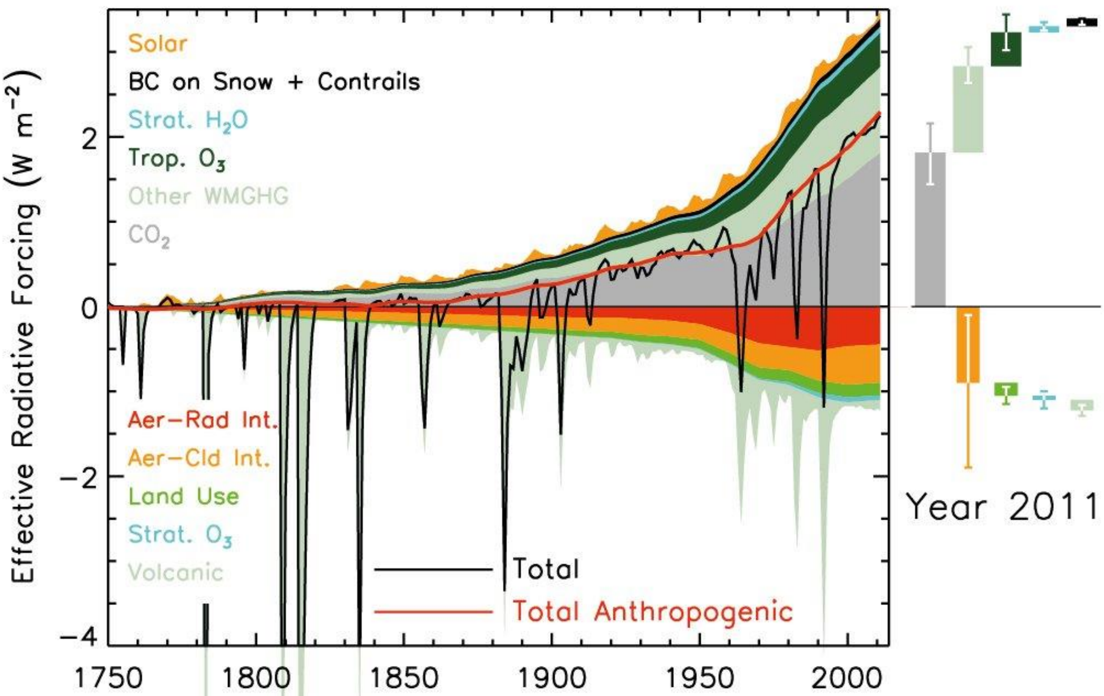
The aim of this paper is to draw on the results of two major scientific studies published in 2020 – one on the climatic impacts of aviation; the other on the climatic impacts of the pandemic - to illustrate why non-CO_2 climate impacts are important, both to policy decisions about the aviation sector, and to more general climate policy debate.

As such, this paper is largely a synthesis and extrapolation of existing scientific findings. Its contribution is not new insights into the science of how aviation affects the climate, Instead, its purpose is to highlight the potential significance of short-term climate forcers – in particular, contrail formation from aircraft – by juxtaposing what recent studies tell us.

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, 2013).

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 (2013), p699. Bars with the forcing and uncertainty ranges (5 to 95% confidence range) for 2011 vs 1750 are given in the right-hand 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 (2013) 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 that was 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 central estimate of the effect of contrail-cirrus in 2011 was +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, developed for different purposes, 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, often used to assess the relative importance of different climate forcing agents, are usually most suitable when there are relatively stable growth trends, and when 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 such metrics may not be particularly suitable for considering major disruption to trends, as has occurred with the pandemic. The second is that use of longer-term metrics tends to devalue solutions which could lead to short term cuts in climate warming *without* a detrimental growth in longer term impacts. This paper focuses on a simple comparison of potential changes in ERF values to illustrate this.

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3. Methodology

In 2020, two key studies were published, which form the basis for this paper.

3.1 Aviation contrail-cirrus effects

The first key study – by Lee et al – synthesises a wide range of existing studies, to reflect the latest understanding of the climate impacts of aviation, including estimated ERF values for the different components of aviation's effect on the climate in 2005, 2011 and 2018 (and with an underlying spreadsheet giving annual values from 2000-2018). It was released as a pre-proof in July 2020 and formally published in 2021.

The work indicates that the ERF values for (a) CO_2 effects; (b) contrail-cirrus effects; and (c) the net effects of other, complex, climate impacts (that occur from emissions of NOx, water vapour, soot and sulphate aerosols) have all increased over time. The largest component of the overall effect is the contrail-cirrus impact. For simplicity, this paper therefore focuses only on the contrail-cirrus impact, given that it is substantial, and that its direct impacts on ERF are clearly short-term (unlike, for example, NOx impacts, which play out over a longer time period). However, the overall climate benefits from the reduction in aviation activities will have been greater than those from the reduction in contrail-cirrus effects, given that there will also have been a reduction in aviation CO_2 and a reduction in the other non-CO_2 impacts. (Whilst these other (quantified) non-CO_2 effects are both cooling and warming, in aggregate, the Lee et al study indicates that they have a net positive ERF – i.e. a warming effect[1].)

Specifically, in 2018, their central estimate of the ERF due to aviation was +100.9mWm^{-2}, with 34.3mWm^{-2} being due to the CO_2 from aviation; 57.4mWm^{-2} coming from contrail-cirrus; and +9.2mWm^{-2} resulting from the effects of the other pollutants.

For their calculations, Lee et al assume that contrail-cirrus ERF is directly related to flight track distance. Therefore, to get a crude understanding of how such values might have changed in 2020, and might further change in the future, data from IATA (the International Air Transport Association) about changes in available seat kilometres (ASK) on planes is used as a proxy for changes in flight track distance, and, therefore, changes in contrail-cirrus effects.

This assumption has various weaknesses (as discussed below). However, the purpose of this paper is not to provide a precise estimate of impacts, but to give a rough order of magnitude of how large they could be.

A more accurate estimation would require a substantial amount of data on meteorology and flight patterns for the year. A recent preprint (Schumann et al 2021) does report on modelled contrail formation over Europe for March-August 2020, and these results are briefly discussed below. There are also important practical investigations taking place, (see Doyle 2020). However, to the author's knowledge, there is no available work which provides an accurate global estimate for the year at present.

[1] Lee et al also highlight that several new effects are now being discussed, but that "*substantial uncertainties*" preclude the inclusion of these in calculations.

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3.2 Global CO_2 reductions

The second major study – published in July 2020 by Forster et al – involves estimates of both the immediate likely impacts of the pandemic on climate change, including changes in global fossil carbon emissions and associated ERF values; and of potential future impacts, depending on the economic recovery packages that Governments choose to adopt.

Their scenarios include a 'baseline' pathway; a 'two year blip' scenario, where countries return to their baseline pathway by 2023; a 'moderate green stimulus' pathway; and a 'strong green stimulus' pathway.

Pathway spreadsheets are given in the GitHub repository for the paper's data[2]. This has enabled the calculation of various figures used in this paper.

As part of these calculations, 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 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. These calculations suggest that the 'moderate green stimulus' pathway is equivalent to a 3-4% annual drop in CO_2 emissions from 2019; whilst the 'strong green stimulus' pathway is equivalent to a 6-7% drop in CO_2 emissions each year from 2019.

The Forster et al study considers a range of pandemic effects, including changes in contrail formation. However, personal correspondence has clarified that the modelling results reported for this element are considered unreliable at present.

4. How contrail-cirrus effects may have changed in 2020, compared to what might have occurred without the pandemic, and future possibilities

4.1 Indicative calculations

As already stated, Lee et al estimate that, in 2018, a central estimate of the ERF due to aviation was +100.9mWm^{-2}, with 34.3mWm^{-2} being due to the CO_2 from aviation, 57.4mWm^{-2} coming from contrail-cirrus and +9.2mWm^{-2} resulting from the other pollutants.

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).

Without the pandemic, the recent growth in aviation was expected to continue (IATA 2018, Bock & Burkhardt 2019). Latest data from Airlines for America[3] suggests that, between 2011 and 2018, aircraft miles increased each year, equivalent to annual growth of +4.3%, and increased by a further 3.5% between 2018 and 2019. In December 2019, pre-pandemic, IATA (2019) were predicting that available seat kilometres (ASK) would have increased by 3.5% in 2019 (compared with 2018) and, further, that they would increase by 4.7% in 2020

[2] http://github.com/Priestley-Centre/COVID19_emissions.
[3] https://www.airlines.org/dataset/world-airlines-traffic-and-capacity/#, accessed 1/3/21

(compared with 2019), which, averaged over the two years, is reasonably similar to the annual increase in air miles that occurred between 2011 and 2018.

Suppose, then, that without the pandemic, the average annual growth in aviation contrails between 2018 and 2020 had been equivalent to that which occurred between 2011 and 2018. This might have led to a contrail-cirrus effect in the order of about 62mWm^{-2} in 2020.

Then suppose that, as a first order approximation, the annual reduction in contrail-cirrus effects has been proportionate to the reduction in aviation activity. According to latest IATA estimates, in 2020, global ASK were only 43.5% of those operated in 2019, (IATA 2021). If, as a result, contrail-cirrus also reduced by this amount, the ERF from this component of aviation in 2020 might be about 27mWm^{-2}. The implied difference would be a reduction of about 35mWm^{-2} for the year.

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 about +64mWm^{-2} in 2025 and 78mWm^{-2} in 2030.

4.2 Limitations of the approach

These calculations are inevitably inaccurate – contrail-cirrus effects from aviation are hugely dependent on when and where flights take place, including geographical region, altitude, time of day, season and prevailing weather conditions (see, for example, Lund et al, 2017, Dahlmann et al 2016, Stuber & Forster 2007).

According to IATA data (IATA 2021), although all markets have taken a hit, international flights have been more affected than domestic flights, and different markets have been differently affected at different times. Hence, the estimates given above are likely to be inaccurate for many reasons. For example, the lack of impact in the early part of 2020, when colder conditions would affect some areas of high aviation traffic, might mean that this estimated reduction is too high. Alternatively, the greater reduction in longer flights – which usually involve a greater proportion of mileage undertaken at altitudes likely to generate contrail-cirrus effects – might have increased the reduction experienced.

A preprint by Schumann et al (2021) models the potential effects of the reduction in air travel on contrail formation over Europe between March and August 2020, compared to 2019, and suggests that air miles reduced by 72%, whilst contrail formation reduced by 78% (with the latter figure being higher partly because prevailing weather conditions were not favourable to contrail formation anyway). Surprisingly, their model then suggests that the resultant change in contrail radiative forcing was lower than this. Referee comments[4] highlight that further explanation would be useful for this unexpected result, and that it will be important to compare modelled results to satellite observations.

This discussion highlights the complexities of the topic, and the challenges of generating actual accurate estimates for real world changes. However, the purpose of this paper is not to provide a precise estimate of actual impacts. Instead, it is to give an 'order of magnitude' estimation for the sort of change that such a dramatic drop in air travel might, ceteris

[4] https://doi.org/10.5194/acp-2021-62-RC1

paribus, bring about, and extrapolating from best available global evidence seems appropriate for this purpose.

In section 6 of this paper, the figures in this section are then compared with the estimates of CO_2 impacts discussed next.

5. How CO2 effects may have changed in 2020, compared to what might have occurred without the pandemic, and future possibilities

Understanding the effects of the pandemic on global carbon dioxide emissions was the focus of various studies during 2020 (Le Quéré et al 2020, Forster et al 2020), with more specific estimates towards the end of the year. Specifically, in December, the 2020 Global Carbon Budget estimated that fossil carbon emissions (i.e. those produced by energy use and industry but excluding those from land-use change) reduced by 7%, compared with 2019 (Friedlingstein et al, 2020); whilst the International Carbon Monitor programme has suggested the reduction was 6.4% (Liu et al 2020, Tollefson, 2021).

The study by Forster et al (published in July 2020) went further than simply assessing the likely changes in emissions, and assessed what the likely climatic effects of the pandemic-induced changes in emissions might be. It suggested that, for fossil CO_2 emissions, in terms of the impacts of changes in ERF in 2020 compared to what would have happened if countries had followed their expected 'baseline' pathways, the difference would be only -4 to -5mWm^{-2}. (The range reflects the different potential recovery pathways that Forster et al envisaged towards the end of 2020.) Consequently, Forster et al (2020) concluded that, in 2020, "*the direct [climatic] effect of the pandemic-driven response will be negligible*". Moreover, this conclusion was based on assuming reductions in fossil carbon that were equivalent to 12-15% for the year as a whole, which are higher figures than the reduction that actually occurred.

However, the same study also looked forward, and estimated the difference in ERF values from fossil CO_2 that could arise as a result of different government decisions about economic recovery strategies from the pandemic over the longer term. It highlighted how the cumulative effects of these decisions will become more important over time and that "*economic investment choices for the recovery will strongly affect the warming trajectory by mid-century*".

Specifically, their 'two year blip' pathway, where countries return to their previous baseline pathway by 2023, suggests an increase in ERF from fossil carbon, from 2019 values, of +203.9mWm^{-2} by 2025 and +387.2mWm^{-2} by 2030. In contrast, following a 'moderate green stimulus' pathway (equivalent to annual cuts in CO_2 emissions of only 3-4% p.a.) 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 (equivalent to annual cuts in CO_2 emissions of 6-7% p.a.) would mean an increase in ERF from fossil carbon of only +152.4mWm^{-2} by 2025 and +212.6mWm^{-2} by 2030.

In other words, they estimate that the difference between adopting a 'strong green stimulus' pathway, and a 'two-year blip' scenario, would generate an ERF difference of 51.5mWm^{-2} by 2025. By 2030, this ERF difference would have increased to 174.6mWm^{-2}.

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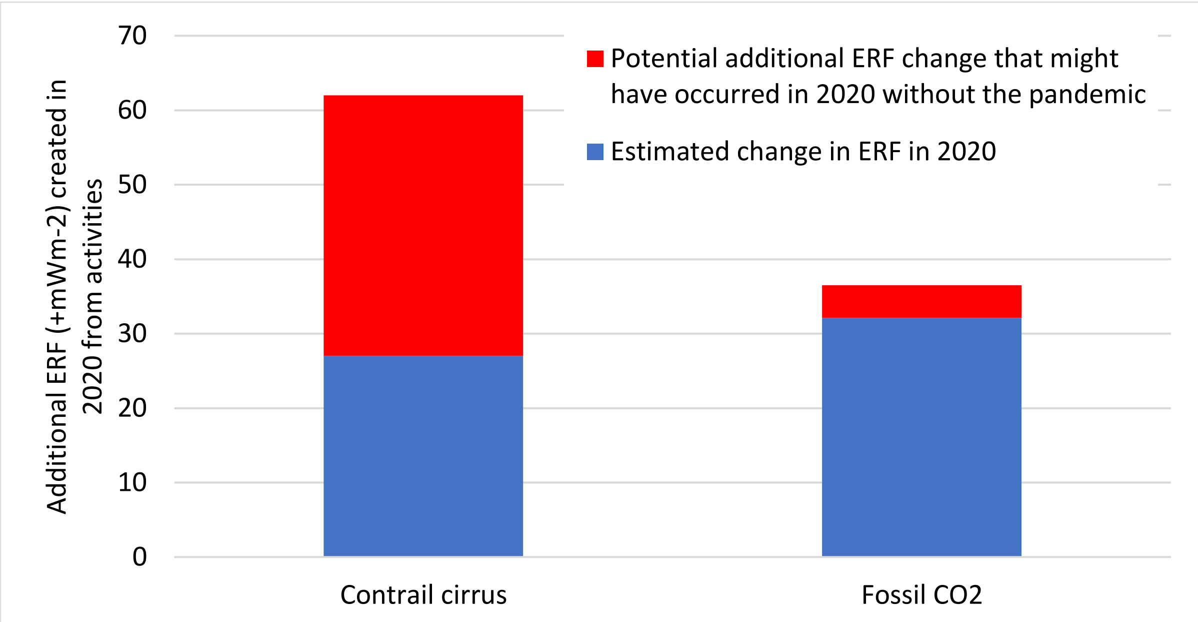
Even adopting a 'moderate green stimulus' pathway (compared to returning to previous activities) is estimated to make a difference of 119.1mWm^{-2} by 2030.

6. Comparing the ERF estimations for contrail-cirrus and CO2 changes

The calculations from the sections above have been used to create Figures 2 and 3.

First, Figure 2 illustrates the first-order estimations for changes to ERF in 2020 as a result of the activities that actually took place, compared to those that might have taken place without the pandemic. It suggests that the decrease in atmospheric effects caused by the reduction in contrail-cirrus (from aviation) is potentially 7-8 times greater than that caused by the reduction in global fossil CO_2 emissions (from all sectors).

Figure 2: *Potential additional ERF contribution from fossil* CO_2 *emissions (all sectors) and contrail-cirrus impacts (from aviation) in 2020, with and without the pandemic (first order approximations)*



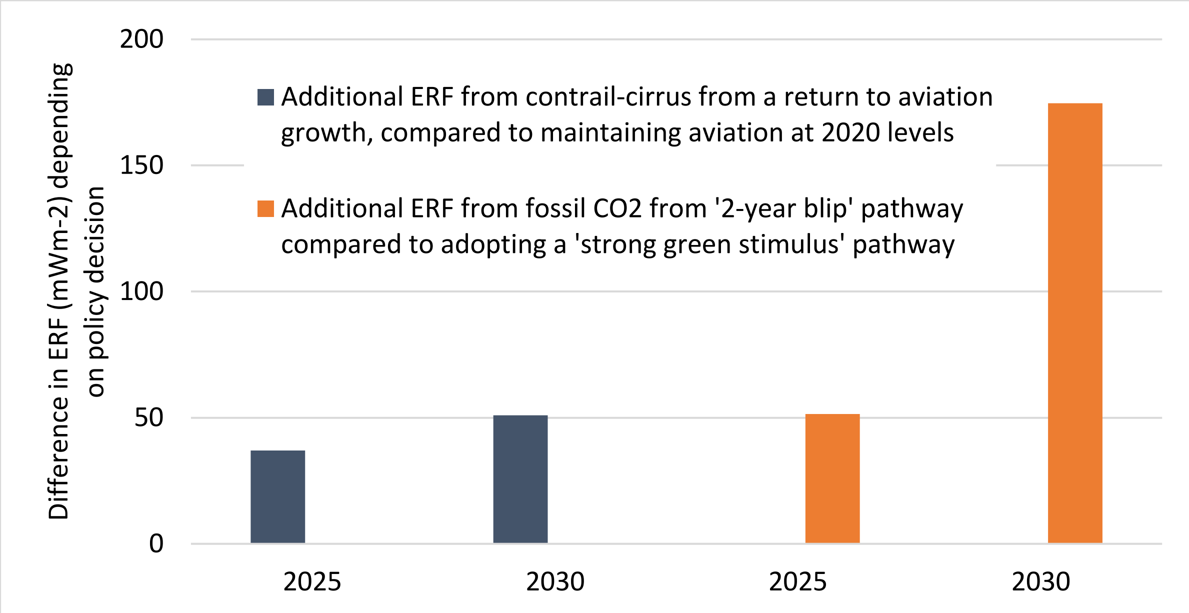
Note that ERF occurring as a result of activities prior to 2020, or from other emissions, is not represented here.

Second, Figure 3 looks at the effects of choosing different policy scenarios over a longer time period on impacts in 2025 and 2030. Specifically, it compares:

- The additional ERF generated from contrail-cirrus from aviation, if aviation returns to 2019 levels in 2023, and then continues on its previous growth trajectory, compared to a scenario of limiting aviation to 2020 levels; and
- The additional ERF generated from CO_2 emissions from human activities (excluding land-use change), if countries return to their previous trajectories by 2023, compared to a scenario where they adopt 'strong green' recovery pathways.

Because aviation contrail-cirrus only has short-term direct effects on the climate, the potential reduction in ERF in 2025 or 2030 from constraining aviation at 2020 levels is not that different to the reduction that may have been realised from the actual changes between 2019 and 2020. In contrast, because the effects of fossil CO_2 are cumulative, annual cuts in CO_2 lead to substantial differences in ERF 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. At the same time, even in 2030, the potential additional atmospheric effect from allowing aviation to return to its previous trends is not trivial.

Figure 3: *Difference in ERF values from (a) aviation contrail-cirrus, and (b) fossil* CO_2 *emissions from all sectors, in 2025 and 2030, as a result of choosing different pathways (first order approximations)*



As already highlighted in the sections above, these calculations are simplistic, and there are many caveats. It should also be noted that ERF values for contrail cirrus always have considerably greater uncertainty ranges than ERF values for carbon dioxide emissions.

The other issue is that aviation is also a contributor to fossil carbon, responsible, in 2018, for 2.4% of anthropogenic emissions of CO_2 (including those from land use change), according to Lee et al (2021). As mentioned above, inclusion of aviation's CO_2 effects, and other non-CO_2 effects, would therefore increase the overall ERF values for the effects of different policy choices for aviation. 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.

7. Discussion

The calculations given in this paper are deliberately simplistic, in order to compare and contrast the potential magnitudes of changes in climatic effect that result from limiting aviation contrail-cirrus effects, compared to achieving reductions in CO_2 emissions from all sectors (excluding land use change). They do not provide actual estimates of changes – rather they are intended to highlight issues which seem of sufficient importance that they merit further discussion.

At face value, they suggest that, in 2020, as a result of the pandemic, the beneficial short-term atmospheric effect from the reduction in aviation contrail-cirrus could be considerably greater than that occurring from the reduction in all carbon dioxide emissions from fossil fuel use and industry. Longer-term, the cumulative effects of adopting a low carbon

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pathway outweigh the effects of only limiting aviation, although even by 2030, the effect of simply limiting aviation is not negligible in comparison to the potential benefits from reducing all carbon dioxide emissions.

In considering these findings, the first key point to make is that 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 (2021) 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 *"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 aviation, 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 recent commentary has implied that, if the pandemic-engendered changes to behaviour have made such little difference to CO_2 emissions, the world is 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, and there are 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 policy 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 – 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.

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