Appendix 2 – Centre for Aviation Emissions Report

The impacts of aviation on climate with a focus on non-CO_2 emissions and effects

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Aviation is responsible for a range of emissions that affect climate that can be quantified in terms of its 'Effective Radiative Forcing' (ERF, in watts per square metre), for which a positive forcing implies warming, and a negative one, cooling. These effects are summarized below and in Figure 1.

- Emissions of CO_2 result in a positive ERF.
- Emissions of nitrogen oxides (NO_x, where $NO_x = NO + NO_2$) result in the formation of tropospheric ozone (O_3), an important greenhouse gas, via atmospheric chemistry, with a positive ERF.
- Emissions of NO_x also result in the destruction of ambient methane (CH_4), again via atmospheric chemistry, which is accompanied by a parallel, decadal loss of tropospheric O_3 and a reduction in stratospheric water vapour, with a negative ERF.
- Emissions of water vapour into the stratosphere result in a positive ERF.
- Emissions of sulphur dioxide (SO_2) arising from sulphur in the fuel, which is oxidized to form sulphate particles, resulting in a negative (termed "aerosol-radiation interaction") ERF.
- Emissions of soot particles result in a positive aerosol-radiation interaction ERF.
- The formation of persistent linear contrails that may develop into contrail cirrus clouds (depending upon atmospheric conditions) results in both positive and negative ERF effects but overall, cause a positive ERF effect.
- Sulphate and soot emissions may also interact with low and high-level clouds (termed "aerosol-cloud interactions"), respectively, causing ERFs of highly uncertain magnitude, likely to be negative in the case of sulphate, and of uncertain sign in the case of soot. The effects are also dependent on the background aerosol.

Aviation is calculated to represent about 3.5% of the total (2018) anthropogenic radiative impact on climate, approximately 66% of which is currently attributable, with considerable uncertainty, to non-CO_2 emissions (Lee et al., 2021). This ERF from aviation CO_2 + non-CO_2 ERF has been separately calculated to represent approximately 4% of the contribution to global mean surface temperature increase since pre-industrialization, or approximately 0.04 ± 0.02 °C to 2019 (Klower et al., 2021).

Figure 1. Best-estimates for effective radiative forcing (ERF) terms from global aviation from 1940 to 2018.

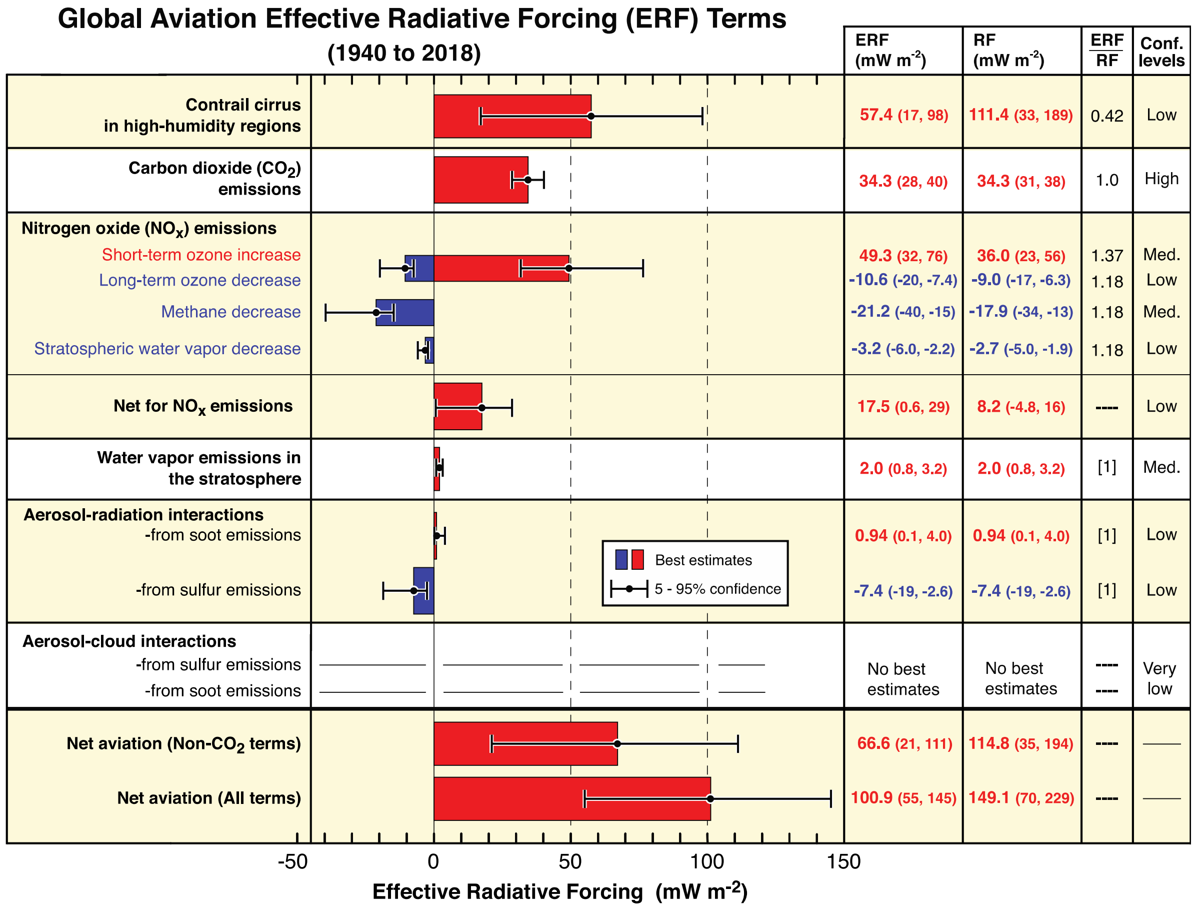

Figure 1. The bars and whiskers show ERF best estimates and the 5–95% confidence intervals, respectively. Red bars indicate positive terms and blue bars indicate negative terms. Numerical ERF and RF values are given in the columns with 5–95% confidence intervals along with ERF/RF ratios and confidence levels. RF values are multiplied by the respective ERF/RF ratio to yield ERF values. ERF/RF values designated as [1] indicate that no ERF/RF estimate is available yet. Taken from Lee et al. (2021).

What is clear from Figure 1 is that the non-CO_2 effects are complex, and uncertain. They range from effects on the chemical composition of the atmosphere to changing the nature and properties of clouds. In contrast, the CO_2 effect is clear, well understood, and has much smaller uncertainties.

A recent publication has dealt systematically with the challenges of mitigating non-CO_2 effects from aviation. Below, the abstract is repeated, verbatim, since it is a succinct summary of the high-level challenges (Lee et al., 2023):

"The uncertainties over the effects of aviation non-CO_2 emissions on climate and air quality are assessed in the context of potential mitigation measures for liquid hydrocarbon fuels. Aviation non-CO_2 emissions that affect climate include nitrogen oxides (NO_x), aerosol particles (soot and sulphur-based), and water vapour. Water vapour and aerosols have small direct radiative effects but are also involved in the formation of contrails and contrail cirrus, currently, the largest non-CO_2 effect on climate. These non-CO_2 effects on climate are quantified with low confidence, compared to that of CO_2, which is quantified with high confidence. The sign of the NO_x radiative effects may change from positive to negative. The effects of soot and sulphur emissions on cloudiness are very poorly understood and studies indicate forcings that range from large negative through to small positive. NO_x and soot emissions can be reduced through changes in combustion technology but have trade-offs with each other and CO_2. Soot can also be reduced through reduced aromatic content of fuels. In all cases, there are complex choices to be made because of trade-offs between species, and CO_2. Contrail cirrus and soot aerosol-cloud interactions potentially have opposing signs but are both related to soot emissions (at present) and need to be considered together in mitigation strategies.

Because of the uncertainties and trade-offs involved, it is problematic to recommend definitive courses of action on aviation non-CO_2 emissions since they may be of limited effect or have unintended consequences. Aviation's non-CO_2 effects on climate are short-term, as opposed to those of CO_2, which last millennia. If aviation is to contribute towards restricting anthropogenic surface warming to 1.5 or 2^{o}C then reduction of emissions of CO_2 from fossil fuels remains the top priority. In terms of air quality, the situation is more straightforward with emissions standards being set by the International Civil Aviation Organization for NO_x and non-volatile particulate matter (and other minor species), which need to be complied with."

In considering mitigation of non-CO_2 effects, their relative magnitude needs to be clarified, since the relative magnitude to the total is often cited as a reason for policy intervention. At present, non-CO_2 forcings represent some 66% of the total radiative effect from aviation. However, this reflects the recent strong historical growth rate of aviation. If the growth rate were to lessen, be constant, or even decline, the relative proportions would adjust. The non-CO_2 forcings would adjust very quickly, whereas the CO_2 fraction would adjust slowly, since CO_2 accumulates in the atmosphere. For example, if CO_2 emissions were constant, the non-CO_2 forcings would equilibrate quickly, whereas the CO_2 forcing would increase (because of the accumulation effect). Ultimately, under such a hypothetical scenario, CO_2 would become the dominant fraction of the total. This is illustrative but highlights that the "66%" is not a fixed fraction.

Closing comments

The science of non-CO_2 effects is far from complete. It has been shown that these effects can vary over time, some even to become negative forcings, switching from positive (in the case of 'net NO_x', Skowron et al., 2021). The soot cloud interaction could not be assigned a best estimate in our recent assessment (Lee et al., 2021), nonetheless, plausible estimates of the size of this range from around zero to 100s of milliwatts per square metre, negatively (i.e. cooling). If this upper end of the range were the case, the net effect of aviation non-CO_2 would be a net negative. This lack of sufficient understanding has recently been recognized by the Government's announcement of a 10s of millions £ NERC research programme, commencing in 2024.

References

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