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Dedoussi, I.C.

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Implications of future atmospheric composition in decision-making for sustainable aviation

Irene C Dedoussi

Section Aircraft Noise and Climate Effects, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands

E-mail: i.c.dedoussi@tudelft.nl

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1. Introduction

Aviation emissions lead to degraded air quality and adverse human health impacts, making air quality one of the leading environmental externalities associated with aviation. Aviation emissions have been growing steadily over the past decades, and, despite the current hindrance in air traffic due to the COVID-19 pandemic, they are forecasted to continue to grow in the long-term. As a result, mitigating aviation's adverse air quality impacts is an increasingly pressing challenge for the aviation industry. At the same time, the aviation industry has inherently long timelines, indicating that sustainability-related regulatory and technological decisions made presently will take effect over the next 30+ years.

Over such timelines, the changing atmospheric composition, driven by meteorological and background (non-aviation) emissions changes, results in a changing atmospheric response to emissions. This work summarizes recent advancements on this and discusses their implications for the aviation sector. First, aviation emissions and the resulting air quality impacts are described. The role of the atmospheric sensitivities to emissions and their evolution over time is then discussed. Finally, the implications for the long timelines associated with aviation mitigation options are underlined. Current challenges as well as opportunities for future research to resolve current assessment shortcomings are also presented.

2. Aviation emissions and air quality impacts

Civil aviation emissions result in degraded air quality and have been estimated to lead to ∼16 000 early deaths every year (Yim *et al* 2015, Grobler *et al* 2019). While aviation's air quality impacts are primarily treated and regulated as a near-airport problem (usually referred to as local air quality) there is increasing modeling evidence that these impacts spread regionally and intercontinentally due to emissions from all flight stages (Cameron *et al* 2017, Quadros *et al* 2020). Specifically, over 75% of the aviation-attributable air pollution concentrations and human health impacts are estimated to originate from high-altitude (cruise) emissions and thus do not necessarily occur in the vicinity of an airport (Barrett *et al* 2010, Yim *et al* 2015). When these regional and global air quality impacts of aviation are taken into consideration (as opposed to only near-airport, or landing and take-off (LTO) impacts), the societal cost of aviation's air quality impacts exceeds that of climate effects, making air quality the leading environmental externality associated with aviation (Grobler *et al* 2019).

Aviation fuel burn and the resulting emissions have been steadily growing over the past decades. Using US Federal Aviation Administration's AEDT inventory, Grobler *et al* (2019) report that 240 Tg of aviation fuel were consumed in 2015, which is in agreement with other inventories (Graver *et al* 2020), and within ∼10% of the value reported by Lee *et al* (2021) for the same year. This represents a ∼28% increase in fuel burn since 2006, or ∼2.5% per year (Wilkerson *et al* 2010). For more recent years, between 2013 and 2018, Lee *et al* (2021) estimate a 5% increase in fuel burn per year, which is a result of revenue passenger kilometers increases outpacing technological and other operational fuel efficiency improvements. While in 2020 (and, at the time of writing, at least partially also in 2021) this growth has been hindered by the slowdown in air traffic due to the COVID-19 pandemic, aviation forecasts predict the long-term resuming of this positive growth rate post the COVID-19 crisis (ICAO 2020).

The air quality impacts of aviation emissions originate from fuel combustion by-products, including nitrogen oxides (NO_x), sulfur oxides (SO_x), hydrocarbons, soot, and organic carbon. These emissions are proportional to the aviation fuel burnt, and thus have also been growing steadily over time. Beyond fuel burn however, for some emissions species such as NO_x, the emissions index, quantifying the mass of emissions per mass of fuel, also evolves over time. Between 2006 and 2015, the fleet average emissions index of NO_x has been estimated to have increased by ~6% (from 14.1 g kg^{-1} in 2006 (Wilkerson *et al* 2010) to 15.0 g kg^{-1} in 2015 (Grobler *et al* 2019)). This increase is likely associated with the increasing engine thermal efficiency resulting from higher combustor temperatures. As such, NO_x emissions increases outpace the fuel burn growth.

While historically aviation has been growing at a long-term steady pace despite economic and other setbacks, emissions from other anthropogenic sectors have been also been changing rapidly, following regulatory and technological developments (leading to decreases) or rapid economic growth (leading usually to increases, at least initially). For example, in the US and Europe between 2000 and 2017 NO_x emissions have decreased by 56% and 39%, and SO_x emissions by 84% and 62%, respectively (US EPA O 2015, European Environment Agency 2020). It is noted that these trends are not uniform globally. As a result, the long-term air quality impacts of aviation are expected to grow in both absolute terms and relative to those of other sectors (with the latter being dependent on the region).

3. Atmospheric sensitivity to emissions as a driver of impacts

The main pollutants associated with aviation's regional and global air quality and human health impacts are fine particulate matter ($PM_{2.5}$) and ozone. $PM_{2.5}$ has been considered the main driver being responsible for more than 85% of aviation's air quality impacts, but more recent ozone human health impacts functions indicate that the aviation-attributable human health impacts of ozone may be higher, and can even exceed those of $PM_{2.5}$ (Eastham and Barrett 2016, Quadros *et al* 2020). The formation pathways of both pollutants from jet engine combustion by-products are primarily non-linear. While $PM_{2.5}$ can be directly emitted (e.g. in the form of soot), the majority of aviation-attributable $PM_{2.5}$ takes the form of secondary $PM_{2.5}$, consisting of nitrate, sulfate and ammonium. Secondary organic aerosols are estimated to comprise ~2% of aviation-attributable $PM_{2.5}$ (Quadros *et al* 2020), although their formation and human health impacts are still an active area of research, in terms of the scientific understanding, and capabilities to measure and model them. Ozone forms from gaseous emissions of NO_x and volatile organic compounds.

How much air pollution forms from aviation activity depends on the aviation combustion by-products quantity (mass) as well as on how the atmosphere responds to these emissions towards the formation of the aforementioned $PM_{2.5}$ and ozone pollutants. Previous work has associated the areas where aviation-attributable $PM_{2.5}$ forms with increased background concentrations of available ammonia, for both LTO and full-flight emissions (Woody *et al* 2011, Barrett *et al* 2010). More recently, favorable Gas Ratio, an indicator for the potential of NO_x and SO_x to form $PM_{2.5}$, and formaldehyde to NO_x ratio, an indicator of the ozone formation regime, have been associated with increased aviation-attributable concentrations for LTO and full-flight regional impacts (Quadros *et al* 2020). As a result, for example, aviation fuel burn over Europe leads to 45%–50% higher global human health impacts than the same fuel burn over North America and Southeast Asia (although these impacts do not necessarily occur in Europe) (Quadros *et al* 2020). These regional differences between the atmospheric response have been noted outside the context of aviation for other near-ground emissions sources. This high regional variation indicates the role of the background atmospheric composition in setting the atmospheric response (sensitivity).

While substantial effort is invested in estimating the evolution of aircraft fuel burn and the resulting aviation emissions over time or the projected future fuel burn and emissions from policy or technological mitigation decisions, the future changes in the atmospheric response to emissions are assessed in less detail. Woody *et al* (2011) estimate that aviation LTO-attributable $PM_{2.5}$ concentrations in the US would grow by a factor of 3.5 between 2004 and 2025, while the aviation emissions would only grow by a factor of ~2, indicating the effect of the changing atmospheric sensitivity between the years. Regionally and for full-flight emissions, Quadros *et al* (2020) find that the air quality sensitivity to full-flight regional aviation fuel burn increased by 6%–12% between 2005 and 2013. Beyond aviation emissions, Dedoussi *et al* (2020) find that the $PM_{2.5}$ population exposure sensitivity to NO_x emissions increased by ~20% between 2006 and 2011 in the US. Holt *et al* (2015) also find an increasing NO_x to $PM_{2.5}$ formation pathway with reducing anthropogenic emissions. For $PM_{2.5}$ these are largely driven by the rapid changes in NO_x emissions, and less rapid changes in ammonia emissions. This non-linear pathway between emissions changes and resulting air quality has also been noted in the context of the short-term effects of emissions reductions due to the COVID-19 pandemic lockdowns (Kroll *et al* 2020). The non-linearity in the atmospheric response also affects the methodological choice between total impact assessments and individual source apportionments as noted in literature before (Dedoussi *et al* 2020).

As a result, as emissions beyond aviation are evolving over time, the atmospheric response to emissions also changes over time. This, in turn, thus affects how much air pollution forms from aviation emissions.

4. Implications for the assessment of future sustainable options

The aviation industry has uniquely long timelines and inertia. A typical aircraft development cycle lasts between 4 and 8 years before the aircraft enters the fleet, and the average aircraft lifetime in the fleet is an additional ∼30 years (Dray 2013). In line with these timelines, most current aviation sustainability targets have long-term outlooks: EU's Clean Aviation trajectory (e.g. European Green Deal) aims for 2035–2050, ACARE's Flightpath for 2050, and NASA's N + 3 concepts for 2035 onwards. Decisions for sustainable aviation made presently will thus in practice affect aircraft that will be flying multiple decades out in the future.

The aforementioned decisions towards sustainable future aircraft and operations involve technological, regulatory or operational changes to the current fleet. Examples include combustor-level CO_2 vs NO_x emissions trade-off optimization, replacing commuter and short-haul aircraft with electric aircraft, using alternative aviation fuels, implementing climate charged airspaces or other operational measures, and introducing taxes associated with the emissions, among others. Each of these options affects differently the spatiotemporal distribution of the different species emitted by aircraft. Given finite financial and other resources, deciding between these potential emissions mitigation option pathways can result in one emissions species traded against a different one, within similar or different time horizons. As a result, the evolving non-linearities in the atmospheric response have to be taken into account in the environmental assessments of these mitigation options.

Since the presently discussed aviation sustainability options will (a) have multi-decadal impacts on the flying fleet and (b) likely heterogeneously change the spatiotemporal distribution of the different species emitted by the aviation sector, using current-atmosphere assumptions to assess the air quality and atmospheric impacts of these alternatives, as per current practice, may be introducing error. Atmospheric conditions at the corresponding timeline would need to be taken into account when performing environmental assessments, such as cost-benefit analyses in decision-making.

At the same time, taking future atmospheric conditions into account presents challenges due to the uncertainty involved and the computational cost associated with comprehensive quantification of a wide range of future atmospheric composition scenarios. There are specifically three areas of research that merit further investigation in order to assess and potentially improve the shortcomings of present-atmosphere assumptions:

- High-altitude processes, driven by growing aviation emissions: aviation is a locally dominant emissions source in the large flight corridors in the Northern Hemisphere, and with aviation emissions rapidly growing, the marginal local (high-altitude) atmospheric processes (e.g. plume processes, aerosol microphysics, etc) may change. Such plume-level processes have been shown to have an effect in local (plume) photochemistry, associated ozone production, and effective NO_x and resulting atmospheric contributions of aviation emissions (Fritz *et al* 2020).
- Near-surface processes, driven by changing non-aviation emissions: changes in non-aviation emissions are expected to change the near-surface atmospheric response to emissions, thus affecting how much air pollution forms from a unit of aviation emissions. This will likely change both in magnitude compared to a present atmosphere, and relatively between the emission species. While this has been assessed in hindcasts there is no comprehensive assessment of how this will evolve globally and at different timelines in the future (e.g. under different Representative Concentration Pathway (RCP) or Shared Shocioeconomic Pathway (SSP) scenarios).
- Climatological changes: these are likely to affect atmospheric transport pathways (e.g. circulation) and tropospheric photochemistry (Jacob and Winner 2009). This 'climate penalty' on the air quality impacts of aviation mitigation emissions scenarios is likely to vary between regions globally.

Beyond expanding the scientific understanding of the aforementioned areas, it is also critical that it becomes relevant for informing present-day decision-making. Ways for (partially) incorporating them in practice include quantifying and correcting for the bias of current assessments, incorporating the changing atmospheric responses in decision-making tools, and quantifying the (increased) uncertainty associated with including the future atmospheric composition in assessments. While the current shortcomings are framed here in the context of assessing aviation's air quality impacts, they have been noted to also affect climate (non-CO_2) relevant pathways (Skowron *et al* 2021).

Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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ORCID iD

Irene C Dedoussi https://orcid.org/0000-0002-8966-9469

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