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ICAO CAEP/12 Assessment Report: Assessment of the impact of airport emissions on local levels of NOx and human health; impacts of cruise emissions of NOx on human health; impacts of cruise NOx on climate

Authors

Didier Hauglustaine, Richard C. Miake-Lye, Saravanan Arunachalam, Steven R. H. Barrett, David W. Fahey, Jan S. Fuglestvedt, Paul Madden, Agnieszka Skowron, Peter van Velthoven, and Donald J. Wuebbles.

Abstract

The current view is that aviation NO_x emissions over the 1940-2018 period have contributed to a net warming of the climate system. However, the uncertainty associated with the estimates of the net climate forcing remains high. A recent study suggests that the net climate impact of aviation NO_x might switch to a net cooling depending on future background atmospheric composition, future aircraft emissions or when new processes or refined parameterizations are considered. The estimated impacts of NO_x emissions on the climate system relative to other forcing agents are dependent on the choice of the climate metric and time horizon considered. In response to the important challenges raised by climate change, a number of studies have focused on how to reduce the climate impact of aviation through changing flight operations. In the case of NO_x, lowered flight altitudes provide a possible mitigation option for reducing the NO_x climate impact at the cost of increased CO_2.

Aircraft ground operations and the landing and takeoff cycle emit various gaseous and particulate pollutants or their precursors, which are known to affect human health. Aircraft LTO emissions contribute to premature mortality around major airports. At the local scale, NO_2 health impacts were shown to outweigh $PM_{2.5}$ health impacts. Most NO_x emissions from aviation do not occur near the ground and more than 90% occur above 3,000 ft. Those emissions still contribute to the background levels of O_3 and thus to the O_3 at the ground level. Similarly, a few studies suggest that cruise emissions could potentially be a dominant source of surface level particulate matter globally and of aviation-related premature mortality.

The options for controlling aviation NO_x are limited and are countered by the international growth in commercial aviation and by the mandate to increase engine energy efficiency by increasing engine core temperatures. Historically the continued reductions in NO_x have tended to increase fuel burn and the resulting emissions of carbon dioxide (CO_2), the primary gas of concern to the changing climate. Thus, there arises a trade-off between reducing impacts on climate due primarily to CO_2 and reducing impacts on air quality from NO_x.

Key messages

- Based on a recent assessment, aviation NO_x emissions over the 1940-2018 period have contributed to a net warming of the climate system. The uncertainty associated with the estimates of the net NO_x climate forcing remains high.
- A recent study suggests that the net climate impact of aviation NO_x might switch to a net cooling depending in particular on future background atmospheric composition, aircraft emissions or when new processes or refined parameterizations are considered in the atmospheric chemistry models used to assess NO_x emissions.
- The climate impacts associated with the O_3 and CH_4 responses to aircraft NO_x emissions occur at very different time scales. The estimated impacts of NO_x emissions on the climate system relative to other forcing agents are dependent on the choice of the climate metric and time horizon considered.
- Key pollutants for air quality are nitrogen dioxide (NO_2), ozone (O_3), and fine particulate matter ($PM_{2.5}$). Cruise emissions are estimated to be the dominant aircraft source of surface level ozone (increase relative to other emissions sources of 0.3 to 1.9% globally) and $PM_{2.5}$ (increase relative to other emissions sources of 0.14 to 0.4% in high traffic regions) and hence a dominant cause for aviation-induced premature mortality globally.
- Particle number concentration (PNC) is a good marker for traffic and aircraft emissions, and increasing number of studies are reporting elevated PNC due to aircraft emissions in the vicinity of airports. Aviation-attributable NO_2 health impacts are estimated to outweigh $PM_{2.5}$ health impacts.
- The global COVID-19 pandemic and resulting lockdowns led to large reductions in transportation activity and associated emissions impacts in 2020. Due to the pandemic, all-sector CO_2 worldwide emissions in 2020 decreased by -4% and the emissions from aviation fell by nearly -50%.
- Past studies suggest reducing climate impacts increases the emissions of NO_x, and reducing NO_x increases fuel burn and resulting emissions of CO_2. Moving forward, new technology may allow both CO_2 and NO_x emissions to be reduced.

- Effects on O_3 due to NO_x last for less than a month in the upper-troposphere and lower-stratosphere while the lifetime of CO_2 is centuries to millennia. Therefore, even a small increase in CO_2 that could accompany technological NO_x emission reduction could have a significant effect on climate.
- Studies on how to reduce the climate forcings from aviation include improving engine efficiency, reducing NO_x emissions, reducing contrail formation and/or technology development for contrail avoidance.
- There remain many uncertainties, and a more complete assessment of trade-offs in light of recent technological developments is needed.

1. Introduction and motivation

Nitrogen oxides (NO_x) continue to be a key pollutant of concern for aviation and that concern has resulted in improved combustor emissions performance from new aircraft engines as new NO_x standards have been adopted. There remains a strong push for higher core temperatures for better engine specific fuel consumption (sfc), which counter-balances combustor NO_x improvements. Aviation NO_x emissions have impacts on local air quality and human health, both through emissions in and around airports, but also from emissions at altitude affecting background concentrations. NO_x emissions also affect climate by changing atmospheric ozone (O_3) and methane (CH_4) levels, two important greenhouse gases, thus affecting the Earth's radiative balance.

This paper examines and summarizes the current scientific understanding of the aviation NO_x impact upon the environment. The understanding of the effects of aircraft NO_x emissions upon the atmosphere and climate continues to improve and is discussed in Section 2. The impact of NO_x on climate results from a complex balance of offsetting effects and the current view is that the net aviation NO_x effect has likely resulted in a warming of the climate system. However, several recent studies suggest that the net effect could turn into a net cooling when new processes or refined parameterizations are considered. In contrast to aircraft emissions, reductions of surface O_3 precursor emissions are projected because of reduced use of fossil fuels in the power production, industrial, and transportation sectors. A cleaner background atmosphere may also to some extent, mitigate the future aviation NO_x climate impact as described in the recent literature (Skowron et al., 2021). This change of the future aviation NO_x effect to a net cooling could significantly affect our view of the NO_x impact on climate. Despite significant advances in knowledge, the impact of NO_x on climate remains highly uncertain as addressed in Section 2.

Aircraft ground operations and the landing and takeoff (LTO) cycle result in the emission of various gaseous and particulate pollutants or their precursors, which are known to affect human health. The key pollutants of interest from a human health perspective are essentially nitrogen dioxide (NO_2), O_3 and fine particulate matter. For ground level emissions, most other sources of NO_x are being reduced through clean air regulation and transition to alternative energy sources. For aircraft, recent studies show the pervasive influence of ground level emissions on the reduction of air quality around major airports and also at the regional scale (Woody et al., 2011, 2013, 2015, 2016; Vennam et al, 2017). Several studies (Arunachalam et al., 2011; Levy et al, 2012; Rissman et al., 2013a, b) estimate a significant health impact from these ground level emissions. In addition, several studies indicate that cruise altitude emissions could significantly be recirculated to the lower atmosphere and be an important source of O_3 and of particulate matter at ground level (e.g., Barrett et al., 2010; Hauglustaine and Koffi, 2012; Yim et al., 2015; Eastham and Barrett, 2016). These studies are summarized in Section 3 of this paper, along with a discussion of the implications of the large reductions in transportation activity that arose in 2020, due to the global pandemic related to SARS-CoV-2 and the subsequent travel restrictions.

Reducing aviation NO_x is challenging and are countered by the international growth in commercial aviation and by the mandate to increase engine energy efficiency by increasing engine core temperatures. In the recent past, aviation NO_x emissions have been reduced by technology improvements in combustor design, driven by increased stringency in NO_x emissions regulations. However, continued reductions in NO_x may have the potential to increase fuel burn and the resulting emissions of carbon dioxide (CO_2) if no technological advances are made. Thus, there could arise a trade-off between reducing impacts on climate due primarily to CO_2 or reducing impacts on air quality due primarily to NO_x (and also particulate matter). An important issue affecting the trade-off issue is the much shorter atmospheric lifetime of NO_x (and the resulting effects on O_3 and CH_4) relative to that of CO_2. However, the NO_x/CO_2 trade-off is not a fundamental limit and technological progress is possible with new combustor architectures and other technical solutions being considered (Prakash et al., 2021). In response to the important challenges raised by climate change, a number of studies have focused on how to reduce the climate impact of aviation through changing flight operations. This is particularly the case for reducing contrail formation and the contribution to climate change from contrails and induced cirrus. In the case of NO_x, the climate impact varies strongly with flight altitude and location (Gilmore et al, 2013) as the lifetime of pollutants increases higher-up. As discussed below, lower flight altitudes provide another possible mitigation option for reducing the climate impact of NO_x, although this would likely entail an increase in CO_2 emissions. These trade-offs and mitigation options are addressed in Section 4.

2. Climate impact of NO_x

The burning of fossil fuels by aircraft occurs at high temperature, leading to dissociation of the nitrogen (N_2) and oxygen (O_2) molecules in the air. The resulting components then rapidly recombine into NO_x (NO and NO_2) molecules that are emitted at the engine outlet and that affect the photochemistry of the atmosphere. Well above the Earth's surface, the emitted NO_x catalyzes the formation of O_3, leads to the production of OH radicals, and hence increases the oxidation of CH_4. Both O_3 and CH_4 are efficient greenhouse gases, and these perturbations result in a warming effect due to the O_3 increase and a cooling effect due to the CH_4 destruction, respectively. These result in offsetting effects on the climate forcing, albeit at different timescales since the lifetime of O_3 is of the order of weeks at flight altitudes, while that of CH_4 is of the order of 10 years. The long-term CH_4 decrease also has secondary effects that lead to further cooling: a decrease in background O_3 and a reduction in stratospheric water vapor (H_2O), another potent greenhouse gas.

Lee et al. (2021) provides a comprehensive updated assessment of aviation induced climate forcings, including uncertainties, and consideration of recently acquired knowledge. For instance, they considered the difference between the transient CH_4 response to NO_x emissions and the chemical steady-state response, or they considered the CH_4-induced long term effect. **Table 1** gives an overview of the NO_x associated climate impacts in terms of *Effective Radiative Forcings* (ERF), the preferred metric to calculate radiative forcing of climate because it includes the fast responses to a radiative perturbation. In earlier studies (e.g., Lee et al., 2009), the Radiative Forcing (RF) was the usual metric to quantify the radiative perturbation. The total ERF, up to the present, by aviation NO_x emissions is about half the CO_2 forcing but it should be kept in mind that very different lifetimes are associated to these two individual components. The last column of **Table 1** provides estimated conversion factors between these two metrics. Based on the calculated ERFs, the total (net) climate effect of aircraft NO_x emissions is positive, leading to a warming of the climate system.

Table 1: Best estimates and low-high limits of the 90% likelihood ranges for aviation NO_x and CO_2 radiative effects in terms of Effective Radiative Forcing (ERF) [mW/m^2] for the base year 2018, the sensitivity of the ERF to the NO_x emissions [$mW/m^2/(TgN/yr)$] and the ERF/RF ratio. The NO_x impacts are the short-term O_3 increase, the CH_4 reduction, the CH_4-induced long-term reduction of O_3, and the CH_4-induced reduction of stratospheric water vapor (SWV) (from Lee et al., 2021).

	ERF in 2018	**Sensitivity to emissions**	**ERF/RF**
Short-term O_3 increase	49.3 (32, 76)	34.4 ± 9.9	1.37
CH_4 reduction	-21.2 (-40, -15)	-18.7 ± 6.9	1.18
Long-term O_3 reduction	-10.6 (-20, -7.4)	-9.3 ± 3.4	1.18
SWV reduction	-3.2 (-6.0 -2.2)	-2.8 ± 1.0	1.18
Net NO_x	17.5 (0.6, 29)	5.5 ± 8.1	
CO_2	34.3 (28, 40)		1.0

As illustrated in **Figure 1**, Lee et al. (2021) performed an ensemble analysis covering studies from almost two decades to provide the best estimate of aircraft NO_x induced climate perturbations. It has been found that none of the radiative forcing estimates show any trend over time of publication and the results from mid-1990s models are within the envelope of forcings generated more recently. The standard deviation of the distributions of the short-term and the long-term NO_x components are reasonably small. In contrast, the sign of the net NO_x ERF varies from positive to negative, and despite the advances in knowledge, it remains highly uncertain.

The short-lived O_3 and long-lived CH_4 radiative forcings are strongly anticorrelated, Holmes et al. (2011) provided a correlation coefficient $R^2=0.87$, and Lee et al. (2021) calculated $R^2=0.49$ in their model ensembles. This decrease in the strength of this anticorrelation in the latest study is due to a consideration of a broader range of both global atmospheric chemistry-climate models and present-day aviation emission inventories. It has been shown that the plausible causes of the modeling uncertainty in climate forcings from aviation NO_x are the processes that control the background tropospheric abundance of NO_x (Holmes et al., 2011). Recently it has been investigated in detail by exploring the impacts of emissions from lightning NO_x (Khodayari et al., 2018) and surface NO_x (Skowron et al., 2021) on the aviation NO_x effects. The lower the background NO_x, the more efficient the O_3 production (Gilmore et al., 2013) (e.g., increasing the lightning NO_x emissions from 3.7 to 7.4 TgN/yr decreases the short-term O_3 forcing by 22% (Khodayari et al., 2018)). However, a strong dependence of the aircraft CH_4 lifetime reduction on background NO_x has also been shown (Skowron et al., 2021). A 30% reduction of surface NO_x increases the positive short-term O_3 forcing by 16%, but the magnitude of the negative long-term CH_4 forcing increases even more, as by 28%. Thus, the less background tropospheric NO_x, the smaller the ERF from aviation NO_x. In addition, aircraft plume-scale chemical and mixing processes have not been properly considered in most global atmospheric chemistry model calculations. Based on a few studies, plume processing could reduce effective NO_x emissions by up to 50% and reduce ozone due to titration by NO in the plume (Meijer et al., 1997; Cariolle et al., 2009; Cameron et al., 2013; Fritz et al., 2020). However, large differences were found among these various studies and the magnitude of impact of the instant dilution versus plume processes on tropospheric ozone ranges from about +5% to +30% at cruise altitude. Additional work is required to better account for effective NO_x emissions in large scale models.

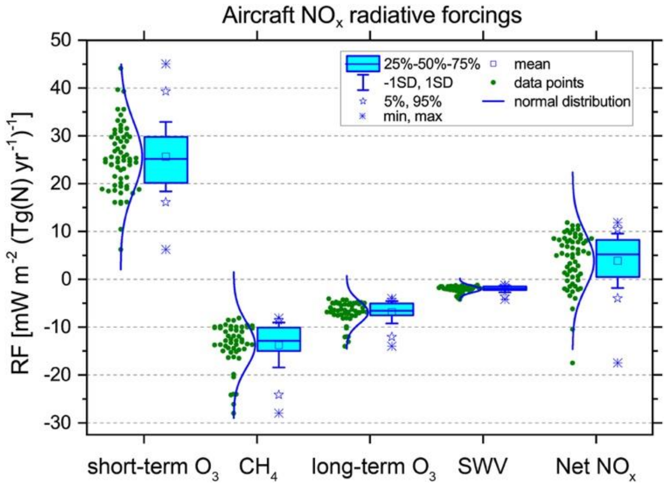

Figure 1. Results from an ensemble of 18 models from 20 studies for aviation NO_x climate forcing: short-term O_3 increase; CH_4 reduction, CH_4-induced long-term reduction of O_3, CH_4-induced reduction of stratospheric water vapor (SWV), and Net NO_x. Each data point represents a radiative forcing normalized by the NO_x emission [$mW/m^2/(TgN/yr)$] (from Lee et al., 2021).

Most studies determine the aircraft climate forcings by a perturbation approach (two simulations, with and without, or reduced, aircraft emissions). If the alternative attribution method is applied (tagging method), an increase of the short-term O_3 forcing by about 60% is calculated (Grewe et al., 2019). The tagging approach relates to another scientific question, namely the contribution and effectiveness of mitigation options of an individual sector under current atmospheric background conditions rather than under an evolving background. Other potential aspects that are not considered in most of the analyses are the direct formation of nitrate aerosols and indirect enhancement of sulfate aerosols (via increased OH and SO_2 conversion to particles). These effects from NO_x emissions are associated with large uncertainties and are addressed in only a few modeling studies (Unger, 2011; Pitari et al., 2015). The effects of NO_x on aerosol abundances are expected to result in negative forcings, and the inclusion of these processes would reduce the net NO_x climate forcing. An alternative to the perturbation and tagging approach is the use of an adjoint (Gilmore et al., 2013), which can yield the sensitivity of O_3 to NO_x emissions as a function of any location and time.

At present, all scenarios predict increased aircraft NO_x emissions in the future and the projected range of possible aircraft NO_x emissions in 2050 varies from 1.6 to 5.6 TgN/yr (Olsen et al., 2013; Skowron et al., 2021). It is often an intense rise of emissions compared to current conditions, 1.43 TgN/yr in 2018 (Lee et al., 2021), that drives the increase in the aviation net NO_x forcing for 2050 (Olsen et al., 2013; Unger et al., 2013; Khodayari et al., 2014; Brasseur et al., 2016; Skowron et al., 2021). The short-term O_3 forcing in 2050 ranges from 30 mW/m^2 to 162 mW/m^2 and the CH_4 forcing in 2050 varies from -36 mW/m^2 to -72 mW/m^2. In contrast to aircraft emissions, surface O_3 precursor emissions are projected to decrease under various scenarios. Skowron et al. (2021) have shown that these decreases resulting in a cleaner background atmosphere in the year 2050, which to some extent mitigates the aviation NO_x forcing response. Moreover, the revision to the CH_4 forcing formulation (Etminan et al., 2016) provides a perspective that the net NO_x climate impact from aviation decreases with air traffic growth and corresponding increased aviation NO_x emissions. The switching of the future NO_x effect to a net cooling has been calculated with RFs varying from -1.4 to -8.5 mW m^{-2} (Skowron et al., 2021).

ERFs can be used to calculate various emission metrics for climate warming for different integrated time horizons, e.g., over 20, 50 or 100 years. Traditionally, in climate policy assessments, the *Global Warming Potential* (GWP) (Fuglestvedt et al., 2010) has been used as a metric for climate warming. The GWP of NO_x for a certain time horizon is calculated as the ratio of the time-integrated ERFs of an equal mass emission pulses of NO_x and CO_2. An alternative metric, the *Global Temperature change Potential* (GTP) (Shine et al., 2005; Fuglestvedt et al, 2010), is an estimate of the ratio of the expected temperature difference due to equal mass emission pulses of NO_x and CO_2 at a certain time horizon. In addition, the GWP^*, introduced by Allen et al. (2018) and Cain et al. (2019), is new metric that is distinctly different in character from the GWP and GTP metric. It provides a new usage of GWP that compares the change of annual emissions of short-lived pollutants to a CO_2 emission pulse to obtain a CO_2 warming equivalent over a certain time period. The choice of an appropriate emission metric depends amongst others on the purpose and policy target. **Figure 2** illustrates the use of these different metrics to account for NO_x emissions when calculating the ratio of the total ($CO_2 + NO_x$) to the CO_2 only climate impact of aviation emissions. Based on the ERFs provided in **Table 1**, the effect of NO_x is to increase the total ($CO_2 + NO_x$) effect by about 50% compared to that of CO_2 solely. The use of the GWP_{20}, which integrates the radiative forcing over a 20-year time horizon, shows that the effect of NO_x (dominated by the short-term O_3 forcing at this time horizon) is to increase the so-called *CO_2-equivalent* emissions by 86%. The use of the commonly adopted GWP_{100} results in an *CO_2-equivalent* total emission larger by only 16% because the long-term cooling effect associated with CH_4 comes into play at this time horizon. When accounting for the climate system inertia and using the GTP_{20} metric, the climate response of aviation NO_x becomes dominated by the CH_4 long-term cooling, resulting in a total *CO_2-equivalent* emission reduction of 30%. This reduction is progressively reduced for the GTP_{50} and further for the GTP_{100} since the CH_4 lifetime remains relatively short (about 10 years) compared to CO_2. In the case of the GWP* metric, which better accounts for the different physical behaviors of *Short-Lived Climate Forcers* (SLCFs) and CO_2, the increased effect of aircraft NO_x equivalent emissions above CO_2-only emissions is 34%.

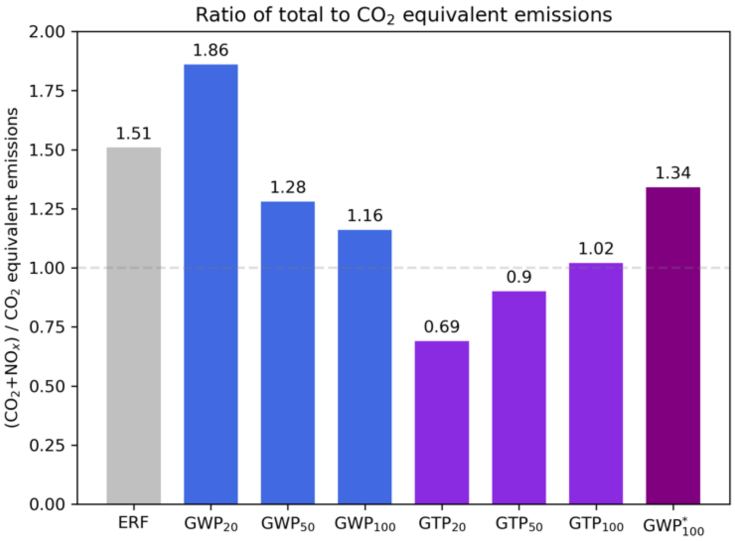

Figure 2. Ratio of the total ($CO_2 + NO_x$) to CO_2 only equivalent emissions calculated using different metrics (GWP, GTP, GWP^*) (based on Lee et al., 2021).

An alternative to physical metrics with selected time horizons is to use an economic approach with selected discount rates. In this case the ratio of total monetized climate impacts from all emissions to monetized climate impacts due to only CO_2 emissions as been estimated by Grobler et al. (2019). At a 3% discount rate this ratio is 1.42, decreasing to 1.23 at a 2% discount rate, and increasing to 2.73 at a 7% discount rate. Grobler et al. (2019) also provide uncertainty ranges. High discount rates have a similar effect to short time horizons in that they emphasize the short-term forcers. A benefit of economic approaches to this issue is that the results can be used in cost-benefit calculations, which are a common way to help inform policy deliberations. It is also possible to incorporate other impacts. Based on this single study, when the monetized climate *and air quality* impacts metric with a 3% discount rate is used, the ratio of total ($NO_x + CO_2$) to CO_2-only impact is estimated to be 3.2. A value significantly larger than those obtained with climate impact metrics and illustrated in **Figure 2** but with high uncertainty.

3. Air quality and health impacts

Aircraft emit various trace gases (NO_x, SO_x, CO, CO_2, hydrocarbons), water vapor and particulate matter during their entire range of activity, from landing and takeoff operations to cruise modes in the upper atmosphere. Besides impacting climate as seen in Section 2, these emissions also affect surface air quality. In addition to immediate, local exposure near airports, these emissions go through various physical and chemical processes to form secondary pollutants that are known to affect human health. The key pollutants of interest from a human health perspective are nitrogen dioxide (NO_2), ozone (O_3), and fine particulate matter of diameter less than 2.5 microns ($PM_{2.5}$).

The understanding of the effects of aircraft emissions on surface air quality and health during cruise and LTO phases have continued to advance. A number of studies have highlighted the effect of high-altitude cruise emissions on surface air quality. Barrett et al. (2010) estimated that cruise emissions contribute to 80% of all aviation-related premature mortality due to aviation $PM_{2.5}$ globally. Several other studies also showed that cruise emissions were the dominant source of surface level particulate matter (PM) due to aircraft emissions (Jacobson et al., 2013; Lee et al., 2013; Morita et al., 2014; Yim et al., 2015). Eastham and Barrett (2016) found that most aviation-attributable changes in near-surface ozone and $PM_{2.5}$ were found to be the result of cruise-altitude NO_x. This NO_x generates long-lived ozone which descends to the surface where it both directly exposes the population and promotes the formation of particulate matter from non-aviation emissions. A later study by Quadros et al. (2020) found that aviation-attributable ozone impacts may even exceed $PM_{2.5}$ in terms of health impacts. Across all of these studies, surface air quality impacts are diffused but mostly restricted to the northern hemisphere. Cameron et al. (2017) found that aircraft emissions increase near-surface O_3 by 0.3 to 1.9% globally with qualitatively similar spatial distributions, and the CTMs calculated an increase in surface level $PM_{2.5}$ of 0.14 to 0.4% primarily over high-traffic regions in the North American midlatitudes.

Impacts on air quality from LTO emissions have generally been found to be much smaller than those from cruise emissions. The understanding of LTO emissions on local air quality has been refined by accounting for aerosol direct feedback effects (ADFE). Over the US, Moniruzzaman et al. (2020) calculated that ADFE reduce aircraft LTO attributable O_3 and $PM_{2.5}$ changes by about 20% for the year 2005, with notable differences between global and regional model applications. For example, while the global modeling study of Yim et al. (2015) found that aircraft LTO attributable O_3 in North America was 25.4 ppt, the recent study over the continental U.S. by Moniruzzaman et al. (2020) found 6 ppt with feedback and 8 ppt without feedback. Similarly, while the global model of Yim et al. (2015) found the $PM_{2.5}$ change due to LTO emissions is 1.2 ng/m^3, the U.S. study (Moniruzzaman et al., 2020) found 2.2 ng/m^3 with feedback and 2.9 ng/m^3 without feedback. The use of a coupled model with ADFE (Moniruzzaman et al., 2020) shows more localized changes in air quality by aircraft LTO emissions across the domain which were absent without ADFE, and which are masked when looking at domain averages for both O_3 and $PM_{2.5}$. This nuance due to treatment of ADFE in regional or global scale models becomes important for accurately quantifying the maximum health risk due to air pollution exposures in densely populated areas.

Levy et al (2012) using a 2005 emissions inventory projected that aviation impacts due to $PM_{2.5}$ would increase by a factor of 6.1 from 2005 (75 premature deaths due to $PM_{2.5}$) to 2025 (460), with a factor of 2.1 attributable to emissions, a factor of 1.3 attributable to population factors, and a factor of 2.3 attributable to changing non-aviation concentrations which enhance secondary $PM_{2.5}$ formation. More recently, Arter et al. (2021) assessed air quality and health-related impacts from landing and takeoff operations (LTO) in the US for recent years (2011 and 2016) and compared to 2005 used in the Levy et al. (2012) study. More recent assessments are important given the slowdown in global aviation from earlier forecasts and to capture the post 2008 recession. This new study estimates 80 (68 – 93) and 88 (75 – 100) $PM_{2.5}$ attributable premature mortalities in 2011 and 2016, respectively. Based upon these new inventories, the O_3 attributable health outcomes exhibit a net benefit in the US in that the titration impacts surrounding the airport remove O_3. They estimate that -28 (-14 to -56) and -54 (-27 to -110) O_3 attributable premature mortalities were due to LTO emissions in 2011 and 2016, respectively. Further, aviation-attributable NO_2 health impacts were also assessed, and these were shown to far outweigh $PM_{2.5}$ health impacts. They estimated 610 (310 – 920) and 1100 (570 – 1700) NO_2 – attributable premature mortalities, due to LTO emissions in 2011 and 2016, respectively. Arter and Arunachalam (2021) recently illustrated that NO_x emissions during LTO cycles are the largest contributor to any nonlinearity in O_3 or $PM_{2.5}$ formation, and that first order sensitivities should be enough to capture the impacts of LTO emissions on the formation of ambient O_3 and $PM_{2.5}$ for any emission control strategy looking at emission perturbations less than 100%.

Aircraft emissions from one region or airport may contribute to poor surface quality and premature mortality in another state. Aircraft LTO emissions contribute to premature mortality as far as 300 km away from major airports via the formation of secondary particulate nitrates and sulfates (Arunachalam et al., 2011). In a more recent study that quantified the transport of air pollution among the contiguous US by various anthropogenic emissions sectors, Dedoussi et al. (2020) showed that of all the 7 sectors studied for the years 2011 and 2018, the aviation emissions due to LTO alone increased from 2011 to 2018 (by 60%, and contributed about 0.3% to total impacts in 2018), while all other sectors showed a decrease. In another recent study that quantified the global health risk due to fossil-fuel based combustion, Vohra et al. (2021) used a refined global scale model with updated methods for epidemiology and estimate 8.7M deaths due outdoor air pollution. While they didn't quantify the health risk due to aviation alone, their updated health risk numbers due to aviation are expected to change from all other quantitative estimates above.

Particle number concentration (PNC) is a good marker for traffic and aircraft emissions, and increasing number of studies are reporting elevated PNC due to aircraft emissions in the vicinity of airports in the recent few years. PNC were positively correlated with flight activity (Hsu et al., 2012; Hudda et al., 2016; Stafoggia et al., 2016). PNC were measured to be higher at the location downstream of the runway (Hsu et al., 2012; Hudda et al., 2020, 2018, 2016; Riley et al., 2016; Shirmohammadi et al., 2017; Stafoggia et al., 2016; Zhu et al., 2011). However, some studies found higher PNC at the downstream location on the takeoff path (Stafoggia et al., 2016; Zhu et al., 2011) where some other studies found higher PNC under the landing path (Hudda et al., 2020; Hudda and Fruin, 2016; Riley et al., 2016). Airport-related emissions were found to account for about 20% of total PNC at Italy's Venice airport (Masiol et al., 2016). By incorporating emissions data from aircraft engine studies and an updated aerosol treatment module specific to aircraft emissions in a regional-scale model, Huang et al (2017) showed that aircraft emissions due to LTO increased PNC at major airports in the North America by 1.2 to 5.2 times compared to the background concentrations from non-aviation sources. The largest modeled increase (5x) was seen at the Los Angeles International (LAX) airport. Ultra-fine particle emissions have been shown to have multiple adverse health effects including positive links to elevated systemic inflammation of the lung (Habre et al, 2018) and pre-term birth due aircraft emissions from LAX (Wing et al, 2020).

The global pandemic related to SARS-CoV-2 and the subsequent COVID-19 related lockdowns led to large reductions in transportation activity, specifically during early 2020. Le Quere et al (2020) showed that daily CO_2 emissions dropped by 17% in early April compared to mean 2019 levels, with the aviation sector alone seeing a 60% drop. Similarly, Liu et al. (2020a) found an abrupt 8.8% decrease in global CO_2 emissions (−1551 Mt CO_2) in the first half of 2020 compared to the same period in 2019. The magnitude of this decrease is found to be larger than during previous economic downturns or World War II. Liu et al. (2020a) estimated that emissions from global aviation decreased by −44% (−200.8 Mt CO_2) during the first half of 2020, of which roughly 70% of the drop was related to international flights. The total number of flights and global aviation emissions show two large decreases, one in Asia near the end of January and another coincident with travel bans and lockdown measures in the rest of the world that began in the middle of March 2020. By the end of March 2020, there were 85% fewer flights than during the same period in 2019. Global aviation emissions began to rebound in late April and gradually increased through the end of July. However, international flight emissions in July 2020 were still 72.0% lower than the emissions in July 2019. According to an updated emissions dataset (Liu et al., 2020b), due to the COVID-19 pandemic, all-sector CO_2 worldwide emissions in 2020 decreased by 4% and the emissions from aviation fell by nearly 50 percent.

Corresponding reductions in criteria air pollutants are also expected from lockdowns (Gkatzelis et al., 2021). After accounting for the effects of meteorological variability, Venter et al (2020) reported declines in the population-weighted concentration of NO_2 by 60% and $PM_{2.5}$ by 31%, with marginal increases in O_3 by 4% in 34 countries. In the US alone, aircraft activity saw a 62% reduction in April, with individual airports like New York's John F. Kennedy (JFK) reporting reductions by up to 84%. In Europe, Zurich airport saw a drop of 91 per cent in aircraft activity from February to April 2020, which led to an 83% reduction in NO_x, while NO_2 concentrations and fine particle concentrations decreasing by around 50% in and around the airport (Fleuti, 2021). We expect additional local scale studies quantifying changes in air quality and health risk due to reduced aircraft activity around cities and airports to be available in the near future. However, the majority of air quality degradation due to aviation emissions is based on the expectation of a long-term (chronic) increase in population exposure. These changes in aviation emissions will therefore only be significant in the event of a long-term downturn in aviation activity.

4. Trade-offs and optimal scenarios in the context of engine emissions metric

Traditionally, one of the issues facing the aviation industry has been whether to focus on reducing impacts on climate change or on reducing impacts on air quality. Ideally there would be no trade-off, but in practice, reducing climate impacts tends to increase the emissions of NO_x and its effects on O_3, and reducing NO_x tends to increase fuel burn and resulting emissions of CO_2, the primary gas of concern to the changing climate. As a result, there have been a number of studies that have considered aspects of these trade-offs. Moving forward, there is the possibility that technological developments could lead to the ability to both reduce CO_2 and NO_x. As a result, these developments need to be considered carefully in future analyses and associated policy evaluations.

Most of the premature deaths due to outdoor air pollution, recently re-estimated to 8.7 million in 2018 by Vokra et al. (2021), is associated with direct impacts of small-sized particulate matter less than 2.5 microns ($PM_{2.5}$). However, there is also extensive data showing that O_3 is harmful to human health by affecting the human respiratory system, increasing risk of asthma, air passage inflammation, and reduced lung function (e.g., Schraufnagel, 2019a, b). As a result, O_3 levels can contribute to death, even though recent studies have provided mixed results on the direct link between O_3 and mortality (Atkinson et al. 2016). As discussed earlier, the aviation impact on near-surface O_3 is dominated not by near-surface emissions but by the large-scale changes in tropospheric (and lower stratospheric) ozone due to cruise-altitude NO_x emissions. Although the net impacts are small relative to non-aviation emissions, changes in near-surface ozone due to aviation emissions have been estimated to contribute to thousands of premature mortalities per year (Eastham and Barrett, 2016; Quadros et al., 2020). These impacts are also likely to continue rising. Using a global climate-chemistry model, Hauglustaine and Koffi (2012) showed for instance that depending on the future scenario, NO_x emissions from aircraft could contribute by 30– 40% to the summertime 8h-average daily maximum surface O_3 increase due to transport emissions in Europe and in the United in 2050.

One of the issues affecting the trade-off is the large difference in the atmospheric lifetimes of NO_x (and the resulting effects on O_3) in the atmosphere relative to that of CO_2. Neglecting methane feedbacks, the short-term effects on O_3 after emissions of NO_x last for less than a month in the troposphere while the lifetime of CO_2 is centuries to millennia (Joos et al., 2013). Case studies by Freeman et al. (2018) have shown that for a scenario of a 20% reduction in NO_x emissions for current aircraft technology, the consequential CO_2 penalty of 2%, which may not be representative of future technological advances, increased the total radiative forcing and thus the overall climate. For a 2% fuel penalty, NO_x emissions needed to be reduced by >43% to realize an overall climate benefit but note that 2% would be a very large change and economically expensive. This may be achievable with new low-NO_x combustor designs (e.g. new staged and lean combustor designs, if they are designed for cruise NO_x emissions reductions) being developed by industry, as well as other concepts such as post-combustion emissions control which has been estimated to provide a 95% reduction in NO_x emissions for any given flight in exchange for a 0.5% increase in fuel burn (Prashanth et al., 2021). The difficulty of implementing practical after-treatment should not be underestimated. Conversely, to ensure that the fuel penalty for a 20% NO_x emission reduction did not increase overall forcing, a 0.5% increase in CO_2 was found to be the “break even” point. With the time scales of the climate effects of NO_x and CO_2 being quite different, careful analysis of proposed emissions trade-offs will be necessary, even in the case where only climate is considered. Aviation is also presented with a major challenge to reduce its overall contribution to climate change. Aviation currently accounts for 2-3% of the total annual human-related emissions of CO_2, but as other surface sources are reduced to mitigate future changes in climate, aviation could become a larger portion. Fuel efficiency has become a major focus for the aviation sector. The aviation community is also considering the use of alternative fuels (e.g., biofuels) as a way of reducing this impact. However, a switch to such fuels likely would result in similar emissions of NO_x.

Incorporating air quality concerns could significantly change these considerations. Grobler et al (2019) estimated monetized climate and air quality impacts per unit of fuel burned during both LTO and cruise. They too found that climate impacts from NO_x emissions are small relative to those of CO_2. However, they also found that the monetized air quality impacts of cruise NO_x emissions (per unit of fuel burned) are comparable in magnitude to the total monetized climate impact of aviation emissions, including CO_2 and contrails. This implies that trading a 2% increase in fuel burn for a 20% decrease in NO_x emissions may result in net benefits, with air quality benefits exceeding climate costs by potentially an order of magnitude.

Using the results of Grobler et al (2019), Miller[1] (2019) estimate the total monetized climate and air quality impacts that are implied by the CAEP/8 NO_x standard. The standard allows for higher NO_x emissions at higher engine

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[1] A peer-reviewed paper based on this Master Thesis (Miller, C.J., P. Prashanth, F. Allroggen, C. Grobler, J.S. Sabnis, R.L. Speth, and S.R.H. Barrett, 2021, An Environmental Cost Basis for Regulating Aviation NOx Emissions, submitted to *Environmental Research Communications*) is currently under review.

overall pressure ratio (OPR), consistent with the increasing difficulty of controlling NO_x at higher OPR (i.e. higher combustor entry temperature). This suggests increasing air quality and human health impacts at higher OPR. However, higher OPR is typically associated with higher efficiency and thus lower CO_2 emissions, which means reduced climate impacts given the relatively higher importance of CO_2 than NO_x in terms of climate impacts. The approach employed by Miller (2019) was to take ICAO EDB (emissions databank) measurements of LTO emissions and extrapolate those to cruise using BFFM2 (Boeing Fuel Flow Method 2) for NO_x and a dimensional analysis approach for fuel burn and CO_2. A simple cycle model was used to relate OPR to cycle efficiency. Using this approach, the implied CO_2 emissions as a function of OPR and allowable NO_x emissions was estimated, and converted to monetized climate and air quality damages, as shown in example results in **Figure 3**. The results from this single study suggest that higher OPR leads to reductions in overall climate impacts, but increasing air quality impacts that can outweigh the climate impacts as OPR increases. There is much greater uncertainty in the impact costs of NO_x at altitude on LAQ than there is in the climate impact cost of CO_2 and in fuel cost estimates, so there remains uncertainty in this finding.

As a result of the challenges raised by climate change, a number of studies have been focused on how to reduce the climate forcings from aviation. Skowron et al. (2021) suggest there should be special considerations given to reducing climate impacts. Some existing research studies have been aimed at both reducing fuel burn and the resulting emissions of CO_2, while others have been more focused on reducing contrail formation and the contribution to climate change from contrails (e.g., see IPCC 2013; Brasseur et al. 2016; Lee et al. 2021). Varying flight-cruise altitudes has also been proposed as an option to mitigate the aircraft climate impact. An earlier study by Søvde et al. (2014) found that when aircraft fly lower by 2000 ft, the radiative forcing from NO_x emissions decreases by about 30% and increases by about 30% when they fly 2000 ft higher. By looking at the broader range of aviation impacts, Matthes et al. (2021) found that flying lower by 2000 ft leads to a reduction of the radiative forcing of non-CO_2 (NO_x on O_3 but also contrail-cirrus) effects together with increased CO_2 emissions and impacts, when cruise speed is not modified.

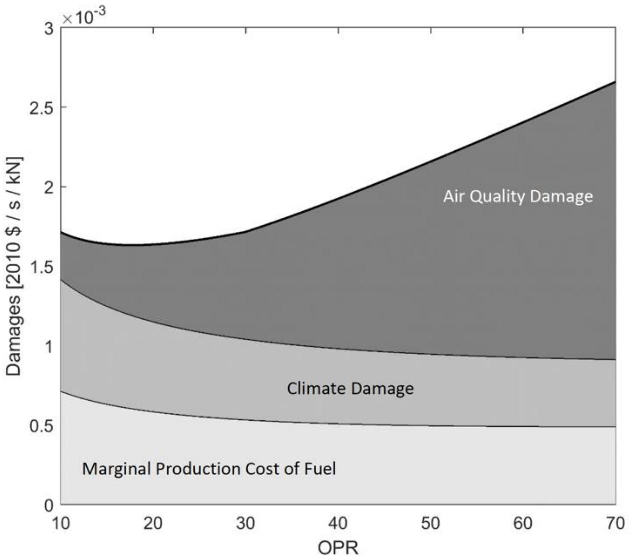

Figure 3. The estimated total monetized climate and air quality impacts, along with fuel production cost, as a function of overall pressure ratio (OPR) that is implied by (and at) the CAEP/8 allowable NO_x limit. From Miller (2019). The monetization approach is from Grobler et al. (2019). The results are for engines rated at 89 kN and above.

Other studies (e.g., Avila et al. 2019; Teoh et al. 2020) have considered the effects of technology development that would allow for contrail avoidance. These studies suggest a small change in flight altitude would reduce the aviation contribution to climate forcing over the short-term but they do not consider the long-term CO_2 or the NO_x effects.

5. Conclusions and future work

The impact of NO_x on climate results from a complex balance of offsetting effects. The current view is that the net aviation NO_x effect likely results in a warming of the climate system. However, the uncertainty associated with the estimates of the net climate forcing remains high. Several recent studies suggest that the net climate impact of aviation NO_x might be a net cooling depending on future background atmospheric composition, future aircraft emissions or when new processes or refined parameterizations are considered. The radiative forcings associated with the O_3 and CH_4 responses to aircraft NO_x emissions involve very different time scales. The use of the ERFs is therefore important and needs future work. The estimated impacts of NO_x emissions on the climate system relative to other forcing agents are dependent on the choice of the climate metric and time horizon considered.

Aircraft ground operations and the landing and takeoff cycle emit various gaseous and particulate pollutants or their precursors, which are known to affect human health. The key pollutants of interest from a human health perspective are essentially NO_2, O_3 and $PM_{2.5}$. For aircraft, recent studies show the pervasive influence of ground level emissions on reductions in air quality around major airports and also at the regional scale. Airport emissions of NO_x from aircraft are an important but minor source of ground level O_3 compared to other surface sources that largely result from fossil fuel burning in power production and transportation systems. Most NO_x emissions from aviation do not occur near the ground and largely occur at cruise altitudes. Those emissions still contribute to the background levels of O_3 and thus to the O_3 at the ground level. Similarly, several studies also showed that cruise emissions were a dominant source of surface level particulate matter globally and of aviation-related premature mortality. Particle number concentration (PNC) is a good marker for traffic and aircraft emissions, and increasing number of studies are reporting elevated PNC due to aircraft emissions in the vicinity of airports in the recent few years. Aircraft LTO emissions contribute to premature mortality around major airports. At the local scale, NO_2 health impacts were shown to outweigh $PM_{2.5}$ health impacts.

The global pandemic related to SARS-CoV-2 and the subsequent COVID-19 related lockdowns led to large reductions in transportation activity, specifically during early 2020. The global CO_2 emissions decreased by almost -9% in the first half of 2020 compared to the same period in 2019 and emissions from global aviation decreased by -44% during the first half of 2020, of which roughly 70% of the drop was related to international flights. Due to the COVID-19 pandemic, all-sector CO_2 worldwide emissions in 2020 decreased by -4% and the emissions from aviation fell by nearly -5%.

The options for controlling aviation NO_x are limited and are countered by the international growth in commercial aviation and by the mandate to increase engine energy efficiency. In the recent past, aviation NO_x emissions have been reduced by technology improvements in combustor design, driven by increased stringency in NO_x emissions regulations. However, historically the continued reductions in NO_x has tended to increase fuel burn and the resulting emissions of carbon dioxide (CO_2), the primary gas of concern to the changing climate. Thus, there arises a trade-off between reducing impacts on climate due primarily to CO_2 and reducing impacts on air quality due primarily to NO_x (and also particulate matter). However, new technologies in both combustor (e.g. lean and staged designs) and emissions control may mean it is possible to reduce both NO_x and CO_2. An important issue affecting the trade-off issue is the much shorter atmospheric lifetime of NO_x (and the resulting effects on O_3 and CH_4) relative to that of CO_2. In response to the important challenges raised by climate change, a number of studies have focused on how to reduce the climate impact of aviation through changing flight operations. This is particularly the case for reducing contrail formation and the contribution to climate change from contrails and induced cirrus. In the case of NO_x, the climate impact varies strongly with flight altitude as the lifetime of pollutants increases higher-up. Lowered flight altitudes provide another possible mitigation option for reducing the climate impact of NO_x at the cost of increased CO_2.

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