Impacts of Aviation NO_x Emissions on Air Quality, Health, and Climate

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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, which counter-balance 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.

A recent report[1] was written by the Impacts and Science Group (ISG) within the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP) that enlisted subject matter experts from the ISG to examine and summarize 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, resulting in a better understanding of the impacts of NO_x. The NO_x impact 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 and provide a net cooling, which 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.

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 at the regional scale, indicating a significant health impact from these ground level emissions. Aircraft LTO emissions contribute to premature mortality around major airports and, at the local scale, NO_2 health impacts were shown to outweigh $PM_{2.5}$ health impacts.

In addition, several studies indicate that cruise altitude emissions could significantly be recirculated to the lower

1 To be published later in 2022: https://www.icao.int/environmental-protection/Pages/environment-publications.aspx

atmosphere and be an important source of O_3 and of particulate matter at ground level. 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. Some studies suggest that cruise emissions could potentially be a dominant source of surface level particulate matter globally and of aviation-related premature mortality.

Reducing aviation NO_x is challenging and is 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 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.

In response to the important challenges raised by climate change, several 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 as the lifetime of pollutants increases higher-up. 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 discussed in the ISG NO_x Report.

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. 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 (LTO) emit various gaseous and particulate pollutants or their precursors, which are known to affect human health. 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. Countering these increasing NO_x impacts, in the short term there was a large reduction in transportation activity that arose in 2020, due to the global COVID-19 pandemic and the subsequent travel restrictions.

The key messages of the Impacts and Science Group (ISG) Report on NO_x impacts are:

- 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 forcing 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 considering recent technological developments is needed.