

# Science Overview

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## Summary Report

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## **Summary**

This report presents an overview of the latest scientific consensus understanding of the effect of aviation emissions on the atmosphere for both local air quality and climate change in order to provide a contextual framework for raising future questions to help assess the environmental benefits of technology goals. Although studies of the two issues share a common framework (of quantifying the emissions, the change in concentrations in the atmosphere, and the environmental impacts), the communities of practitioners are distinctly different. The scientific community will continue to provide guidelines on trade-off among different contributors to a specific environmental impact, such as global climate, or local air quality. Ultimately, monetization of the costs and benefits of mitigation actions is the proper tool for quantifying and analyzing trade-offs between the two issues. Scientific assessment of the impacts and their uncertainties are critical inputs to these analyses. Until environmental effects of aviation emerge as a policy driven issue, there is little incentive within the scientific community to focus on research efforts specific to trade-off studies between local and global impacts.

## 1. Introduction

This report presents an overview of the latest scientific consensus understanding of the effect of aviation emissions on the atmosphere for both local air quality and climate change in order to provide a contextual framework for raising future questions to help assess the environmental benefits of technology goals. The questions may take the form of what are the environmental benefits that would result if goals were achieved, what are the consequences for other aviation pollutants, and whether tools exist to evaluate the trade-off? Since the Panel's focus is on reduction of  $\text{NO}_x$ , the particular emphasis of this briefing paper is on the impacts of ozone ( $\text{O}_3$ ) from aviation  $\text{NO}_x$  ( $\text{NO}_x = \text{NO} + \text{NO}_2$ ) emissions in the contexts of climate change and local air quality. Emissions of  $\text{NO}_x$ , particularly at cruise altitudes, lead to formation of  $\text{O}_3$ , a 'greenhouse' gas and small reductions in methane ( $\text{CH}_4$ , another greenhouse gas). In terms of local air quality, the driver is primarily human health impacts from particles,  $\text{O}_3$  and  $\text{NO}_2$  (a particular issue in Europe); local regulations differ in this respect. With everything else being the same, an engine design with a smaller  $\text{NO}_x$  emission index (defined as g of  $\text{NO}_x$  emitted per Kg of fuel use) would deposit less  $\text{NO}_x$  in the atmosphere resulting in smaller impacts. However, it is necessary to consider all emissions/effects of aviation since there are potentially both atmospheric and technological 'tradeoffs'. In particular, there is the well-known technological tradeoff between  $\text{NO}_x$  emissions and fuel efficiency, since current technology trends for fuel efficiency tend to result in greater challenges for combustion engineers in designing low- $\text{NO}_x$  engines. Depending on the exact magnitudes, a less efficient engine with a smaller emission index may deposit more  $\text{NO}_x$  in the atmosphere.

To facilitate studies on trade-offs among environmental impacts from aviation, one must start with scientific investigations that quantify the impacts. A second step is to select representative metrics with policy relevance so that diverse impacts can be put on the same common scale. Within the context of CAEP, step 1 is aligned with the responsibilities of the Research Focal Points, while step 2 is more related to activities of FESG. The IPCC Special Report on Aviation (IPCC, 1999) serves as an excellent example of the first step. IPCC's Working Group 1, whose mandate is to provide the assessment of the scientific aspects of the climate system and climate change, produced the report. An example of the second step is Wit et al. (2005), a study that was commissioned by the Environment DG of the European Commission to scope out the possibilities for incorporating  $\text{CO}_2$  and non- $\text{CO}_2$  effects into the European Emission Trading scheme. These steps are likely to be iterative as proposed policy options will raise new science questions, and new science will expand or limit policy options. Past experiences show that clearly defined policy-related scientific needs will help focus the scientific community to marshal their intellects to provide the needed answers.

Within the first step, there are three sub-steps: quantifying the emissions, the changes in ambient concentrations, the actual environmental impacts (i.e. radiative forcing or some other environmental response such as change in surface temperature or impact upon human health), and the corresponding uncertainties. The relationship between some aviation emissions and changes in concentrations (in particular surface  $\text{O}_3$ , and, to a lesser extent, global  $\text{O}_3$ ,  $\text{CH}_4$ , and  $\text{CO}_2$ ) depends on the magnitudes of emissions

from other (non-aviation) sources. This is why one must consider aviation emissions in the context of other emissions that affect the atmospheric budget of the pollutant. It should be noted that one does not always need information from all three sub-steps to formulate effective policy. In the case of CO<sub>2</sub>, for example, the environmental impact as a well-mixed greenhouse gas (GHG) is independent of the geographical locations of emission. Thus, the amount emitted is a good metric to compare with other well-mixed GHGs, once an 'equality' metric such as global warming potential (GWP) has been adopted. A similar argument has been used to justify using an inventory approach in formulating policy on local air quality. Such an approach is appropriate as long as one is certain that processes in the hot engine exhaust plume do not change the nature of the emitted gases. However, as one attempts to compare different impacts, climate change versus local air quality for example, one would have to examine the actual environmental impacts and derive a common currency for trade-offs.

The purpose of this report is to present the scientific consensus concerning the understanding of the environmental impacts from aircraft engine emissions. Thus, the emphasis is not on 'cutting edge' scientific research. Some of the developing science will be discussed in separate presentations at this meeting. Two major themes are discussed: local impacts associated with emission associated with operation in airports including landing and take-off (LTO emissions); and global impacts associated with non-LTO emissions 3000 ft above the ground. It is likely that non-LTO emissions at cruise have only modest impacts on local air quality compared to local sources, and that emissions around specific airports do not affect global concentrations (Tarrason et al., 2004). This allows a partial decoupling of the two issues, which supports the case for different metrics. This also reflects the reality of the situation where the two issues are studied by two distinct communities of practitioners. In addition, the two issues call for different approaches. Emissions at cruise altitudes have a different impact on concentrations in the upper troposphere compared to the same amount emitted at the ground, which depends on physical (e.g. washout, dry deposition) and chemical processes/regimes. In studying the effects from non-LTO emissions, the scientific interest coincides with the need of the aviation industry to quantify the importance of these effects in order to advise technology and policy development. In contrast, aviation emissions at the ground are one of many land-based sources that degrade local air quality. Here, the scientific interests are not focused on the priorities of the aviation community. One must leverage the work within the wider community to solve aviation specific problems.

Assessing the trade-offs in reducing different emissions relies on an understanding of the impacts of the emissions and on the costs and benefits associated with their reduction. The impacts and their uncertainties are being addressed in the scientific work summarized in this report. For some emission impacts, large uncertainties exist at present. For instance, the effects of LTO and non-LTO emissions on regional air quality are only beginning to be explored. For PM (particulate matter) especially, inventory development is in its infancy, and questions of specific HAP (hazardous air pollutants) emissions are poorly understood. In addition, trade-offs would likely involve

environmental effects beyond emissions, such as noise, which is not being covered in this review.

## **2. Impacts on global climate from cruise emissions**

Present commercial subsonic aircraft operate at cruise altitudes between 8-13 km (in the upper troposphere-lower stratosphere), where they release gases and PM, thereby altering the atmospheric composition and changing the energy balance of the atmosphere-earth system. Primary emissions from aircraft include CO<sub>2</sub>, water vapor (H<sub>2</sub>O), NO<sub>x</sub>, sulphur oxides (SO<sub>x</sub>), soot and unburned hydrocarbons (UHCs). These emissions lead to changes in ambient concentration of the emitted species (e.g. CO<sub>2</sub>), and indirectly to changes in concentrations of other species through photochemical interactions (changes in concentration of O<sub>3</sub> and CH<sub>4</sub> as a result of NO<sub>x</sub> emissions). In addition, aircraft cause contrails under certain environmental conditions that may, in turn, enhance cirrus cloudiness.

The Intergovernmental Panel for Climate Change (IPCC) is the premier international organization that provides consensus policy-relevant scientific information for defining mitigation processes for global climate issues. In the IPCC process, peer-reviewed results from top research groups are compared and reported, and opinions from an expert panel are offered. An individual chapter usually involves many authors, and contributing authors and is twice reviewed by a wider scientific base, and finally by government representatives. The IPCC reports use radiative forcing (RF) to compare the climate impact of the different gases and particles. RF (here measured in milli Watts per square meter, mWm<sup>-2</sup>) expresses an instantaneous change in the energy balance of the earth-atmospheric system resulting from a perturbation in concentrations of GHGs in the atmosphere. A sustained positive radiative forcing imposes a warming effect, a negative forcing a cooling one. Carbon dioxide is the most important well-mixed GHG because of the large quantities released and the long residence time of this gas in the atmosphere. Its RF is well known. Well-mixed GHGs have long residence times (~ several decades or longer). The long residence time in the atmosphere means that the changes in concentrations are independent of where the gas is emitted, and once emitted, the forcing will persist for decades or centuries even if emissions were to cease and the temperature effect persists even longer. For these long-lived GHGs, the steady state temperature change for a sustained forcing is expected to be proportional to the RF, with approximately the same proportionality constant for all GHGs. Current trading policy for long-lived GHGs is based on GWP weighting with an integration time horizon of 100 years (GWP-100 weighted), which gives the equivalence mass of CO<sub>2</sub> that will have the same cumulative forcing 100 years following emission.

IPCC acknowledges that there are much larger uncertainties associated with evaluating the climate impacts from short-lived gases. Once emitted, they typically remain in the atmosphere for less than a year. In addition, the spatial pattern of the change depends on where and when the emissions occur. For example, because only a small fraction of the NO<sub>x</sub> emitted at the ground is transported to the upper troposphere, NO<sub>x</sub> emitted at cruise altitudes has a much larger impact on ozone in the upper

troposphere than the same amount emitted at ground level. Changes in concentrations will also be the largest near flight routes and therefore have a more regional effect on climate. It is unclear whether the global averaged temperature response to the global averaged forcing will bear the same relationship as the long-lived GHGs. For these reasons, there are conceptual difficulties in using a GWP for  $\text{NO}_x/\text{O}_3$  as the chemical (and thus RF) effect varies in space (location, altitude). Finally, using a 100 year integrated effect approach would artificially minimize the short-term impacts because the effect really occurs only in the first couple of years.

Emission inventories for aviation emissions at cruise are made using fuel use and emission indices (g of pollutants emitted per Kg of fuel use). The impact of aviation on climate has been analyzed by IPCC Special Report on Aviation (IPCC, 1999) and the issues were revisited briefly in the IPCC' Third Assessment Report (IPCC, 2001). As explained above,  $\text{CO}_2$  emitted by aircraft at cruise altitudes has the same effect as  $\text{CO}_2$  emitted by a source at ground level. Fuel use for aviation in 1992 was 2% of all combustion sources, and 13% of the transport sector.

For the following short-lived species, the RF will depend on the location of emission (flight path) in addition to the total fuel use:

**Water vapor** released into the free troposphere by aircraft has little effect on RF because of the copious amount of water already in this part of the atmosphere. However, water vapor (and PM) emitted into the upper (cold) regions of the troposphere often triggers the formation of line shaped contrails, which tend to warm the earth's surface. Persistent contrails may also disperse to form (optically thin) cirrus clouds (called contrail cirrus), which could have an additional warming effect. The direct RF of  $\text{H}_2\text{O}$  and the RF of linear contrails (for a given contrail coverage) is fairly well known, however, the RF associated with contrail cirrus is highly uncertain. In addition, prediction of contrail coverage and cirrus remain a challenge. The residence times of water and contrail in the upper troposphere are of the order of days, and hours respectively.

**Sulphate and soot aerosols** have a much smaller direct forcing effect compared with other aircraft emissions. Soot absorbs heat and has a warming effect; sulphate reflects radiation and has a small cooling effect. In addition, accumulation of sulphate and soot aerosols might influence the formation and the radiative properties of clouds. Direct RFs are fairly well known; however, indirect RF through changing cloud properties is highly uncertain. Addition uncertainties come from the emission indices of soot.

**Nitrogen oxides**, though not in themselves GHGs, produce an indirect radiative forcing by changing  $\text{O}_3$  and  $\text{CH}_4$  concentrations in the atmosphere. Nitrogen oxides are chemically reactive gases, which produce  $\text{O}_3$  under the influence of sunlight. As a consequence of complex tropospheric chemistry,  $\text{NO}_x$ , will also reduce the ambient atmospheric concentration of  $\text{CH}_4$ . The RFs of  $\text{O}_3$  and  $\text{CH}_4$  are fairly well known, of similar magnitude but opposite sign.

Table 1 summarizes estimates of instantaneous RF and the uncertainties from changes in concentrations from historical aircraft emissions reported by IPCC (1999). A recent study by Sausen et al. (2005) showed that the magnitude of the O<sub>3</sub> and CH<sub>4</sub> responses are 25% and 50% smaller. The results for soot and contrails are factor of 1.6 and 3 smaller respectively. These values are consistent with the uncertainty estimates provided in the IPCC report. Finally, the values given in the Table should NOT be used to compare forcing in trade-off studies for two reasons. First, the numbers are RF associated with the changes in concentrations associated with cumulative emissions from the historical fleet, rather than annual emission. Second, they are instantaneous forcing and do not account for the difference in persistence between long-lived and short-lived GHGs.

**Table 1:** Radiative forcing (RFs) [mW/m<sup>2</sup>] due to aviation emissions from historical operation of the subsonic fleet in the year 1992 as reported in by IPCC (1999).

Emission/concentration	RF [mW/m <sup>2</sup> ] Range*	comment
CO <sub>2</sub> /CO <sub>2</sub>	18.0 13 to 23	Instantaneous forcing due to a change in CO <sub>2</sub> concentration of 1 ppmv resulting from cumulative CO <sub>2</sub> emission from historical operation of the fleet to 1992. For comparison, the change in CO <sub>2</sub> concentration from 1992 emission is 0.07 ppmv.
NO <sub>x</sub> /O <sub>3</sub>	23.0 13 to 45	Instantaneous forcing from changes in concentration due to the steady state response of the atmosphere to a persistent operation of a fleet with 1992 emissions. Typical time to reach steady state is a few months for O <sub>3</sub> , about 10 years from CH <sub>4</sub> .
NO <sub>x</sub> /CH <sub>4</sub>	-14.0 -44 to -4	
H <sub>2</sub> O/ H <sub>2</sub> O	1.5 1.5 to 3	Instantaneous forcing from changes in concentration due to the steady state response of the atmosphere to a persistent operation of a fleet with 1992 emissions. Typical time constant is weeks.
SO <sub>x</sub> ,PM/Sulphate	-3.0 -.5 to 0	
Soot/ Soot	3.0 2 to 8	
H <sub>2</sub> O, PM/ Contrails	20.0 5 to 60	

\* The range represents a subjective estimate (as cited in the IPCC report) that there is a 67% probability that the true value falls within the range. The uncertainties arise from a combination of the uncertainties in predicting the change in concentration and in predicting the environmental impact from a given concentration change.

### 3. Local impacts from aircraft engine emissions at airports

The impacts of airport emissions (from aircraft engines and sources associated with other activities at the airport) on local and regional scales is part of the broader problem of local and regional air quality monitoring and should be considered in the

broader context of those environmental factors specific to the region's air quality problems. It is well known that the same emissions could cause different changes in ambient concentrations at different locations. In addition, the actual health impact will depend on the population exposure, which in turn depends on the population number and distribution in the region being considered.

Aircraft engine emission levels are specified for the certification of new engine designs. Specifically, levels of  $\text{NO}_x$ , CO, UHCs, and smoke are regulated and documented for this certification process. For the gaseous emissions, the emission levels are determined for each of four power settings (idle, approach, climb, and take-off), and these four power settings are used in developing inventories for aircraft operations in airports. In addition to the emissions levels and emissions rates, time-in-mode must be used, and an "ICAO cycle" has been specified, which stipulates the times relevant for each of the four power settings during typical operation. In the case of  $\text{SO}_2$  emissions, fuel sulfur content is the additional parameter needed. The application of ICAO certification data with the ICAO cycle is used in models such as the FAA's Emission Dispersion Modeling System (EDMS) to develop inventories of gaseous emissions from aircraft operating at airports using operational data of airplanes and engine types taking off and landing at a given airport.

As mentioned in section 1, gaseous and particulate properties evolve at the engine exit plane until atmospheric processing takes over, perhaps minutes after emission. Initial chemistry and microphysics occurring in the plume and subsequent dispersion needs to be fully understood so that the inventories developed from engine measurements can be applied in local and regional models. The atmospheric science community that determines impacts, on both human health and on visibility, typically does not address the near field nor dispersion processes that propagate the emissions from the engine to the local scale. So both plume models and dispersion models with chemistry and microphysics need to be developed, first to scope the problem and then refined, if necessary, to address the question. If needed, the plume modeling and EDMS-type dispersion modeling elements need to be exercised fully and coordinated with each other.

CO is relatively long lifetimes (~ weeks) and can affect the local hydroxyl concentration resulting in changes in concentrations of ozone and methane. CO from engine emission is often much smaller than other local sources.

$\text{NO}_x$  (NO and  $\text{NO}_2$ ) is a participant in ozone formation, and also contributes to nitric acid and acidification of aerosols (fog) and rain. In fact, the US EPA has recently recognized  $\text{NO}_x$  as a precursor of  $\text{PM}_{2.5}$  in their revisions to the Clean Air Act General Conformity Regulation. Tracking  $\text{NO}_x$  will serve multiple purposes as a criteria pollutant of  $\text{NO}_2$ , precursor for ozone, and precursor for  $\text{PM}_{2.5}$ . Since the atmospheric impacts are not unique for aviation, these are being studied and updated independently. The relative contribution from aviation  $\text{NO}_x$  may become larger as other sources reduce  $\text{NO}_x$  through exhaust treatment. Quantification of and inventories for aviation  $\text{NO}_x$  emission are well in hand. Thus, new work in further developing metrics for  $\text{NO}_x$  emissions is not needed except for the plume evolution issues.

In addition to  $\text{NO}_x$  contributing to ozone production and PM mass, the  $\text{NO}_2$  component of  $\text{NO}_x$  has specific health impacts of its own, primarily affecting respiratory function. While the former effects occur on larger scales (urban airsheds) due to the rates of formation of ozone and PM, exposure to  $\text{NO}_2$  depends on the local fractionation of  $\text{NO}_x$  into NO and  $\text{NO}_2$ , and is sensitive to the very localized concentration levels of  $\text{NO}_2$  emissions. In Europe, in particular, inventories of  $\text{NO}_2$  on very localized scales around airports are being developed to assess  $\text{NO}_2$  exposures. In this context, it is important for  $\text{NO}_x$  fractionation to be determined from aircraft engines as a function of engine operation, and to follow that fractionation as the emissions evolve downwind from their release point.

For **Hydrocarbon (HC)** emissions, total inventories can be developed from the ICAO database. However, HCs are interrelated with volatile particles and, in addition, increased interest may arise in regard to specific hydrocarbons owing to their potential as Hazardous Air Pollutants (HAPs). As such, more detailed emissions characterization may be required in the future. Some important initial work on speciation of HC emissions has begun, but dependences on engine and fuel properties are not well known at this time. There are also uncertainties about which HAPs are present in engine exhaust that may warrant focused attention. Further research in characterizing HAPs and better understanding the interrelationships among the HC emissions is needed to move forward sensibly and reduce those emissions that have the largest hazard potential in a systematic way. Elemental metals, for instance, have been measured from petroleum-powered aviation sources that have been identified by the EPA as HAPs.

For **particulate matter (PM)** emissions, inventories do not exist and knowledge is lacking at present as to how aviation particles differ from other emission sources, considering both volatile and non-volatile particles. There is significant recent and ongoing research in this area on how they depend on engine operating conditions and engine type and technology. Smoke is controlled through the measurement of a Smoke Number, SN, and was developed in parallel with the various gaseous emission measurement approaches in the 1970s, to reduce the visible smoke trails behind airplanes. Only the maximum smoke emission level is regulated, irrespective of at which engine power level that maximum occurs. Thus, while visible smoke has been reduced significantly in the last decades and the application of the SN can be deemed a success, there is currently no reliable means of developing an inventory of aircraft particle emissions. To properly evaluate the influence of aviation growth on local air quality, uniformly consistent methodologies, both measurement technology and procedures (such as probe and sampling system designs) are critical. A subset of fine PM has been recognized as hazardous to human health. This fraction of fine PM needs to be more readily understood. To illustrate how emissions may have different impacts at different locations, the US EPA has identified  $\text{NO}_x$ , hydrocarbons,  $\text{SO}_2$ , and ammonia as indicators of secondary fine PM. Emitted  $\text{NO}_x$  may have very different impacts in area where ammonia is present. It is well understood that the sulfur in fuels directly contributes to the gaseous emissions of sulfates and  $\text{SO}_2$  from aviation sources. What is less understood is

how sulfates and SO<sub>2</sub> contribute to secondary fine PM generation, not only as individual contributors, but also in a heterogeneous mixture with other pollutants. □

#### 4. Trade-offs

Reducing emissions across the board is one way to minimize environmental impacts. Unfortunately, designs that reduce one emission may have negative impacts on another emissions. This is the reason why one must consider trade-offs in such designs.

There are trade-offs at many different levels depending on how one defines the trade space. In the context of this report, one can consider the following:

- trade space on global climate impacts from emissions at cruise
- trade space on LAQ and health (PM vs. ozone) from emissions at airports
- trade space between noise and LAQ at local level from airport operation
- trade space between air quality at local versus regional level
- trade space between global, regional and local impacts

Uncertainties associated with estimating the environment impacts play an increasingly important role in trade studies as one includes more dissimilar environmental impacts in the trade space. The scientific consensus that warming from well-mixed GHGs is proportional to radiative forcing allows one to consider the trade-off among well-mixed GHGs without having to specify the exact constant of proportionality. If one considers the trade-offs are among CO<sub>2</sub>, NO<sub>x</sub>, H<sub>2</sub>O and PM emissions at cruise, the outstanding science question is whether RF (instantaneous or cumulative) from short-lived GHGs (NO<sub>x</sub>, H<sub>2</sub>O, and PM emissions) and their effects on ozone and contrails can be used as a proxy for temperature response in the same way as it is done for well-mixed GHGs (CO<sub>2</sub>). The policy question is whether to have a separate metric for short-lived GHGs. Wit et al. (2005) provides an example of how one would approach this. This is one area where Science can provide critical input.

The trade-off at the local level between the effects of changes in ozone and PM presents a challenge because the issues will involve health impacts, crop damage, and visibility impairment. The scientific community will be called upon to provide estimates of these impacts and their uncertainties for the approach to work. Furthermore, the results will be site-specific, with different criteria for different airports depending on population density and land use around the airport. For regional trade-offs, the outcome will depend on the size of the region.

Monetization of the costs and benefits of mitigation is beginning to be used in quantifying and analyzing all of these types of trade-offs, and the scientific assessment of the impacts and their uncertainties are critical inputs to these analyses. However, economic analysis of the impacts and of the investments required to make emissions reductions is the other key element for the evaluation of trade-offs. Policy makers will need to draw on the integration of the scientific inputs and the economic analyses, as well

as the social costs and technological requirements, to make decisions on how to implement trade-off requirements for reducing the overall cost of emissions.

In deriving strategies for technology developments to minimize environmental impacts, one must remember that the environmental impacts depend on emissions of the whole fleet, not those of a single engine. Technology or regulation could drive the airline industry to change their mode of operation and introduce a vastly different fleet. In such cases, trade-off studies would involve fleet designs and predictions of emissions from the new fleet so that the environmental impacts can be assessed.

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