

## Evaluating the Impacts of Aviation on Climate Change

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Aviation is an integral part of the global economic and transportation systems. In fact, aviation expansion outpaces the economic growth. Projections indicate that over the next 2 decades, the demand for aviation could grow to about 3 times its present level. This projected growth will likely result in higher aviation emissions and associated impacts on the environment and on human health and welfare, depending upon a variety of factors (such as the size and mix of the operational fleet necessary to meet the stated demand, as well as mitigation steps that could include new technological advances, more efficient operational procedures, market-based options, or regulatory intervention). Nonetheless, it is critical to balance the economic benefits of air travel with environmental concerns associated with this projected aviation growth.

Presently, there are gaps and uncertainties in our understanding of highly interdependent environmental impacts of aviation, which include air quality, climate, and noise. Without realizing all dimensions of benefits and related trade-offs, actions to address environmental concerns in one domain may have unintended consequences in another. To study this, the U.S. government's *Joint Planning and Development Office* [2004] developed the Next Generation Air Transportation System: Integrated plan. The NextGen vision calls for development by 2025 of environmental protection that allows sustained aviation growth. In particular, the NextGen objective is to reduce uncertainties for climate impacts to a level that enables appropriate actions to address them.

In order to provide scientific input to NextGen within its stated time frame, action is now needed to understand and quantify the potential climate impacts of aviation and develop emission-based metrics that can suitably capture these impacts. This article describes the key science issues, the state of understanding, and the associated gaps and

recommended research related to aviation-induced emissions and their effects on climate.

### Aviation-Induced Climate Concerns

The chemical species released during the fuel combustion process in aircraft engines include carbon dioxide ( $\text{CO}_2$ ), water ( $\text{H}_2\text{O}$ ), nitrogen oxides ( $\text{NO}_x$ ), and sulfur oxides ( $\text{SO}_x$ ) along with small amounts of soot carbon ( $\text{C}_{\text{soot}}$ ), hydrocarbons (HC), and carbon monoxide (CO), as shown in Figure 1. Once released at cruise altitudes within the upper troposphere and lower stratosphere

(UT/LS), these species interact with the background atmosphere and undergo complex processes, resulting in potential climate impacts and related welfare loss as depicted in Figure 1.

Although each component of this cause-effect chain is conceptually simple, the quantification of the overall magnitude of aviation-induced climate impacts is highly uncertain. In 1999, a major international coordinated effort to assess the impacts of aviation on the global atmosphere was sponsored by the United Nations Intergovernmental Panel on Climate Change (IPCC) [IPCC, 1999]. Figure 2 displays the IPCC estimates of climate forcing of aviation emissions in terms of radiative forcing (RF) for the years 1992 and 2050 (based on the IPCC Fa1 emissions scenario that considered midrange economic growth and technology advances

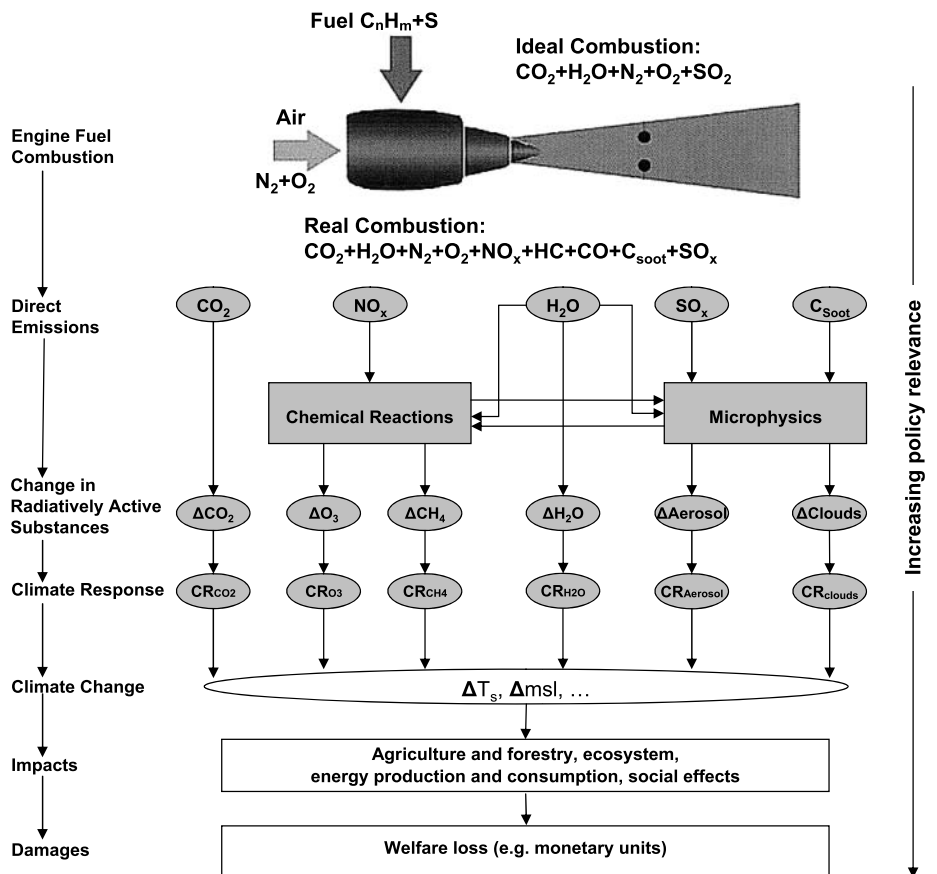


Fig. 1. Schematic of emissions released during aircraft fuel combustion and their resulting potential impacts on climate change and welfare loss.

for both improved fuel efficiency and  $\text{NO}_x$  reduction).

In 1992, aviation contributed about 2% of the total anthropogenic  $\text{CO}_2$  emissions and accounted for globally and annually averaged RF (GAARF) of about 0.02 watts per square meter. In contrast, the GAARF for all non- $\text{CO}_2$  aviation emissions combined (excluding cirrus clouds) is as large as that of  $\text{CO}_2$  alone, though characterized by relatively large uncertainties. Figure 2 clearly indicates that the level of scientific understanding to estimate climate response due to non- $\text{CO}_2$  emissions for both cases ranges from fair to very poor.

GAARF has widely been used as a metric of climate change for long-lived greenhouse gases. However, there are continued questions about its viability and usefulness for other greenhouse gases [National Academy of Sciences, 2005]. A fundamental issue is that some RFs (e.g., those from contrails, induced cirrus clouds, and ozone from  $\text{NO}_x$  emissions) are spatially inhomogeneous and seasonally varying. Therefore, RF from each of these various sources could produce a different temperature change at the surface of the Earth per unit change in GAARF. In addition, values given in Figure 2 represent the change in forcing from changes in concentrations due to all prior aviation activities. Since the atmospheric effects due to aviation emissions have very different timescales, ranging from several hundred years for  $\text{CO}_2$  to a few hours for contrails, such RF estimates do not capture the relative importance of the short- and long-lived effects.

While new scientific understanding and data sets have become available since the last IPCC report on the impact of aviation on climate change [IPCC, 1999], there has been no comprehensive U.S. or international attempt to update the assessment and associated uncertainties. Over the past several years, there has been a lapse in research activities in the United States on the climate impacts of aviation. In fact, a report to the U.S. Congress on aviation and the environment [Waitz *et al.*, 2004] clearly stated that the climate change impact of aircraft is a topic of great contention and there are no major U.S. research programs to address this.

Under the European TRADEOFF program, Sausen *et al.* [2005] updated the GAARFs for the year 2000 and compared them against the corresponding interpolated GAARFs based on IPCC estimates for year 1992 and year 2050. The overall conclusion from that study remains unchanged: There are significant uncertainties in quantifying the climate impacts of aviation emissions. Presently, there are several European research programs (e.g., QUANTIFY) under way that have focused on understanding the impacts of aviation on atmospheric composition and climate.

In North America, a 2006 workshop on the impacts of aviation on climate change, which was sponsored by the U.S. Federal Aviation Administration (FAA) and assessed and documented the present state of scientific knowledge, identified the key underlying

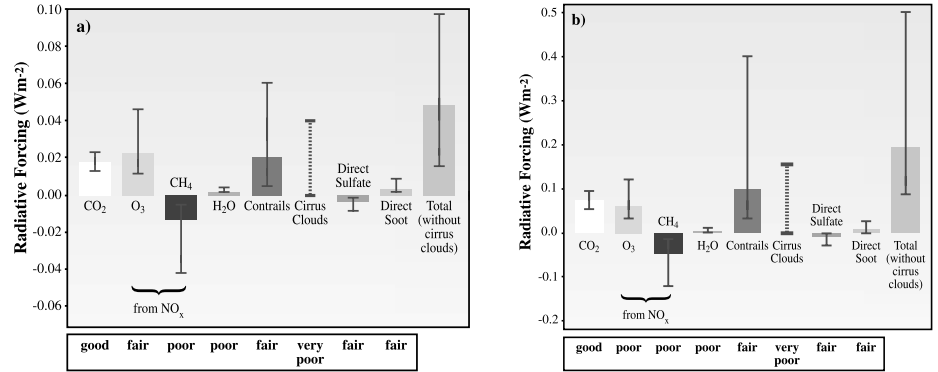


Fig. 2. Estimates of globally and annually averaged radiative forcing (GAARF), measured in watts per square meter, from subsonic aircraft fleet for (a) 1992 and (b) 2050. In both cases, the forcing represents the difference caused by historical operation of the fleet from its first introduction to 1992 or 2050. The forcing for  $\text{CO}_2$  is calculated using changes in  $\text{CO}_2$  concentration relative to the historical operation. Values for other forcings are approximated by the steady state responses to a fleet with repeated annual emissions at the 1992 and 2050 levels, respectively. See the text on why GAARF may not be a suitable metric for climate impacts of aviation emissions. Adapted from IPCC [1999].

uncertainties and gaps as well as ongoing and further research needed, and explored the development of climate impact metrics. The workshop also sought to focus the scientific community on aviation–climate change research needs.

The data shown in Figure 2 clearly indicate that the largest uncertainties are associated with the indirect forcing resulting from changes in the distributions and concentrations of ozone ( $\text{O}_3$ ) and methane ( $\text{CH}_4$ ) as a consequence of aircraft  $\text{NO}_x$  emissions, and the direct effects (and indirect effects on clouds) from emitted aerosols and aerosol precursors, and effects associated with contrails and cirrus cloud formation. Because of the issues with the RF metric noted above, workshop participants were asked to examine those issues as well as alternatives for metrics. A brief summary of the major topics covered at the workshop is found below; the full report is available at <http://web.mit.edu/aeroastro/partner/reports/climatewrksp-rpt-0806.pdf>.

#### Emissions in the UT/LS and Resulting Chemistry Effects

The potential importance of aircraft  $\text{NO}_x$  emissions on tropospheric and stratospheric  $\text{O}_3$  is well recognized. Aviation-perturbed  $\text{O}_3$  can also affect the tropospheric oxidizing capacity, and thus levels of  $\text{CH}_4$ , an important greenhouse gas. The database of observations pertaining to the UT/LS has been greatly expanded since the IPCC assessment, and the new data are being used to evaluate global models. In addition, improvements to the representation of atmospheric transport processes have resulted in better models for the composition and fluxes of  $\text{O}_3$  and other species in this region.

However, uncertainties in model predictions and gaps in understanding remain. The large disagreements between the modeled

and measured abundances of hydrogen oxides ( $\text{HO}_x$ ) and  $\text{NO}_x$  gases in the upper troposphere point to either measurement errors or errors in tropospheric chemical mechanisms and rates. There remain uncertainties related to the removal of atmospheric  $\text{NO}_x$  through the coupling of large-scale transport, convection, cloud, and precipitation processes.

A detailed intercomparison of current models and measurements, emphasizing the UT/LS and free troposphere, is needed. This process should lead to model improvements and the reduction of uncertainty in model predictions. Also needed is an expanded analysis of the wealth of data currently obtained in the UT/LS by aircraft and satellite platforms with a focus on regions perturbed by impacts of aviation emissions. Presently, most analyses of aviation impacts are evaluated relative to current atmospheric conditions. Estimates of projected climate response should consider the atmospheric conditions expected at the time of future fleet. In the longer term, field campaigns are required to address issues with  $\text{HO}_x$ - $\text{NO}_x$  chemistry in the UT and to better understand background processes.

#### Contrails and Cirrus Clouds

Contrails form if ambient air along the flight track is colder and moister than a threshold based on known thermodynamic parameters. Early contrail evolution depends, in poorly understood ways, on aircraft and engine emission parameters. In ice-supersaturated air masses, contrails can organize themselves in regional-scale clusters that add significantly to the natural high cloud cover and have the potential, albeit with large uncertainties, for a relatively large positive radiative forcing. Factors controlling the radiative properties of cirrus clouds and

contrail-cirrus (e.g., ice crystal habit, vertical profiles of ice water content, effective radius) also are poorly constrained by observations. The extent of global distribution of supersaturation in the upper troposphere has not been adequately verified to enable its reliable prediction.

Many uncertainties and knowledge gaps related to aircraft emission of aerosols persist, including their role in plume evolution and their interaction with the background atmosphere and the formation of cirrus clouds. The magnitude of the atmospheric impact depends on details of plume processing and on the relative ability of background aerosol particles to act as ice-forming nuclei. In addition, models do not adequately treat the radiative properties of cirrus, thus limiting their abilities to study contrail-cirrus cloud interactions. Large uncertainties exist as to how properties of ambient aerosols are perturbed in the presence of jet engine emissions under various atmospheric conditions and aircraft configurations.

In order to improve the representation of relevant processes in regional and global models that are responsible for formation of contrails as well as contrail-induced cirrus clouds, coordinated regional-scale campaigns are needed to measure variables to characterize the growth, decay, and trajectories of contrail ice particle populations and to define the abundance and properties of ambient aerosols as well as gaseous aerosol precursor concentrations. Process studies that explore the role of emitted aerosol particles, and how volatile aerosols interact with each other and with background aerosols, are required to understand the indirect effect of emitted aerosol particles. Laboratory measurements are urgently needed to develop aerosol-related parameterizations of heterogeneous ice nucleation for use in models.

Long-term recommended research needs include enhanced instrumentation to establish background concentrations and characteristics of heterogeneous ice nuclei and measure supersaturation accurately. Also required is the development of new concepts relating to ice phase processes for treatment of cirrus and associated aviation effects in climate models.

#### *Climate Impacts and Climate Metrics*

As stated earlier, with the exception of CO<sub>2</sub> emissions, there remain significant uncertainties in almost all aspects of aircraft effects on climate. In particular, estimates of radiative impacts due to contrail and contrail-induced formation of cirrus clouds are highly uncertain [e.g., Minnis *et al.*, 2004; Hansen *et al.*,

2005]. Projections for aviation-induced radiative impacts are even more unreliable because of uncertainties in prediction of future atmospheric conditions and their interactions with projected aviation emissions.

Metrics are needed to measure different climate forcings and place them on a common scale in order to assess the overall impact of aviation on climate and to quantify the potential trade-offs on the climate impact due to changes in aircraft technology, aircraft operations, and various policy scenarios. Such trade-offs might consider, for example, NO<sub>x</sub> reduction technology versus fuel efficiency, or the effects of changing flight altitudes. Climate change metrics play an important role in quantifying these trade-offs. As stated earlier, RF has long been used as a proxy for climate impact for greenhouse gases, but there are doubts about its viability and usefulness. The concept of efficacy, which depends on the specific perturbation to the climate system, has been introduced to account for the fact that a unit global mean radiative forcing from different climate change mechanisms does not necessarily lead to the same climate impact. In addition, RF is not an emission metric capable of comparing the future impact of projected aviation emission scenarios. The applicability of emissions metrics, such as global warming potentials, to short-lived greenhouse gases has not been adequately tested and evaluated.

There is no published study that utilizes the current understanding of the impact of aviation emissions on atmospheric composition, as reflected in state-of-the-art atmospheric models, to examine the possible choices, dependencies, and problems for metrics suitable for evaluating aviation trade-offs. Such studies would need to explore the utility of existing metrics and the possibility of designing new metrics.

#### *Conclusions and Next Steps*

Aviation-focused research activities are required to address the uncertainties and gaps in the understanding of current and projected impacts of aviation on climate and to develop metrics to better characterize these impacts. This may entail coordination and/or expansion of existing and planned climate research programs, or new activities. Such efforts should include strong and continuing interactions among the science and aviation communities as well as among policy makers to develop well-informed decisions. More concrete steps would include further ranking and prioritizing of identified research needs; creating a research road map with associated roles and responsibilities

of various participating agencies and stakeholders; and identifying resources needed to implement the road map. In coordination with participating federal research agencies of the U.S. Climate Change Science Program, the FAA is exploring possible means of addressing research needs identified by the workshop.

#### *Acknowledgments*

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