Joint Planning & Development Office
Environmental Integrated Product Team

Partnership for AiR Transportation
Noise and Emissions Reduction

# A Report of Findings and Recommendations

## Workshop on the Impacts of Aviation on Climate Change
## June 7-9, 2006, Boston, MA

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# Contents

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## Acknowledgement

I first want to acknowledge the effort of the Next Generation Air Transportation System/Joint Planning and Development Office (NGATS/JPDO) Environmental Integrated Product Team (EIPT) and the Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER) in getting the Workshop established and to thank the FAA Office of Environment and Energy and NASA Science Mission Directorate's Applied Science Program for providing the support for setting up the actual Workshop. Given that there were no special travel funds provided for attending the Workshop, I also thank the many organizations that contributed this to the participants. The Subgroup leaders, Anne Douglass, Bernd Kärcher, and Wei-Chyung Wang, did a wonderful job of chairing their sessions and organizing the writing for the Workshop report. A special thank you to Mohan Gupta and Malcolm Ko for their extensive help with the meeting preparations and in reviewing this report. I also greatly appreciate the additional reviews of the report we received from David Fahey, Mark Jacobson, and Brian Toon. Finally, I want to also express a big thank you to all of the speakers and participants for their time and efforts. The community interest and participation in this Workshop was exemplary, particularly given the short-lead time for the Workshop. It is this community interest and involvement in establishing the relevance of the issues and in laying the groundwork for the research associated with aviation and climate change that will lead to the successful new research efforts we all hope will result from this Workshop.

Workshop Chair

Don Wuebbles

## Executive Summary

The effects of aircraft emissions on the current and projected climate of our planet may be the most serious long-term environmental issue facing the aviation industry [IPCC, 1999; Aviation and the Environment – Report to the United States Congress, 2004]. However, there are large uncertainties in our present understanding of the magnitude of climate impacts due to aviation emissions. With extensive growth in demand expected in aviation over the next few decades, it is imperative that timely action is taken to understand and quantify the potential impacts of aviation emissions to help policymakers address climate and other potential environmental impacts associated with aviation.

The climatic impacts of aviation emissions include the direct climate effects from carbon dioxide ($CO_2$) and water vapor emissions, the indirect forcing on climate resulting from changes in the distributions and concentrations of ozone and methane as a consequence of aircraft nitrogen oxide (NOx) emissions, the direct effects (and indirect effects on clouds) from emitted aerosols and aerosol precursors, and the climate effects associated with contrails and cirrus cloud formation. To enable the development of the best strategy to mitigate these climatic impacts scientists must quantify these impacts and reduce current uncertainties to enable appropriate action. The only way to ensure that policymakers fully understand trade-offs from actions resulting from implementing engine and fuel technological advances, airspace operational management practices, and policy actions imposed by national and international bodies is to provide them with metrics that correctly capture the climate impacts of aviation emissions.

*As a first step in response to the need to address these issues, the Next Generation Air Transportation System/Joint Planning and Development Office (NGATS/JPDO) Environmental Integrated Product Team (EIPT)*[1] *and the Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER)*[2] *convened a panel of experts from around the world to participate in a "Workshop on the Impacts of Aviation on Climate Change" during June 7-9, 2006 in Boston, MA.* The stated goals of the workshop were to assess and document the present state of knowledge of climatic impacts of aviation; to identify the key underlying uncertainties and gaps in scientific knowledge; to identify ongoing and further research needed and to make prioritized recommendations as to how additional funding may be leveraged to take advantage of other on-going funded research programs; to explore the development of metrics for aviation climate-related trade-off issues; and to help focus the scientific community on the aviation-climate change research needs.

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[1] The EIPT is one of eight integrated product teams of the NGATS/JPDO charged with the role of formulating a strategy that allows aviation growth consistent with the environmental-related goals of NGATS. The JPDO, jointly managed by FAA and NASA, serves as a focal point for coordinating the research related to air transportation for all of the participating agencies (Federal Aviation Administration, NASA, the Departments of Commerce, Defense, Homeland Security, Transportation, and the White House Office of Science and Technology Policy).

[2] PARTNER is a Center of Excellence supported by the Federal Aviation Administration, the National Aeronautics and Space Administration, and Transport Canada.

This report documents the findings and recommendations of the Workshop. While the report does not represent a peer reviewed assessment, the intention is to use the results to provide guidance for the agencies and private sector stakeholders participating in the EIPT to develop and implement an aviation climate research plan to reduce uncertainties to “levels that enable appropriate actions” [Next Generation Air Transportation System-Integrated Plan, 2004].

A major internationally coordinated effort to assess the impacts of aviation on the global atmosphere was sponsored by the U.N.’s Intergovernmental Panel on Climate Change (IPCC, 1999). Since then, while new information has become available, there has been no comprehensive attempt to update the assessment of the science and the associated uncertainties. During this time period, there have also been discussions of how to define the best metrics to account for the wide range of spatial and temporal scales of aviation-induced climate impacts. This workshop agreed with IPCC (1999) that the three most important ways that aviation affects climate are (1) direct emissions of greenhouse gases including $CO_2$ and water vapor, (2) emissions of NOx that interact with ozone, methane, and other greenhouse gases, and (3) persistent contrails and their effects on cirrus cloud distribution. For this workshop, our focus was on the impacts of subsonic aviation emissions at cruise altitudes in the upper troposphere and lower stratosphere (UT/LS) and on the potential response of the climate system to these emissions. However, it is also recognized that all aircraft emissions must be considered.

Although current fuel use from aviation is only a few percent of all combustion sources of carbon dioxide, the expectation is that this percentage will increase because of projected increase in aviation and the likely decrease in other combustion sources as the world moves away from fossil fuels towards renewable energy sources. In addition, aircraft nitrogen oxides released in the upper troposphere and lower stratosphere generally have a larger climate impact than those emitted at the surface, although some of the much larger surface emissions from energy and transportation sources also reach the upper troposphere.

*The workshop participants acknowledged the need for focused research efforts in the United States specifically to address the uncertainties and gaps in our understanding of current and projected impacts of aviation on climate and to develop metrics to characterize these impacts.* This could be done through co-ordination and/or expansion of existing and planned climate research programs or may entail new activities. Such efforts should include strong and continuing interactions between the science community, aviation system operators and policy developers to ensure that the most up-to-date science is readily available for policy considerations and that scientists are aware of the questions and challenges faced by operators and policy developers. Participants were asked to provide both short-term (three to five years) and long-term prioritized research needs with achievable goals and objectives that can help to address the uncertainties and gaps associated with key questions on aviation induced climate impacts. These research priorities also include the need to identify, develop and evaluate metrics to characterize the climate impacts of aviation to aid the policy-making process.

Research into the environmental effects of aircraft emissions cannot be decoupled from basic atmospheric research, such as fundamental understanding of the physics and chemistry in the UT/LS region and aerosol-cloud interactions in the context of global climate modeling. The overall science focus of this workshop was divided into three particular Subgroups: (1) Emissions in the UT/LS and resulting chemistry effects, (2) Effects of water and particle emissions on contrails and on cirrus clouds, and (3) Determining the resulting impacts on climate from aircraft emissions and defining metrics to measure these impacts.

## Key Findings

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

#### State of the Science

The potential importance of aircraft emissions of nitrogen oxides (NOx) (and also from hydrogen oxides (HOx) from water vapor emissions into the stratosphere) on tropospheric and stratospheric ozone has been recognized for several decades. The effects on ozone ($O_3$) can also affect the production of tropospheric OH and thus affect levels of methane ($CH_4$). There have been substantial improvements in the chemistry-transport modeling tools used to evaluate the impacts of aviation NOx emissions on $O_3$ and $CH_4$ since the 1999 IPCC assessment. The database of observations in the UT/LS has been greatly expanded, and data from the European MOZAIC program (instruments on commercial aircraft) and focused field campaigns are commonly being used to evaluate the global model background state, emphasizing the composition of the upper troposphere and the transition from the troposphere to the lowermost stratosphere. Improvements to the representation of the atmospheric circulation have resulted in better models for the composition and fluxes of ozone and other species in this region. The magnitude of this flux and its spatial and seasonal variability are similar to quantities derived from observations in some models, and uncertainties have been reduced. These improvements should help to better assess the aviation impacts. There are continuing efforts that compare simulations with observations that will likely lead to development of observation-based performance metrics for atmospheric models.

#### Uncertainties and Gaps

One family of uncertainties in evaluating aviation effects on climate derives from specific model formulation errors and can be addressed by laboratory, numerical, or atmospheric studies that focus on the specific process.

- *Aircraft emissions of gases and particles*. Remaining uncertainties in the emissions, both from uncertainties in how much is emitted (e.g., soot, sulfates) from each aircraft and from uncertainties in the global distribution of these emissions with altitude, latitude, and longitude, need further consideration.
- *The fundamental NOx and HOx chemistry of the upper troposphere*. Large disagreements between the modeled and measured abundances of HOx and NOx gases in the upper troposphere point to errors in either the measurements or in the tropospheric chemical mechanisms and rates. This

discrepancy is not found in the lower stratosphere.

- *Lightning NOx.* Better understanding of lightning NOx in terms of sources and their relationship to convection is needed to evaluate the aircraft perturbation, especially for future climates.
- *Plume processing of aircraft NOx in the first 24 hours*. Better understanding of the possible conversion of NOx to nitric acid ($HNO_3$) in the aircraft plume needs to be attained.

A second type of uncertainty involves coupling across different Earth system components, and possible non-linear responses to perturbations and/or feedbacks within the chemical system.

- *The coupling and feedbacks of tropospheric $CH_4$-CO-OH-$O_3$.* There is no single test (based on observations) that gives confidence that any model accurately responds to a $NO_x$ perturbation.
- *Climate change.* Analyses of future aircraft fleets need to be considered relative to the climate expected. Most model studies and all observations of the meteorology and background chemistry are derived from today's climate.
- *Scavenging.* The process whereby gaseous $HNO_3$ (and thus NOx) is removed from the atmosphere involves large-scale transport, convection, cloud processes and precipitation. This coupling is a major uncertainty in current chemistry-transport models.
- *Transport and Mixing.* Aircraft emissions will accumulate in atmospheric regions of relatively slow, or stagnant mixing. The seasonality of these regions, the apparent barriers to mixing, and the rapid mixing through convection or other breakdowns in atmospheric stability are a major uncertainty in evaluating aviation impacts today.

**Research Recommendations and Priorities**

- *Models and Measurements Intercomparison*. A Models and Measurements Intercomparison, emphasizing the UT/LS and free troposphere, should be conducted. This process should lead to model improvements and reduction of uncertainty in model predictions.
- *Vertical transport processes between 2 and 10 km*. Additional measurements and data analyses, along with modeling analyses, are needed to reduce uncertainties in treatment of convection and other transport processes, and in the treatment of lightning effects.
- *Data analysis and modeling*. Expand the analysis of the wealth of data being obtained in the UT/LS by different aircraft and satellite platforms to further constrain the magnitude and seasonality of turnover rates and mixing processes.
- *Re*-examine the impacts of aviation in the UT/LS using several of the improved models.

In the longer-term, field campaigns may be needed to address issues with HOx-NOx chemistry in the UT and to better understand background processes. Further improvements are needed in laboratory studies of heterogeneous processes and low-temperature kinetics.

## B. Contrails and Cirrus

### State of the Science

Contrails form if ambient air along the flight track is colder and moister than a threshold based on known thermodynamic parameters. Contrails initially contain more but smaller ice crystals than most cirrus clouds. Early contrail evolution depends, in not well understood ways, on aircraft and engine emission parameters. At times contrails organize themselves in long-lived, regional-scale clusters in ice supersaturated air masses. The radiative effect of contrails is different during the day than at night. Aircraft-induced contrail-cirrus add significantly to the natural high cloud cover and have the potential, albeit with large uncertainties, for a relatively large positive radiative forcing (direct effect). Line-shaped contrails are only a portion of the total climate impact of aviation on the cloudiness.

Recent correlation analyses between real-time regional-scale air traffic movements and the occurrence of contrail structures detectable with satellites, suggest the global coverage of persistent, spreading contrails (contrail-cirrus) and inferred radiative forcing might be underestimated by an order of magnitude or more, but large uncertainties remain.

Homogeneous freezing of supercooled aqueous solution droplets initiated by rapid mesoscale temperature fluctuations is a ubiquitous pathway to form cirrus clouds in-situ globally. A global impact of aircraft soot particles processed in dispersing plumes on cirrus (indirect effect) cannot be excluded. By number, aviation might double the background black carbon loading in the UT/LS. The indirect effect depends, along with details of plume processing, on the ability of background aerosol particles to act as ice-forming nuclei. The potential of soot particles emitted by aircraft jet engines to modify high cloudiness in the absence of contrails is affected by the frequent observation of high supersaturations with respect to the ice phase, the relatively small number of heterogeneous ice nuclei (IN) in cirrus conditions, and the ever-presence of mesoscale temperature fluctuations inducing large cooling rates and setting the stage for cirrus formation.

### Uncertainties and Gaps

A number of uncertainties and gaps were identified in contrail-cirrus and other aircraft-induced effects on cirrus clouds:

- *Plume particle processing*. It is not well understood how properties (number concentration, surface area, composition, and mixing state) of ambient aerosols are perturbed in the presence of jet engine emissions under various atmospheric conditions and aircraft configurations. Detailed investigations of the microphysical and chemical processes governing the evolution of aviation aerosols in the time scale of days after emission is required.
- *Optical properties of contrails, contrail-cirrus, and cirrus*. Factors controlling the radiative properties of cirrus clouds and contrail-cirrus (ice crystal habit, vertical profiles of ice water content, effective radius) are poorly constrained by observations. The balance between cooling from reflection of sunlight and warming from trapping of heat radiation is also poorly understood.
- *Detection and prediction of ice supersaturation*. Contrails and the expansion of contrails into cirrus clouds occur in an ice supersaturated environment. However, the global distribution of supersaturation in the upper troposphere is not adequately known.

- *In-situ measurements of aerosol chemistry and small ice crystals*. Cirrus ice crystals can range from a few to hundreds of µm or more in size. Measuring this large range requires several instruments and improved agreement between instruments. Existing instrumentation also cannot easily measure the shape of the numerous very small crystals that have been found in contrails and cirrus clouds.

- *Properties of heterogeneous ice nuclei from natural and anthropogenic sources*. The atmospheric effects of ice formation from aviation particles depend on the ice nucleation properties of particles from other anthropogenic and natural sources. However, concentration and chemical composition of IN in the upper troposphere are not well known and are difficult to predict with models.

- *Interactions between heterogeneous ice nuclei and cirrus clouds*. Ice nucleation processes occur within short time scales and are rather localized. Hence it is difficult to determine their relative importance using in-situ measurements. Ice nucleation pathways can be isolated in the laboratory, but the question arises whether the employed IN particles are representative. This issue is particularly important for aircraft because real engine soot and its processing cannot easily be represented in laboratory measurements.

- *Incorporation of effects of aviation-induced particles and cirrus into global models.* Accurate knowledge of ice supersaturation is crucial for quantifying direct and indirect effects of aviation on cirrus cloudiness. Most current models do not adequately represent ice supersaturation, and treat cirrus as a single class of clouds in terms of their radiative properties; thus they are not capable of predicting contrail-cirrus cloud fraction from first principles.

- *Representation of aerosols and contrails in global atmospheric models*. Both models and satellite datasets lack the horizontal and vertical resolution to address many contrail issues. Data useful for validation of aerosol modules is lacking, especially for carbonaceous aerosol. Global models and contrail/cirrus studies need to establish the essential parameters for properly incorporating aviation aerosols and their effects into atmospheric calculations.

- *Long-term trends in contrail-cirrus and cirrus*. Long-term trends can only be ascertained from consistent measurements over extensive periods, but the current satellite record has many uncertainties, limiting the ability to examine past trends. Special care is needed to ensure homogeneous datasets for estimation of future trends in cirrus measurements.

**Research Recommendation and Priorities**

- *In-situ probing and remote sensing of aging contrail-cirrus and aircraft plumes.* A series of coordinated regional-scale campaigns should be designed and executed to measure the appropriate variables using in-situ and remote sensing measurements with the aim to characterize the growth, decay and trajectories of contrail ice particle populations. Such measurements are also needed to define the abundance and properties of ambient aerosols as well as gaseous aerosol precursor concentrations in the troposphere.

- *Regional studies of supersaturation and contrails using weather forecast models have the potential to include our best physics and the high resolution needed to more accurately predict supersaturation*. Development of these models and associated observational datasets may be the best approach for developing our knowledge in the near term, supporting development of more accurate tools for use in global models.
- *Global model studies addressing direct and indirect effects.* Enhance the treatment of relevant processes, including appropriate parameterizations, in global climate models (GCMs) to improve analyses of contrails and cirrus associated with aircraft.
- *Use of existing or upcoming information from space-borne sensors.* Investigate the optical and microphysical properties of contrail and contrail-cirrus, e.g., optical thickness and effective particle sizes (parameters that are essential to the study of the radiative forcing of these clouds) from space-borne sensors.
- *Process studies of plume and contrail development.* 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. Studies that investigate contrail development as a function of emissions and aircraft design and how contrails evolve into cirrus-like clouds would better quantify the direct effect.
- *Laboratory measurements of ice nucleation.* Laboratory data are urgently needed to develop aerosol-related parameterisations of heterogeneous ice nucleation for use in models. It is also recommended to compare different approaches and methods of IN measurements.

Long-term research needs include: (1) development or improvement of instruments that help establish background concentrations and characteristics of heterogeneous ice nuclei and measure supersaturation accurately, and (2) the development and implementation of new concepts for ice phase-related microphysics, supersaturation, radiation, and cloud fraction in climate models enabling a consistent treatment of global aviation effects.

The current suite of satellite instruments is inadequate for evaluating supersaturation. Higher resolution (both horizontally and vertically) is required for the observations. Very accurate measurements of temperatures as well as water vapour mixing ratio are required to derive high quality fields of relative humidity.

## C. Climate Impacts and Climate Metrics

### State of the Science

In assessing the overall impact of aviation on climate, and to quantify the potential trade-offs on the climate impact of changes in aircraft technology or operations, metrics for climate change are needed to place these different climate forcings on some kind of common scale. Radiative forcing (RF) has been used as a proxy for climate impact for well-mixed greenhouse gases. However, recent analyses have demonstrated that a unit radiative forcing from different climate change mechanisms does not necessarily lead to the same global mean temperature change (or to the same regional climate impacts). The concept of efficacy (E) has been introduced to account for this (i.e., E depends on the specific perturbation to the climate system, such as changes in ozone or aerosol distributions related to aircraft emissions). Hence, it is the product of E and RF that should be evaluated and intercompared for the various climate impacts from aviation. However, RF is not an emissions metric capable of comparing the future impact of different aviation emissions. The applicability of emission metrics, such as Global Warming Potentials (GWPs), have not been adequately tested and evaluated. In addition, changes in precipitation and other climate variables besides temperature are of interest. Climate metrics for aviation need to be done in the context of climate metrics for other short-lived perturbations from other sectors.

An update of the IPCC (1999) radiative forcing (RF) from aviation for the “current” time period finds that, with one exception, the IPCC findings have not significantly changed, apart from the increase in air traffic from 1992 to 2000 (Sausen et al., 2005). The exception is RF from linear contrails, which appear to be at least a factor of three smaller. There is still no reliable estimate of RF from aviation-induced cirrus clouds. Based on recent correlation analyses some authors suggest that this RF might be dominating all other aircraft effects. It is critical that appropriate metrics be established before assuming relative climate impacts for various contributions based on potentially inappropriate metrics.

## Uncertainties and Gaps

- *Climate impacts are highly uncertain*. There remain significant uncertainties on almost all aspects of aircraft environmental effects on climate, with the exception of the radiative forcing from the $CO_2$ emissions. The ozone and methane RFs from NOx emissions are opposite in sign, so the extent to which they offset each other is an important uncertainty. Estimates for contrails and cirrus are particularly highly uncertain.
- *Optical properties of contrails, contrail-cirrus, and cirrus*. As discussed in previous section.
- *Defining metrics for trade-offs*. The scientific community may be able to define useful metrics for the climate change and climate impacts associated with aviation, but further study and consensus building is needed.

## Recommended Research and Priorities

- *Radiative effects on climate from contrails and cirrus.* In addition to previously mentioned studies, specific studies aimed at better understanding the climate impacts from contrails and cirrus. Intercomparisons (model to model) and evaluations (compare model to observations) of climate and radiative transfer models.
- *Systematic model intercomparison of efficacy studies*. Evaluate inhomogeneous vertically and horizontally distributed forcing agents. Analyze cirrus changes, ozone changes, $CH_4$, and direct particle effects, and effects of changes in climate state.
- *Identify, develop and evaluate metrics for climate impact assessment and examine their scientific basis.*
- Quantify the uncertainty in proposed metrics and how it propagates (both parametric input uncertainties and model uncertainties).

## D. Studies for Trade-offs Amongst Aviation Emissions Impacting Climate

Along with furthering scientific understanding, there are policy-related needs for sensitivity analyses of the net effects of trade-offs between various interventions in aircraft operations and emissions including:

- NOx reduction technology versus fuel efficiency (i.e., $CO_2$ emissions)
- flight altitude effects (e.g., effects on ozone and contrail formation)
- changing future geographical distributions of the fleet
- differential impact of day/night operations
- routings to avoid certain regions with specialized chemistry (e.g. supersaturated air, cirrus, or polar)
- studies of the co-dependence of physical impacts, e.g. how future climate change may alter the ozone response

Climate change metrics are expected to play an important role in these analyses. The IPCC report provided instantaneous forcing due to the cumulative impacts of aviation. While this is a measure of how the atmosphere has changed due to historical aviation activities, such estimates of radiative forcing for aviation may not provide an appropriate basis for making policy or operational decisions (time-dependent effects likely necessary), nor are they an appropriate basis for fully evaluating the relative impacts of various aviation effects. This argument is not new; indeed, it is widely understood and accepted, and a variety of alternative integral measures have been pursued.

There is currently no study in the peer reviewed literature that can be cited to justify, based on the scientific understanding of the impact of aviation emissions, the possible choices of metrics suitable for trade-off application. Research is needed to examine the effect of different metrics, and the choices within each metric (e.g. time horizon), on evaluating the relative importance of different aviation emissions. Such studies would need to explore the potential of existing metrics and the possibility of designing new metrics. It must be stressed that even if there is a philosophical agreement on an acceptable metric, current atmospheric models may not be able to calculate these metrics with acceptable accuracy.

# 1. Background

Aviation has become an integral segment in global economic and transportation systems, and thus is an indispensable part of modern society, affecting the lives of millions of people directly or indirectly. Environmental concerns from aviation include effects on noise levels near airports, and effects of aircraft emissions on local air quality, regional and global scale atmospheric chemical composition, and on climate change, and resulting impacts of these effects on human and ecosystem health. However, the absolute magnitude and relative importance of these environmental effects are not fully understood.

The U.S. projects demand for air transportation services to grow three fold by 2025 (e.g., Next Generation Air Transportation System, 2004). It is a daunting challenge for both the scientific and technological communities to satisfy this increasing demand, while still protecting our environment. With extensive growth demand expected in aviation over the next few decades, it is imperative that vigorous action be taken to understand the potential impacts of aviation emissions to help policymakers address climate and other potential environmental impacts associated with aviation. To meet the challenges presented by this growth, the President of the United States signed 'Vision 100 – Century of Aviation Reauthorization Act" in 2003 and created a multi-agency integrated plan for the development of a Next Generation Air Transportation system (NGATS). The vision of the NGATS is "A transformed aviation system that allows all communities to participate in the global market-place, provides services tailored to individual customer needs, and accommodates seamless civil and military operations." One of the challenges posed by the vision is achieving growth while reducing environmental impacts.

The potential impact of aircraft emissions on the current and projected climate of our planet is one of the more important environmental issues facing the aviation industry. For example, the recent Report to the U.S. Congress on Aviation and the Environment (Waitz, et al., 2004) states that for the aviation industry, "The (environmental) topic of greatest uncertainty and contention is the climate impact of aircraft."

Although current fuel use from aviation is only a few percent of all combustion sources of carbon dioxide, the expectation is that this percentage will increase because of projected increase in aviation and the likely decrease in other combustion sources as the world moves away from fossil fuels towards renewable energy sources.  In addition, aircraft nitrogen oxides released in the upper troposphere and lower stratosphere generally has a larger climate impact than those emitted at the surface, although some of the much larger surface emissions from energy and transportation sources also reach the upper troposphere.

The integrated national plan for implementation of the NGATS initiative is carried out by a Joint Planning and Development Office (JPDO). The JPDO is comprised of a number of U.S. agencies: National Aeronautics and Space Administration (NASA), Federal Aviation Administration (FAA), Department of Transportation (DOT), Department of Homeland Security (DHS), Department of Commerce (DOC) and the Whitehouse Office of Science and Technology Policy (OSTP). The Environmental Integrated Product Team (EIPT) of JPDO has been tasked with incorporating environmental impact planning into the NGATS. To fulfill this strategy, we must quantify the climatic impacts of aviation emissions (e.g., the direct climate effects from $CO_2$ and water vapor emissions, the more indirect forcing on climate resulting from changes in the distributions and concentrations of ozone and methane associated with aircraft NOx emissions, the direct effects (and indirect effects on clouds) from emitted aerosols and aerosol precursors, and the climate effects associated with contrails and cirrus cloud formation and modification) to enable appropriate policy considerations and actions. Understanding aviation's climate impact is also critical to informing the United States in the best considerations and trade-offs for setting standards in engine emissions, special flight operations, or other potential policy actions through the International Civil Aviation Organization. This cannot be adequately done until the policymakers can correctly capture the environmental effects of aviation emissions, including climate impacts. The extensive investment of new aircraft in the marketplace, with their long service lifetime (25-30 years or longer), emphasizes the urgent need for improving our current understanding of the effects of aviation on climate.

*In response to the need to address these issues, the Science/Metrics Panel of the EIPT and the Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER), the FAA/NASA/Transport Canada sponsored Center of Excellence convened a panel of science experts from around the world to participate in a two and half day "Workshop on the Impacts of Aviation on Climate Change" during June 7-9, 2006 in Boston, MA. This report documents the findings and recommendations of the Workshop. This report is also aimed at providing guidance for the agencies and private sector stakeholders participating in the EIPT to develop and implement an aviation climate research plan to reduce uncertainties to "levels that enable appropriate actions".*

In 1999, a major international coordinated effort to assess the impacts of aviation on the global atmosphere was sponsored by the U.N.'s Intergovernmental Panel on Climate Change (IPCC, 1999). Since then, while new information has become available, there has been no comprehensive U.S. or international attempt to update the assessment of the science and the associated uncertainties. Also, during this time, there have also been discussions of how to define the best metrics to account for the wide range of spatial and temporal scales of aviation-induced climate impacts. This workshop agreed with IPCC (1999) that the three most important ways that aviation affects climate are (1) direct emissions of greenhouse gases including $CO_2$ and water vapor, (2) emissions of nitrogen oxides that interact with ozone, methane, and other greenhouse gases, and (3) persistent contrails along with the effects on cirrus clouds from contrails and from particles emitted from aircraft. For this workshop, our focus was on the impacts of subsonic aviation emissions in the upper troposphere and lower stratosphere (UT/LS) and on the potential response of the climate system to these emissions.

In addition to studies on aviation, the Workshop also drew upon results from studies associated with other activities (e.g., intercontinental (long-range) transport of air pollutants and their effects on ozone in the upper troposphere, particles and associated microphysical properties of cirrus clouds) so that the aviation impacts could be put in context with other anthropogenic activities. Research into the environmental effects of aircraft cannot be decoupled from research on other atmospheric science issues, such as the basic understanding of the physics and chemistry in the UT/LS and aerosol-cloud interactions in the context of global climate modeling.

The stated goals of the Workshop were to assess and document the present state of knowledge of climatic impacts of aviation; to identify the key underlying uncertainties and the gaps in scientific knowledge; to identify ongoing and further research needed and to make prioritized research recommendations; to explore the development of metrics for climate-aviation trade-off issues; to examine how to leverage ongoing research programs to help address aviation-related needs; and to help focus the scientific community on the aviation-climate change research needs of the NGATS. The workshop was designed as an effort to gather guidance on how to address scientific uncertainties and gaps associated with climate impacts of aviation. The overall science focus of this workshop was divided into three particular areas of interest: (1) Emissions in the upper troposphere / lower stratosphere (UT/LS) and resulting chemistry effects, (2) Effects of water and particle emissions on contrails and on cirrus clouds, and (3) Determining the impacts on climate resulting from aircraft emissions and defining metrics for evaluating these impacts. These focal areas were chosen because they are generally recognized by the science community as being the key areas of uncertainty in understanding aircraft impacts on climate. As shown in the agenda and participants lists presented in the Appendices, the Workshop was based around three Subgroups representing these three areas of interest. Plenary sessions attempted to deal with the extensive amount of overlap among these three areas. The discussion below centers around each of these areas and the findings of the designated Subgroups at the Workshop. Note that, there is no attempt at completeness in referencing the discussion that follows.

## *1.1 An Introduction to the Issues*

The types of emissions produced by aircraft engines are similar in many ways to the emissions resulting from other forms of fossil fuel combustion. Figure 1, adapted from the IPCC (1999) report shows the real combustion products from aircraft engines as compared with ideal combustion process and also illustrates the scale of the combustion products. Aircraft emissions are distinct from other sources burning fossil fuel since most emissions occur at cruise altitudes. The most important chemical species emitted by aircraft engines are carbon dioxide ($CO_2$), water ($H_2O$), nitrogen oxides (NO and $NO_2$, collectively termed as $NO_x$), and sulfur oxides ($SO_2$ and sulfate, collectively known as $SO_x$). The small amount of soot emitted may also have chemical and radiative effects. Previous studies have shown that the small amount of emissions of hydrocarbons and carbon monoxide are

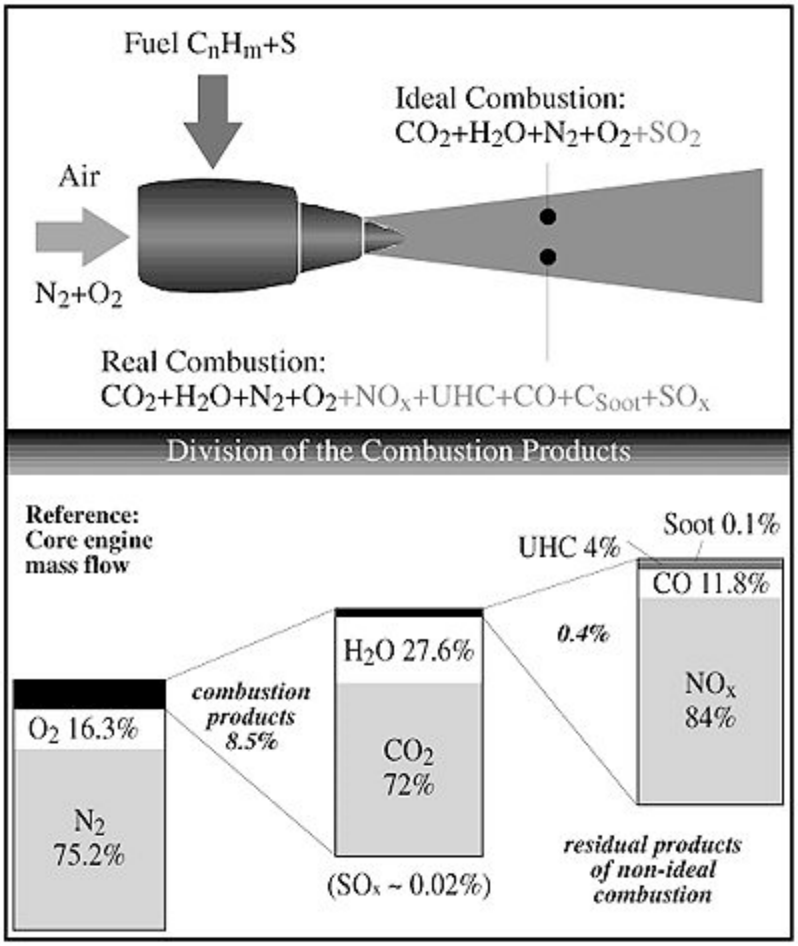


**Figure 1.** Schematic of ideal combustion products and all existing combustion products (adapted from IPCC, 1999). UHC is unburned hydrocarbons.

not important in evaluating effects of aircraft emissions on the global environment.

Aircraft emissions can alter the radiative budget of the Earth and contribute to human-induced climate change through several different ways:

- Aircraft engines emit $CO_2$ and water vapor, important greenhouse gases, that directly affect climate through their absorption and reemission of infrared radiation;
- Aircraft emit $NO_x$ (and HOx produced from water vapor emissions into the stratosphere) that modifies atmospheric ozone concentrations. Ozone affects the radiative balance of the climate system through both its shortwave and infrared (greenhouse effect) absorption;
- Through its resulting net production of upper tropospheric and lower stratospheric ozone, $NO_x$ emissions from subsonic aircraft also reduce the atmospheric abundance of $CH_4$, another important greenhouse gas, through feedback effects on concentrations of tropospheric hydroxyl radicals (OH), the primary reactant for destruction of methane;
- Aircraft emit aerosols in the form of liquid particles containing sulfate and organics, and soot particles. Emissions of sulfur dioxide also increase the aerosol mass in aging plumes. These aerosols can be radiatively active themselves, either by scattering (sulfates) or absorbing (soot) solar radiation or can indirectly affect climate through triggering the formation of persistent condensation trails or altering the natural cloudiness;
- Under the right meteorological conditions, aircraft emissions of water vapor (and aerosols) can lead to formation of contrails and possibly result in effects on upper tropospheric cirrus clouds – these effects may exert spatially inhomogeneous radiative impacts on climate.

Most aircraft NOx emissions are released directly into the chemically complex and radiatively sensitive UT/LS between 8-13 km. At the time of the IPCC assessment, there was concern that heterogeneous chemistry following immediate conversion of sulfur to aerosols from the aircraft engines could affect the impact on ozone from the NOx emissions. However, recent measurements suggest that this immediate conversion is small, such that it will have only a minor effect on the expected changes in ozone.

The effect of aircraft emissions on atmospheric ozone concentration depends on the altitude at which the emissions are injected. The importance of ozone production cycles from the NOx emissions through the oxidation of methane and hydrocarbons become less effective with altitude while the catalytic ozone loss cycles become more efficient. Any uncertainties in how well we understand the atmospheric chemical and physical processes in the UT/LS affect our ability to understand the magnitude of the aviation effects on ozone and methane.

As mentioned above, aircraft influence, under the right meteorological conditions, high clouds *directly* by producing line-shaped contrails that persist and spread in ice-supersaturated air. The resulting clusters of contrail-cirrus are observed on regional scales, sometimes also in regions without significant air traffic, because they are advected with the wind field over large distances. There are also indications that aircraft can influence high clouds *indirectly* by injecting aerosol particles that act as heterogeneous ice nuclei at some point after emission, without contrail-cirrus being involved. In the absence of aircraft emissions, a cirrus cloud might not have formed or the resulting cirrus might have different optical properties.

It is important to recognize that a coupling may exist between the pure direct and indirect effects. It is conceivable that the indirect effect occurs along with contrail-cirrus, because ice supersaturation required for persistence facilitates ice formation at low supersaturations. If that occurs, contrail-cirrus can exert an indirect effect on their own. Cirrus may have different properties because they nucleate in regions with preexisting ice and share the available water. The situation is further complicated by the fact that background cirrus itself might be affected by aircraft in heavily traveled flight corridors.

The climate effects from current aircraft emissions are only a small fraction of the total effects of human activities on climate (e.g., emissions of carbon dioxide from aviation are a few percent of the total emissions from fossil fuel burning and changes in land use). As a result, it is very difficult to use a climate model to directly evaluate the climate effects resulting from aviation. Radiative forcing has been widely used as a metric of climate change to measure the relative efficacy of climate change mechanisms. The radiative forcing of the surface-troposphere system due to the perturbation of an agent (say, a change in greenhouse gas concentrations or a change in the solar constant), is defined by IPCC as the change in net (down minus up) irradiance (solar plus long-wave; in $Wm^{-2}$) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values. The radiative forcing (RF) concept provides a first order estimate of climate change without the need to actually conduct time consuming and computationally expensive climate model simulations. However, as discussed later, this concept has significant limitations for spatially inhomogeneous perturbations to the climate system and can be a poor predictor of the global mean climate response. As a result, alternative definitions have been developed (as will be discussed later).

Figure 2, adapted from IPCC 1999 (Prather et. al., 1999), portrays a causal chain whereby the direct emissions of aircraft accumulate in the atmosphere, change the chemistry and the microphysics, and alter radiatively active substances in the atmosphere, which change radiative forcing and hence the climate.

It is important to consider the relative time scales associated with the effects on climate from these various emissions. After emission, effects of the NOx emissions from aircraft on ozone will last for weeks to months (perhaps a little longer for stratospheric emissions), while affects on methane, because of its long atmospheric lifetime, last for years. Effects from emissions of particles and from contrail formation should last much shorter, generally not more than days to a few weeks. On the other hand, emission of $CO_2$ will affect climate for centuries or longer. After the initial uptake of about half of emitted $CO_2$ by vegetation and the surface ocean, some stays in the atmosphere with a decay time of 100 or more years, and up to a quarter of the emitted $CO_2$ is expected to remain in the atmosphere for many thousands of years.

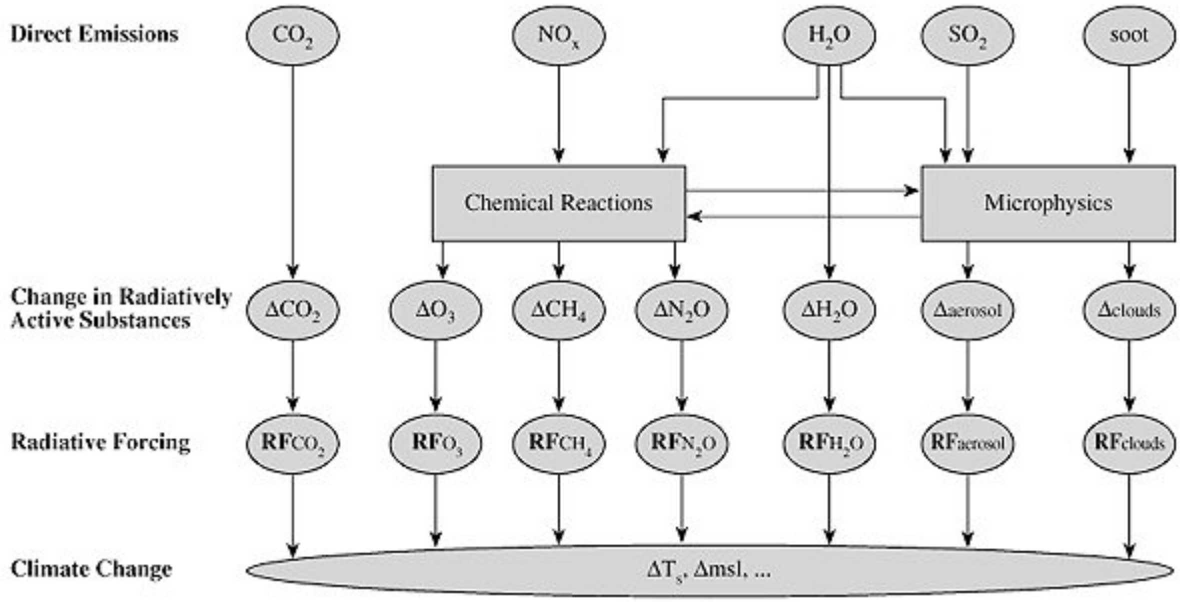


**Figure 2.** Schematic of possible mechanisms whereby aircraft emissions impact climate. Climate impact is represented by changes in global mean surface temperature (□$T_s$) and global mean sea level rise (□msl). Adopted from IPCC (1999).

## 2. State of the Science

The IPCC (1999) assessment served as the starting place for the Workshop. Evaluation of the current state of understanding then grew out of the scientific papers and other publications that have been published since then. Each Subgroup provided their insights into key aspects of the current understanding of the science relative to determining aircraft effects on climate.

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

There have been substantial improvements in the chemistry-transport modeling tools used to evaluate the impacts of aviation NOx emissions on $O_3$ and $CH_4$, since the 1999 IPCC assessment, but as noted in the 2004 report to the United States Congress *Aviation and the Environment*, "there are currently no major research programs in the United States to evaluate the unique climatic impact of aviation." Although there has been no recent assessment, there have been substantial improvements in the models that would be used to produce such an assessment (and a few sensitivity studies of aircraft effects using European models). In the U.S., coupled troposphere-stratosphere chemistry-transport models include those developed by the NASA Global Modeling Initiative (GMI) and the National Center for Atmospheric Research (NCAR) MOZART. An assessment of aviation effects using state-of-the-art models would decrease the uncertainty in the climate response due to chemical changes associated with aircraft emissions because of improved representation of atmospheric transport in the upper troposphere and lower stratosphere UT/LS. However, significant uncertainties remain as discussed below.

The data base of observations in the UT/LS has been greatly expanded since 1999, and data from the European MOZAIC program (in-situ ozone and water instruments on commercial aircraft) and field campaigns are commonly being used to evaluate the global model background state, emphasizing the composition of the upper troposphere and the transition from the troposphere to the lowermost stratosphere. However, the amount of data available is still insufficient to fully establish a climatology for NOx, HOx and many other constituents of the UT/LS.

Improvements to model representations of the stratospheric circulation have resulted in better simulations of the composition of the lower stratosphere and in more realistic fluxes of ozone and other stratospheric species from the lower stratosphere to the upper troposphere. The magnitude of these fluxes and their spatial and seasonal variability are similar to quantities derived from observations in some models, and uncertainties have been reduced. These improvements would have an impact on an assessment of the effects of aviation using state-of-the-art models.

There are continuing efforts that confront simulations with observations, and these efforts may lead to the development of observation-based performance metrics for models. Such efforts serve several purposes. The first is to identify and characterize model deficiencies; such activities lead to model improvements. The second is to identify the existing models for which transport and chemical processes combine to produce the most realistic simulated background atmosphere with which simulated aircraft exhaust will interact. The third is to develop a strategy for understanding the different responses among models used in aircraft assessment efforts.

### *2.2 Contrails and Cirrus*

Because the IPCC identified contrails, contrail-cirrus, and modifications of cirrus by aircraft exhaust as the most uncertain components of the aviation impact on climate, the majority of recent studies have focussed on cloud processes, while a limited number of studies also addressed chemical effects. More recently, ground-based experimental studies on jet engine emissions have been carried out. Most of this research is summarized in a few review papers (Kärcher et al., 2004; Schumann, 2005; Miake-Lye, 2005), from which the following key results have been drawn.

1. Aircraft emissions cause significant, detectable enhancements of $NO_x$, volatile particles, and soot (and possibly $H_2O$ in the lowermost stratosphere) on the plume scale at cruise. Signals at regional scales can only be inferred from models, the magnitudes of which are determined by emission rates and at-

mospheric lifetimes. The contribution relative to ambient levels in the global UT/LS is variable owing to the large variability of particles and most trace gases.

2. Contrail formation relies on known thermodynamic parameters and they develop if the air is colder and moister than a threshold. They initially contain more but smaller ice crystals than most cirrus clouds. Early contrail evolution depends in poorly understood ways on aircraft and engine emission parameters.

3. Aircraft-induced contrail-cirrus add significantly to the natural high cloud cover and modulate the radiative balance, with effects that are particularly important during the daytime. Line-shaped contrails also contribute to a portion of the total climate impact from aviation effects on cloudiness. The direct contrail impact is affected by wind shear and the duration and size of ice supersaturated regions controlling the contrail-to-cirrus transition and contrail-cirrus properties.

4. The upper troposphere is frequently (the lowermost stratosphere occasionally) supersaturated with respect to ice. Homogeneous freezing of supercooled aqueous solution droplets initiated by rapid mesoscale temperature fluctuations is a ubiquitous pathway to form cirrus clouds in-situ globally.

5. The global impact of the indirect effect of aircraft soot particles processed in dispersing plumes on cirrus is unknown, and depends, in addition to details in the plume processing, on the ability of background aerosol particles to act as ice-forming nuclei. By number, aviation might double the background black carbon loading in the UT/LS (Hendricks et al., 2004).

The following findings affect the potential of aircraft exhaust to modify high cloudiness in the absence of contrails (indirect effect). (i) The frequent observation of high relative humidities with respect to the ice phase up to the level where homogeneous freezing commences (>150%). (ii) The relative paucity (low number) of heterogeneous ice nuclei (IN) – insoluble particles that might facilitate the formation of the ice phase – in cirrus conditions. (iii) The ever-presence of mesoscale temperature fluctuations inducing large cooling rates (~10 K/h) on short time scales (10-20 minutes) and setting the dynamical stage for cirrus formation. These observations place bounds on the effect soot particles emitted by aircraft jet engines can exert in the atmosphere: it seems unlikely that exhaust soot particles would be better IN (i.e., cause ice particle formation close to ice saturation) than mineral dust grains or other natural IN, and soot has to compete with IN from these other sources (particularly with mineral dust aerosol) and with liquid particles that freeze homogeneously at times.

Another major research result concerns the direct effect of persistent, spreading contrails (contrail-cirrus). According to recent, yet unpublished, correlation analyses between real-time regional-scale air traffic movements and the occurrence of contrail structures that are detectable with satellites, it seems plausible that the global persistent contrail coverage (and inferred radiative forcing) might exceed the IPCC and more recent European TRADEOFF estimates by an order of magnitude or more (but error bars in these studies are also very large). As satellites are more capable of detecting aged, spread out contrail-cirrus rather than young, very narrow contrails, it is difficult to arrive at more accurate estimates of the direct effect without advances in observational tools or the help of global models. To date, however, global models are not yet able to simulate contrail-cirrus properly due mainly to our limited understanding of the processes affecting them and, as a result, our lack of suitable parameterizations for their subgrid-scale nature.

## *2.3 Climate Impacts and Climate Metrics*

The discussion starts with an update based on recent derivations of the radiative forcing from aircraft emissions relative to the findings in IPCC (1999). This discussion is then followed by an analysis of the concept of climate metrics such as radiative forcing.

### 2.3.1 Radiative Forcing Update

An update of the IPCC (1999) radiative forcing (RF) from aviation for the "current" time period has been presented by Sausen et al. (2005). Figure 3 and Table 1 summarize their results as well as the findings from IPCC (1999). In view of the large error bars of IPCC (1999), the RF from $CO_2$, $H_2O$ and direct effect of sulfate aerosols have not changed significantly, apart from the increase in air traffic from 1992 to 2000. The $O_3$ and $CH_4$ effects are changed due to more recent analyses from European chemical-transport models. The other major change is found for the direct global RF from (linear) contrails; the new value is roughly a factor of 3 smaller than IPCC (1999) based on results from Marquart et al. (2003) and Myhre and Stordal (2001), which were scaled (by fuel burn) to the year 2000 resulting in 6 $mW/m^2$ and 15 $mW/m^2$, respectively. However, another, yet unpublished, study (Penner and Chen, 2006) suggests that the radiative forcing from cirrus, i.e., cloud changes beyond linear contrails, could be significantly larger than those in Figure 3 or Table 1. The overall conclusion from these analyses is that significant uncertainties still remain in quantifying the impacts of aviation emissions on climate. Note that the RF for direct soot in Figure 3 and Table 1 are based on the atmospheric soot concentrations, and does not include the soot incorporated into clouds or long-term deposition to the ground.

In IPCC (1999), similar analyses for projections of the commercial aircraft fleet to 2050 showed much higher radiative forcings from aircraft for 2050 compared to 1992, but with even larger uncertainties on the individual effects.

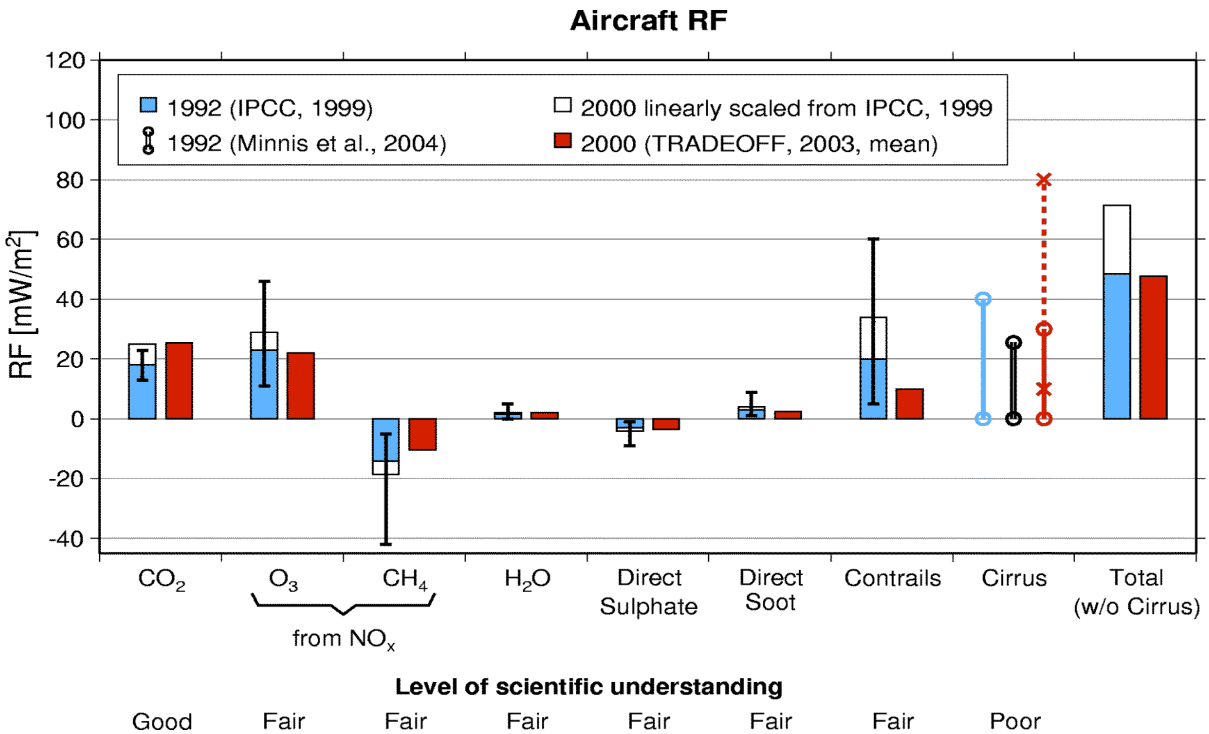


**Figure 3:** Global radiative forcing (RF) [mW/m$^2$] from aviation for 1992 and 2000, based on IPCC (1999) and TRADEOFF results. The whiskers denote the 2/3 confidence intervals of the IPCC (1999) values. The lines with the circles at the end display different estimates for the possible range of RF from aviation induced cirrus clouds. In addition the dashed line with the crosses at the end denotes an estimate of the range for RF from aviation induced cirrus. The total does not include the contribution from cirrus clouds (Sausen et al., 2005).

**Table 1:** Radiative forcing (RF) derived for various emissions from aviation [mW/m$^2$]. The best estimates for 1992 by IPCC (1999) and two estimates for 2000 are given: one is derived from IPCC (1999) by linear interpolation; the second is based on the mean values resulting from the TRADEOFF project. As in IPCC (1999), the European TRADEOFF RFs for $CO_2$, $O_3$ and $CH_4$ were scaled by a factor of 1.15. The RFs from $O_3$ and $CH_4$ are both a result of aircraft $NO_x$ emissions (Sausen et al., 2005).

| **Year** | **Study** | **RF [mW/m$^2$]** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **$CO_2$** | **$O_3$** | **$CH_4$** | **$H_2O$** | **Direct Sulphate** | **Direct Soot** | **Contrails** | **Sum (w/o Cirrus)** |
| 1992 | IPCC (1999) | 18.0 | 23.0 | - 14.0 | 1.5 | - 3.0 | 3.0 | 20.0 | 48.5 |
| 2000 | IPCC (1999)* | 25.0 | 28.9 | -18.5 | 2.0 | - 4.0 | 4.0 | 33.9 | 71.3 |
| 2000 | TRADEOFF | 25.3 | 21.9 | -10.4 | 2.0 | - 3.5 | 2.5 | 10.0 | 47.8 |

* scaled to year 2000

### 2.3.2 Climate metrics for aviation

Emissions by aviation are responsible for a range of atmospheric changes that perturb the radiation budget and hence force climate change. In assessing the overall impact of aviation on climate, and to quantify the potential trade-offs in the climate impact of changes in aircraft technology, operations, or even the amount of aircraft traffic, it is important to place these different climate forcings on some kind of common scale. We refer to methods that attempt to achieve this as “metrics”. Although their existing application to aircraft issues is much more limited, the general usefulness and uncertainties associated with metrics for climate change has been the subject of many published research studies.

There are many difficulties in developing such metrics, which while not unique to aviation, are certainly exacerbated by the nature of aviation’s impacts on climate. Aviation directly leads to increases in carbon dioxide and indirectly to decreases in methane, both of which, as a result of their long atmospheric residence times, are spread relatively homogeneously across the globe. Aviation also leads to increases in ozone and contrails, and other cloudiness changes, which, partly because they are shorter-lived, depend sensitively on the height, time and geographical location of the emissions.

The quantification of climate metrics should, wherever possible, use input from state-of-the-art models; but a prime aim of the development of metrics in this context is that they should then facilitate at least a first order assessment of impacts without compromising the science and without the further use of these complex models and be relatively easily applied. Hence transparency and simplicity of application are necessary attributes of metrics. Clearly such transparency and simplicity come at a cost in terms of compromising the sophistication with which climate effects can be properly represented. The metrics allow the user to explore, for example, the trade-offs in terms of climate impacts of changes in aircraft technology or operations. By providing ranges in the values of metrics, they can also be used to communicate the level of scientific uncertainty, and the impact of that uncertainty, on possible policy options.

*Radiative Forcing*

The most straightforward metric is the traditional one, namely radiative forcing (RF) at some given time due to the cumulative impact (both direct and indirect) of aviation emissions during some prior time period. The global mean RF is linearly related to the expected equilibrium global mean surface temperature change via a model dependent climate sensitivity parameter (e.g. IPCC, 2001). RF allows a first order estimate of the overall impact of aviation on climate, and also the relative size of the different contributors to aviation-induced climate change.

It was originally thought that a unit radiative forcing from different climate change mechanisms in the same positive or negative direction (e.g., due to changes in amounts of greenhouse gases or changes in the solar output) would lead to the same global mean temperature change. However, recent research has indicated that this does not appear to be generally the case, and the concept of efficacy E has been introduced into the radiative forcing concept to account for this (i.e., E depends on the specific perturbation to the climate system, such as changes in ozone or aerosol distributions related to aircraft emissions). Hence, it is the product of E and RF that should be evaluated and intercompared relative to the environmental impacts. In addition, the equal global-mean RFs do not necessarily lead to the same distribution of surface temperature response; broadly the response is largely concentrated in the hemisphere in which it occurs, but beyond this there is little relationship between the spatial patterns of forcing and response (e.g., Joshi et al. 2003; Hansen et al. 2005). This is particularly important in the context of $NO_x$ driven changes in ozone and methane; the ozone changes, and the resulting positive RF are largely in the hemisphere of emission while the negative RF associated with methane decrease is more globally distributed. Hence offsets in the global mean temperature response are not necessarily reflected in the local temperature change (e.g. Berntsen et al. 2005).

IPCC (1999) calculated the change in radiative forcing due to cumulated emissions from the historical aircraft fleet. It was a way to address the question of how the forcing will be different if no aircraft have been operating or a specific emission is omitted. It was NEVER intended that those radiative forcing numbers should be used directly in policy considerations. The convention of calculating RF in this way, as an absolute change in concentrations over a given period of time, is a "backward looking" approach that is not a suitable metric for comparing the impact of <u>emissions</u> (as compared to concentration changes) during some specified period on the subsequent climate change, because of the large contrasts in the residence time of the different contributors to RF (as discussed earlier in this report).

IPCC (1999) also introduced the concept of the radiative forcing index (RFI), which is simply the ratio of the total forcing at a given time to the forcing from carbon dioxide at the same time. Unfortunately, the RFI has been misapplied in some quarters (as discussed by Forster et al. 2006) as a way of crudely accounting for the future non-$CO_2$ climate change impacts of aviation, by simply multiplying the $CO_2$ emission scenarios by the RFI. This example points to the need for scientific oversight of applications of climate metrics in policy considerations.

*<u>Emission Metrics</u>*

For comparison of the climate impact of emissions, a whole class of metrics has been proposed (see e.g., Fuglestvedt et al., 2003). These aim to provide an exchange rate, so that each emission can be given a $CO_2$-equivalence.

The Kyoto Protocol to the UN Framework Convention on Climate Change has adopted the Global Warming Potential (GWP) concept as developed for the IPCC climate assessments to provide this equivalence. The GWP is the time-integrated radiative forcing following a pulse emission of a gas, relative to the same quantity for a pulse emission of carbon dioxide. Hence it accounts for both the radiative strength of the climate change agent and its persistence in the atmosphere; the Kyoto Protocol has chosen the time horizon of 100 years. The GWP concept has been the subject of considerable scrutiny and criticism (e.g. Smith and Wigley, 2000a,b; O'Neill, 2000). Nevertheless, their routine use is now deeply embedded in the policymaking community, possibly because of their ease of application, transparency and the absence of an obvious replacement (Fuglestvedt et al. 2003).

Modifications to the GWP have been proposed – for example, the GWP can be multiplied by the efficacy (Berntsen et al., 2005), and a version of the GWP for sustained (step-change) emissions, rather than pulse emissions, has been proposed and used (e.g. Johnson and Derwent, 1996; Berntsen et al., 2005).

The gases controlled by the Kyoto Protocol are long-lived greenhouse gases, and each gas can be represented by a single value for a given time horizon. The situation is *much* more difficult for emissions of short-lived gases, where the GWP may depend significantly on the location and time of emission, and in the case of aircraft, the altitude of emission. This complexity led IPCC (1999) to reject the possibility of applying GWPs for aviation, although they did not recommend any alternatives. Others (Klug and Ponater, 2000; Svensson et al., 2004) have taken a more pragmatic view and attempted to develop height-dependent metrics for aviation emissions; however these efforts did not use input from state-of-the-art chemical transport models and radiative transfer schemes and hence should be regarded as somewhat crude and preliminary.

There are many potential choices in metric development (e.g. Fuglestvedt et al. 2003; Shine et al 2005). Should pulse or sustained emissions be chosen? What is the dependence on the background atmosphere? Should the metric integrate the “climate effect” over time (as the GWP does, integrating the radiative forcing)? Or should it be the climate effect (e.g. temperature change) at some particular time? In either case, a choice has to be made of the time of the end-point. What climate effect should be used? The most basic is radiative forcing, but in principal, it could be temperature change, precipitation change, frequency of extreme events, sea-level rise, or even the monetary value of the “damage” due to the climate change. In general, the more a metric reflects the actual impact of climate change, the more uncertain is its calculation, and a balance between practicability and relevance has to be struck (e.g. Fuglestvedt et al. 2003 – see Figure 4 below).

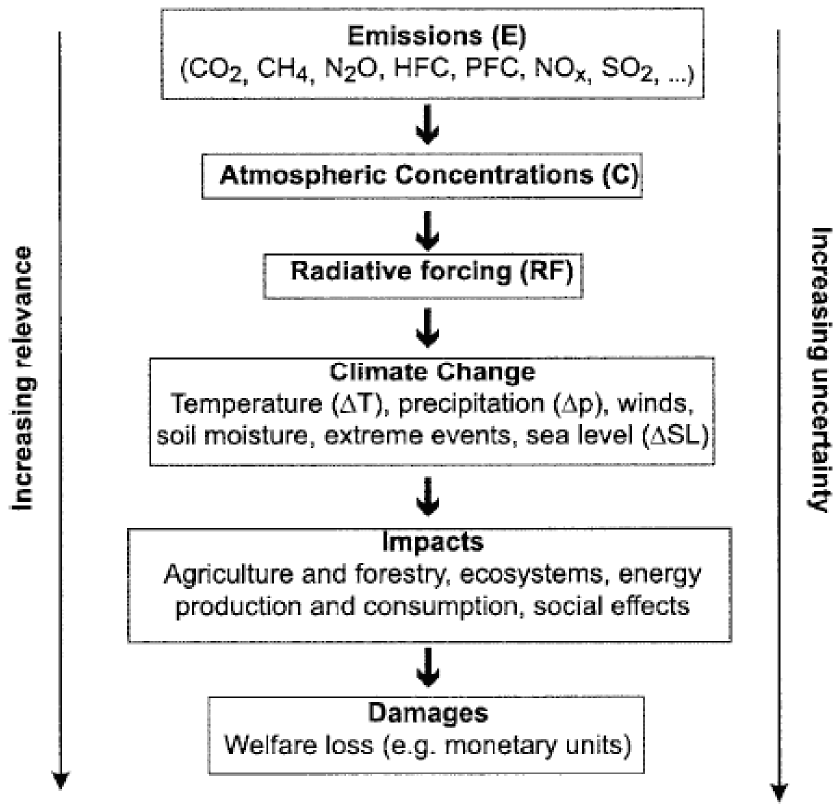


**Figure 4.** A simplified representation of the cause-effect chain from emissions to climate change and damages, as presented by Fuglestvedt et al. (2003).

# 3. Uncertainties and Research Gaps

Each Subgroup identified the key uncertainties and research gaps associated with their topic. The analyses of the state of the science led directly into the discussion on remaining uncertainties and gaps.

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

There are two types of scientific uncertainty that greatly impact the evaluation of aviation's impact from emissions of NOx on climate and global air quality. One family of uncertainties derives from specific model formulation errors and can be addressed by laboratory, numerical, or atmospheric studies that focus on the specific process. In terms of aviation impacts, some key process uncertainties are:

- *Aircraft emissions of gases and particles*. Remaining uncertainties in the emissions, both from uncertainties in how much is emitted (e.g., soot, sulfates) from each aircraft and from uncertainties in the global distribution of these emissions with altitude, latitude, and longitude, need further consideration.
- *The fundamental NOx and HOx chemistry of the upper troposphere*. Large disagreements between the modeled and measured abundances of OH, $HO_2$, NO and $NO_2$ in the upper troposphere have been found in INTEX and other airborne campaigns. These discrepancies point to errors in either the measurements or in understanding of surface emissions, the effects of long-range transport of pollutants, and/or the tropospheric chemical mechanisms and rates. The discrepancy is not found in the lower stratosphere. This uncertainty is fundamental to the calculated increase in $O_3$ and decrease in $CH_4$ from aircraft NOx.
- *Lightning NOx.* Lightning-generated NO provides much of the background $NO_x$ in the upper troposphere. Because the response to $NO_x$ perturbations is non-linear and depends on this background, it is essential to determine what NOx levels would be without aircraft. An understanding of lightning NOx in terms of sources and their relationship to convection is needed to evaluate the aircraft perturbation, especially for future climates.
- *Plume processing of aircraft NOx in the first 24 hours*. The high concentrations of $NO_x$ in the exhaust plume along with other short-lived exhaust products and ice particles can lead to rapid conversion of NOx to $HNO_3$, which effectively cuts off the aircraft perturbation to $O_3$ and $CH_4$. Different implementations of the plume processing in global models still shows a wide range (e.g., from 2 to 10% of the $NO_x$ removed) and needs to be resolved. Zero plume-processing produces a maximum change in ozone, and thus limits can be attached to this effect.

A second type of uncertainty involves coupling across different Earth system components, and possible non-linear responses to perturbations and/or feedbacks within the chemical system.

- *The coupling and feedbacks of tropospheric $CH_4$-CO-OH-$O_3$.* These feedbacks determine the balance of the aviation $NO_x$ climate impacts through greenhouse gases: i.e., between $O_3$ increases and $CH_4$ decreases. There is no single test (based on observations) that gives confidence that a model accurately responds to a $NO_x$ perturbation since the impact on $CH_4$ is a remote response that involves CO and transport away from the region of maximum $NO_x$ perturbation. A related uncertainty involves the cross-over point, i.e., the altitude (as a function of latitude) in the lower stratosphere at which the addition of aircraft $NO_x$ changes from an $O_3$ increase (low altitudes) to a decrease. This cross-over point depends not only on the chemical coupling, but also the transport in the lower stratosphere.

- *Climate change.* Our models and observations of the meteorology and background chemistry are derived from today's climate. It is clear that climate is changing and that the future aircraft fleet will operate in a different atmosphere in terms of both chemistry and transport. Key changes affecting aviation impacts are those to upper troposphere temperature and relative humidity (for contrails and cloud processing, background levels of $O_3$ and $NO_x$ and aerosols, the tropopause boundary (e.g., it has moved up 200 m over the last 2 decades), and the overall rates of vertical transport in the UT/LS.
- *Scavenging.* The removal of aircraft $NO_x$ from the atmosphere typically involves chemical conversion to $HNO_3$ followed by scavenging in aerosols or hydrometeors that deposit it on the ground. The process whereby gaseous $HNO_3$ is scavenged thus involves large-scale transport, convection, cloud processes and precipitation. This coupling is a major uncertainty in current CTMs; however, since most of the $HNO_3$ will not be chemically reactivated to $NO_x$, this introduces only a small uncertainty in aviation impacts.
- *Correlation between operational flight routing and meteorology.* Emissions inventories have generally been evaluated as a mean set of emissions operating on a varying meteorology (and hence transport of those emissions). The correlation of emissions with the meteorology of the day could lead to biases in the location of emissions relative to the tropopause and also in preferentially upward moving air masses (leading to greater accumulation of emissions) or downward moving ones (less accumulation and impact).
- *Transport and Mixing.* Aircraft emissions will accumulate in atmospheric regions of relatively slow, or stagnant mixing. The seasonality of these regions, the apparent barriers to mixing, and the rapid mixing through convection or other breakdowns (e.g., tropopause folds) in atmospheric stability are readily observed in the stratosphere and upper troposphere. It is not easy to quantify this transport, and hence the accumulation of emissions in these regions. This is a key uncertainty in evaluating aviation impacts today. For example, the transport through the lower stratosphere and the transition regions in the upper troposphere may be slow enough to accumulate and enhance the background levels of $H_2O$ in these regions, leading to a direct greenhouse effect as well as perturbing the $HO_x$-$NO_x$ chemistry.

### *3.2 Contrails and Cirrus*

A number of uncertainties and gaps were identified relative to understanding the effects of contrails and aircraft-induced effects on cirrus clouds:

- *Detection and prediction of ice supersaturation*. Contrails and the expansion of contrails into cirrus clouds occur in a supersaturated environment. However, global distributions of supersaturation in the upper troposphere, where aviation-produced cirrus is likely to occur, are not well known. Satellites are currently on line that may be capable of improved detection of supersaturation in the upper troposphere, including the MLS (Microwave Limb Sounder), AIRS (Atmospheric Infrared Sounder) and TOVS (TIROS Operational Vertical Sounder) instruments. Required is a remote sounding instrument that measures both temperature and humidity with good vertical resolution and/or can detect relative humidity directly. However, current retrievals adequate for water vapor and temperature measurements under subsaturated conditions may not be sufficient for supersaturated cases. Existing satellites do not have the horizontal or vertical resolution to accurately define the frequency and extent of supersaturated regions.
- *Optical properties of contrails, contrail-cirrus, and cirrus*. Existing research on contrails and contrail-cirrus indicates that ice particle sizes are smaller on average than in natural cirrus (Baumgardner and Gandrud, 1998; Minnis et al., 1998; Sassen and Hsueh, 1998; Schröder et al., 2000). Because the radiative effects depend contrail dynamics and spatial structure and on many environmental factors including the surface temperature and presence of low level clouds, it is difficult to determine the overall net warming effect on climate for contrails and contrail-cirrus.

  The extent of feedbacks between microphysics and radiation is poorly understood. For example, the behavior of instruments that measure in-situ concentrations and sizes of ice particles may differ dramatically. Some instruments based on particle impaction do not measure high concentrations of small crystals (diameter <70 μm), while optical probes may measure small crystal concentrations orders of magnitude greater than the impaction instruments. The radiative properties of contrails also depends on the shapes of their crystals, and due to the small crystal sizes and the spatial resolution of the imaging probes, the shapes of these small crystals are uncertain. The radiative properties of cirrus clouds and contrail-cirrus also depend on the vertical distribution of their microphysical properties. An examination of those radiative properties using remote sensing instruments (e.g., lidar, radar, radiometers, and interferometers) is often confounded by the presence of lower level clouds.
- *Interactions between heterogeneous ice nuclei and cirrus clouds*. For cirrus clouds, nucleation of ice particles can occur via the heterogeneous action of insoluble ice nuclei (IN). At temperatures below about –38°C, nucleation occurs by the homogeneous freezing of liquid solution droplets. For cirrus forming in-situ, homogeneous freezing occurs in increasingly concentrated solution droplets as temperature decreases below –36°C. Heterogeneous ice nucleation in particles that are partially or fully soluble can potentially cause cirrus formation at warmer temperatures, and, for temperatures below –38°C, lower relative humidities. Heterogeneous ice-nucleation mechanisms (modes) most relevant for UTLS conditions include immersion freezing (ice nucleation induced by an IN previ-

ously immersed in a liquid aerosol droplet), contact freezing “inside-out” (freezing initiated when a solid IN immersed in a liquid aerosol particle collides with the drop surface from the inside), and deposition nucleation (direct nucleation of ice from vapor at a solid particle surface) which may occur in rare cases when IN reach the upper troposphere in a dry state. Very recent research demonstrates the relevance of organics in heterogeneous ice nucleation (Zuberi et al., 2001; Zobrist et al., 2006; Shilling et al., 2006). Not all of these modes have been shown to operate efficiently at cold temperatures. The concentration and nucleation relative humidity of IN mainly determine their impact on cirrus cloud properties (DeMott et al., 1997; Kärcher and Lohmann, 2003).

The basic uncertainty associated with ice nucleation processes is that they occur within short time scales (often only within seconds) and are rather localized (in sufficiently supersaturated patches of air). For this reason, it is extremely difficult to determine their relative importance in in-situ measurements, or to even determine the basic nucleation mode. It is possible to isolate different ice nucleation pathways in the laboratory, but the question arises whether the employed IN particles are representative of atmospheric particles, an issue particularly important for aircraft because real engine soot and its processing cannot easily be represented in laboratory measurements.

Past studies of IN compositions have identified clay particles and mineral dust as important atmospheric IN. Lidar studies have documented the strong cloud-glaciating effect of dust particles from both Asian and Saharan sources. Laboratory studies using surrogates for airborne crustal and mineral dust particles predict the strong ice-nucleation efficiency of such particles throughout cirrus cloud forming temperatures.

Cirrus cloud ice crystal concentrations for sizes above 100 µm and for temperatures both above and below –38°C are typically of order 0.01 $cm^{-3}$, similar to observed IN concentrations. From this, it is reasonable to conclude that the first ice particles in cirrus are formed through heterogeneous ice nucleation, if IN are available.

Aircraft soot particles have to compete with efficient IN in dust layers, but dust aerosol is geographically and seasonally highly variable and it remains uncertain how many dust particles are actually present in aircraft flight corridors. In the absence of dust, measurements in aging aircraft plumes face the difficulty of distinguishing between soot particles from aircraft exhaust and those from other sources (biomass burning, forest fires) present in the background atmosphere. Recent findings that certain organics might cause precipitation of ice-nucleating crystalline solids in liquid particles render efforts to disentangle the roles of various particle types in ice formation even more complicated.

- *In-situ measurements of aerosol composition and small ice crystals*. It is difficult to make in-situ measurements of both the aerosol composition and small ice crystals. The low mass loading of particles provides a challenge to instrumentation even if they can adequately measure particle composition at lower altitudes. Mass spectrometric data indicate that, at least in some regions, a majority of the particle mass in the upper troposphere is carbonaceous (e.g., include organic and elemental carbon). These data do not extend to the most numerous small particles below ~100 nm in diameter, nor is there information on the type of organic molecules. These organics could significantly change the freezing behavior of particles, affecting the evolution of contrail-cirrus and cirrus.

There are significant problems with the measurement of small ice particles. Cirrus ice crystals can range from a few to hundreds of μm or more in diameter. Measuring this range requires several instruments and the agreement between instruments in the size range has not always been good.

Although in cirrus clouds the basic size modes are not in as much question as for mixed phase clouds, it is questionable whether any of the existing probes can obtain accurate sizes of non-spherical ice crystals. Furthermore, not only the size but also the crystal habit is important for the radiative properties of the cloud. Existing instrumentation cannot easily measure the shape of the numerous very small (diameter <20 μm) crystals that have often been found in contrails and cirrus clouds. Ice can form much more easily on some particles in the atmosphere. The measurement of these ice nuclei in both contrail-cirrus and the background atmosphere is crucial to understanding how particles emitted from aircraft compete with background particles in the formation of new or in the modification of existing cirrus. There are many fewer IN than other particles and improved instrumentation to measure their number and properties is needed.

- *Representation of emitted aerosols and contrails in global atmospheric models*. Assessment of aviation effects on cirrus cloudiness in global models requires inputs of the emitted aerosol quantities and their relevant properties. Currently no detailed particle emissions inventories exist, as have been used for assessing gaseous aviation emissions like $NO_x$ and CO as a function of fleet technology and operation under various scenarios. Such detailed inventories of particles including their gaseous precursors $SO_2$ and hydrocarbons are needed to account for the variations in non-volatile and volatile particle number, size, and character across the range of engine technologies currently in use or expected in the future. Because the changes in emission inventories have not been addressed, there have only been a few attempts to study the climate impact of persistent contrails.

  Process studies of the evolution of particle properties and their role as IN will be required to generate effective emission indices for input to the global models, since the characteristics of the emitted particles may have changed significantly by the time the emissions have mixed to global model grid scales. In that regard, global models and contrail/cirrus studies need to establish the essential parameters for properly incorporating aviation aerosols and their effects into atmospheric calculations. As these inputs are determined, the global atmospheric models can account for the effects emitting particles as a function of the frequency and extent of supersaturation with respect to ice, the optical properties of the generated aerosol, and the radiative implications of the resulting high cloud cover generated due to aviation operations.

- *Plume particle processing*. Current global models treat aircraft emissions as well mixed within the grid box, ignoring plume processing of the emissions. However, the effects of non-linear plume processes (both chemical and microphysical) have not been evaluated in depth in the context of global chemical transport models. None of the currently available emission inventories considers the effect of plume processing on species or particle mixing ratios (e.g., $NO_x$ to $NO_y$ re-partitioning, volatile and soot aerosol number concentrations and size) that eventually enter global simulations.

  Two types of aerosols are known to exist in aircraft plumes: the first is associated with soot particle emission and has number emission index of ~$10^{14}$-$10^{15}$ /kg-fuel; the second is due to the formation of volatile particles induced by chemi-ions (e.g., Eichkorn et al., 2002) and has number emission index of ~$10^{16}$-$10^{17}$/kg-fuel. The aviation-generated particles may perturb the abundance and properties of climate-relevant particles in the upper troposphere. To properly assess this perturbation and associated climatic effect, further research is needed to understand the properties, transformation, and fate of aircraft-generated particles.

  Aviation aerosols are composed of water, sulfuric acid, organics, and soot. Particle composition may affect their potential to act as IN. In this regard, it is necessary to characterize the dependence of particle composition on engine operation conditions and fuel properties and the relative contribution of organics versus sulfur to the mass of particles of different sizes as a function of time in dispersing aircraft plumes. The aircraft-generated particles interact with background aerosols through coagulation and mixing, and will eventually become part of ambient aerosols. In addition, photochemistry will provide additional condensable material (e.g., sulfuric acid from emitted $SO_2$).

  Research is lacking on how the properties (number concentration, surface area, composition, and mixing state) of ambient aerosols are perturbed at the presence of jet engine emissions under various conditions. In this regard, a detailed investigation of the microphysical (condensation and coagulation) and chemical processes (oxidation of precursor gases) governing the evolution of aviation aerosols in the time scale of days to weeks after emission is required. Research is also needed to define the abundance and properties of ambient aerosols as well as gaseous aerosol precursor concentrations in the troposphere. Both theoretical modeling and in-situ measurements are needed to advance our knowledge about the perturbation of the climate-relevant particles in the upper troposphere by aviation emissions.

- *Properties of heterogeneous ice nuclei from natural and anthropogenic sources*. The formation of cirrus clouds is characterized by a competition between freezing particles for the available water vapor. Because of this competition, the ice-nucleating behavior of particles from aviation depends on the ice nucleation properties of particles from other anthropogenic and natural sources. The chemical composition of IN in the free troposphere is important to understand both the details of their freezing behavior and their sources.

A special case is elemental or soot-like carbon. The available data indicate that their ice nucleating behavior depends on their source and processing in the atmosphere such as addition of sulfate or organics. For example, elemental carbon from biomass burning probably has different ice-nucleating properties than aviation soot. None of the laboratory studies of ice nucleation has used authentic aviation soot. Sulfates and organics have been shown to affect ice nucleation ability, but the role of organics that condense in the plume behind a jet engine has not been studied in cruise conditions.

It is known from measurements carried out in wave clouds at temperatures close to –38°C that certain aerosol particles nucleate ice at lower supersaturations once they have nucleated ice before (Field et al., 2001). This pre-conditioning effect is neither theoretically understood nor well explored experimentally. Short-lived contrails that form in subsaturated air could lead to pre-conditioning of exhaust soot particles, as it is known that contrail ice crystals mainly form on emitted soot particles. After sublimation, these modified soot particles could facilitate ice formation in the atmosphere, increasing the relative importance of the indirect effect. Conversely, if the soot is not so transformed by this conditioning, it may never be as effective as ambient IN, even though these soot particles previously served as nuclei for contrail particles. Whether or not soot particles are effective IN and to what extent contrail processing changes their properties is a central question.

- *Contrail-cirrus development*. The development of cirrus clouds from contrails and the resulting radiative effects are poorly characterized in current climate models and have only been studied on a limited basis from satellites and in detailed-cloud scale models. The role of wake dynamics in determining immediate contrail ice particle concentrations has not been fully explored. For example, the interactions between the wakes of four versus two engines could, perhaps, dissipate young contrails through induced subsidence, even in nominally supersaturated conditions. Otherwise, once a contrail forms in supersaturated conditions, it will continue growing and spreading. However, knowledge of the impact of the type and numbers of primary and secondary emission particles on the number of ice crystals and hence the potential for particle growth and precipitation is inadequate. Such factors, along with wind shear, local vertical humidity profiles, and wake turbulence, will determine how the contrails grow vertically and horizontally and whether they dissipate in a few minutes or in many hours. The resulting vertical distribution of the particles and their sizes determine the contrail-cirrus optical depth and effective particle size that govern the radiative effects of the cloud.

  A few modeling studies have examined the transformation of young contrails to cirrus clouds and its sensitivity to the number of nucleating particles and wind shear, but the effects of realistic emission particle distributions, induced turbulence, radiation interactions, and the mesoscale environment have not yet been examined in a meaningful way. Such modeling studies are clearly needed but will remain theoretical exercises until the relevant variables can be measured simultaneously. While early field campaigns were conducted to accomplish that goal, the amount of useful data is insufficient to confidently model and understand the processes determining the microphysical and optical properties of contrails and contrail-cirrus in a wide range of atmospheric conditions.

Cloud-to-regional scale measurements and modeling are necessary steps in building a dependable set of tools for determining contrail-cirrus impacts on climate. They form the basis for modeling the effects on a global scale. However, knowledge of the global distribution of contrail-cirrus optical properties and coverage still remains uncertain. To date, satellite-based estimates of contrail particle sizes, optical depths, altitudes, and coverage are confined to only a few regions, seasons, or years. The most studied area is Western Europe followed by the United States. A more comprehensive climatology of aircraft-induced cirrus properties and radiative effects is needed, at least, for those areas where air traffic is significant or will become significant in the near future, e.g., eastern and southern Asia. The climatology should include several years that differ in upper tropospheric humidity in order to determine the variability over the actual range of conditions that occur over time scales greater than a decade. A database of this type will serve as the basis for understanding the direct impact of contrails and contrail-cirrus and for guiding and validating global climate models that include this new class of ice clouds.

- *Incorporation of effects of aviation-induced particles and cirrus into global models.* Current operational weather forecast models [with the exception of an upcoming release of the European Centre for Medium Range Weather Forecasts (ECMWF) Integrated Forecast System] and climate models [with the exception of a recent test version of the German climate model ECHAM] are not capable of predicting supersaturation in the UTLS region. Instead, saturation adjustment schemes are employed that move any excess of water vapor above saturation obtained within one time step due to cooling or transport of ice water. The saturation adjustment dates back to the early days of climate modeling in the late 1960s. It is well justified for warm (liquid phase) clouds, because supersaturation with respect to supercooled water in the atmosphere is very small (up to a few percent at most). However, it is known that cirrus clouds require tens of percent of ice supersaturation to form. Accurate knowledge of ice supersaturation is crucial for quantifying both, direct and indirect effects of aviation on cirrus cloudiness. High-resolution regional models may be needed to do this well.

Many cloud schemes in general circulation models (GCMs) diagnose cloud fraction, mostly as a function of the grid mean relative humidity, which is appropriate for short-lived low levels clouds. Stratiform cirrus clouds in particular are known to be long-lived and can be transported over many grid boxes of a large-scale model during their lifetime. For cirrus, a prognostic description of cloud cover would be more appropriate. The same holds for long-lived contrail-cirrus that add to high cloudiness. In many cases, only ice water mass is prognosed in global models. This hampers the introduction of physically-based links to the nucleation of ice crystals in cirrus clouds, an issue clearly required to distinguish between the many different types of cirrus and to track the indirect effect of aircraft-produced aerosols.

In most global models cirrus is treated as one class of clouds in terms of their radiative properties, although it is well known that anvil cirrus originating from deep convective outflow, stratiform cirrus associated with synoptic weather systems, or wave clouds triggered by strong orographic forcing exhibit distinct size distributions and geometrical properties that eventually control their radiative forcing. Contrail-cirrus form a class of high ice clouds on their own, as they are composed of more numerous small (diameter ~10-30 µm) ice crystals than natural cirrus and likely lack a large (diameter >100 µm) ice crystal mode. Also, known feedbacks between radiation and internal cloud motion remain largely unconsidered in GCMs, because such processes cannot easily be parameterized owing to their small-scale nature. According to cloud-scale numerical simulations, such feedbacks can also occur in contrail-cirrus.

Before at least some of the above described first order problems have been solved, it will be very difficult to provide reliable global real-time forecasts of contrail-cirrus in support of potential contrail avoidance strategies, or possible to accurately predict the impact of aviation-induced cloudiness in future climate change scenarios. While some progress has been made in the past 5 years to deal with ice supersaturation and to parameterize the nucleation of ice crystals in cirrus clouds, harmonizing the complete suite of dynamical, microphysical, and radiative components related to cirrus in global models is a highly interdisciplinary research issue requiring a long-term commitment in well-coordinated scientific projects. This research has to be carried out in concert with laboratory, in-situ, and remote sensing analyses that may provide guidance in developing parameterization schemes of subgrid-scale processes used in GCMs.

- *Global distribution and properties of supersaturation, aerosols, and thin cirrus*. Even if the degree and frequency of occurrence of supersaturation and the composition and size distributions of aerosol and cirrus cloud particles were calculated by GCMs, it would be a difficult task to actually validate them. The problems with detecting and verifying ice supersaturation measurements from satellites have been addressed before. There is no global inventory available that would yield quantitative information about the aerosol budget in the UTLS region, in particular for soot-containing aerosol. Current global model aerosol validation exercises (e.g., the AEROCOM initiative) strongly focus on lower tropospheric aerosols. Cloud climatologies such as contained in the International Satellite Cloud Climatology Project (ISCCP) data set do not include high clouds with optical depths below about 0.2, but such thin cirrus are common in regions where aircraft cruise. Stratospheric aerosol and subvisual cloud climatologies [especially those from the Stratospheric Aerosol and Gas Experiment (SAGE) and the Halogen Occultation Experiment (HALOE)] have limited value in the tropopause region and upper troposphere. Aircraft measurements are useful in checking whether global model predictions capture the atmospheric variability, but do not provide a global coverage.

- *Long-term trends in contrail-cirrus and cirrus*. Based on current knowledge, it is expected that cirrus coverage will increase as a result of contrail-cirrus formation that taps hitherto cloud-free supersaturated air. Whether contrails cause additional cirrus coverage or cause a decrease in cirrus in other locations resulting a zero net change can only be answered by studies of long-term variability. Long-term trends can only be ascertained from consistent measurements over extensive periods. Subjective, but consistently guided, surface observations of cloud types and coverage have been taken over much of the world since the beginning of the jet age and over many locations in earlier years. Satellite observations, primarily in the form of data from the ISCCP, have been analyzed since 1983. Each type of observation has its uncertainties and either one alone is insufficient to confidently determine the overall impact of aircraft on cirrus.

  Recent studies show that for common periods of record, the surface and satellite data agree in the general directions of the trends but not in magnitude. Ensuring that the trends are due to air traffic requires some knowledge of the concomitant trends in upper tropospheric humidity (UTH), a parameter that has not been measured either adequately or consistently for any length of time. While recent efforts to separate the natural humidity effects and anthropogenic impact have had limited success, confidence in the results remains tepid because of the uncertainties in the humidity record and the differences between surface and satellite observations in the magnitudes of the trends. The humidity issue has been skirted, to a degree, by focusing on the relationships between cirrus trends or amounts and upper tropospheric air traffic. Such studies generally agree that cirrus coverage is greater in areas where air traffic occurs, but they do not answer the question regarding the suppression of cirrus in other areas. Solid answers to those questions appear to be dependent on understanding humidity variability in both areas, with special emphasis on ice supersaturated regions.

  While it is not possible to return to the past and reconstruct a more accurate UTH record, it is recommended that improved methods for measuring UTH and supersaturation be standardized and applied consistently on a global basis in the future. Development of innovative methods to unscramble the natural and anthropogenic effects should be continued. Furthermore, both surface and satellite observations should be sustained in order to detect cirrus changes as air traffic patterns evolve over the coming years.

### *3.3 Climate Impacts and Climate Metrics*

There are only limited analyses of the uncertainties associated with current evaluations of radiative forcing resulting from aircraft emissions. Sausen et al. (2005) did not provide new uncertainty estimates (beyond IPCC, 1999), as the sample size of independent experiments was too small to do this on a sound basis. Subjective estimates indicate that the smallest uncertainties are associated with RF from $CO_2$, while the largest uncertainties are from cloud effects beyond linear contrails. More specifically, the following main uncertainties with relevance remain:

- *RF from $O_3$ and $CH_4$:* Here the main uncertainty arises from the change in abundance of the species as stated in Section 3.1. The ozone and methane RFs from NOx emissions are opposite in sign, so the extent to which they offset each other is an important uncertainty.
- *Impact from cirrus clouds:* While the knowledge on linear contrails has increased since IPCC (1999), still at least a factor of 2 remains as uncertainty. Like IPCC (1999), the Sausen et al. (2005) paper does not provide a meaningful estimate of the radiative forcing associated with aviation-induced cirrus changes beyond linear contrails. Sausen et al. rather report of an estimate by Stordal et al. (2005) based on studying the correlation between air traffic and observed cirrus cloud changes: Their "mean" estimate is 30 mW/m2 with very large uncertainty (an upper bound at 80 mW/$m^2$). More recently, a yet unpublished study (Penner and Chen, 2006) suggests much larger effects from indirect cirrus. However, other studies suggest, that even the sign of this effect is uncertain (Hendricks et al., 2005).
- *Efficacy of aircraft-induced radiative forcings:* There are some indications that the efficacy of contrails (and potentially contrail cirrus) is smaller than 1, while the efficacy of aircraft induced ozone changes appears to be larger than 1. These findings need to be confirmed by more modeling studies.
- *Aircraft induced climate change:* As aircraft-induced perturbations in the radiative active species and corresponding heating rates are horizontally and vertically inhomogeneously distributed, the regional pattern of climate change will be different for different aircraft effects, e.g., the climate response to aircraft-induced ozone increase and methane decrease have a different structure and will not compensate. The actual pattern needs to be explored.
- *Metrics for aviation induced climate change:* It is still not clear which climate metrics are most appropriate for analyzing present-day and future aviation activity on climate. There is also a need to use metrics to compare climate impacts due to various trade-off options e.g., between $CO_2$ and NOx emission, or between $CO_2$ and contrail plus contrail cirrus.

# 4. Use of Climate Metrics in Trade-off Studies

There are a variety of potentially important trade-offs for aviation and climate change. These include trade-offs among aircraft and fuel technology, aviation operations, and policy options. The selection of one option over another may potentially result in different magnitudes of climate impacts. More broadly, there are also interdependency oriented trade-offs with other environmental impacts such as local air quality and community noise. These interdependencies are covered in section 4.3.

The focus of this workshop was on those science issues that affect climate impact related trade-offs issues and a need to assess these climate impacts in terms of suitable metrics. For example, it has been suggested that reducing cruise altitude would reduce the number of contrails (it is unclear what the effects would be on cirrus) and reduce the NOx effects on ozone, while affecting fuel burn and the amount of $CO_2$ emissions. Flying higher, on the other hand, would reduce contrail production, but would enhance residence time of pollutants, with resulting chemistry implications. Increasing the engine bypass ratio could reduce $CO_2$ emissions and produce less noise, but result in increased NOx emissions. Some studies have suggested that reducing the amount of high latitude routing might reduce effects on stratospheric ozone, but this would require more fuel burn and increased $CO_2$ emissions. Recently, because of the competing effects of solar versus infrared radiative effects from contrails, it has been suggested that reducing the number of night flights would generally be expected to reduce the climatic effects of the contrails produced [e.g., Stuber et al., 2006]. However, to some extent, the benefit of such reduction in nighttime flights would be offset by an increment in climate impacts due to enhanced daytime aviation activities.

There are two primary motivations for understanding such trade-offs. First, in order to select environmental policies that balance society's economic and environmental needs, national and intergovernmental agencies must have the ability to assess the complete impact of each suggested option, accounting for potential interdependencies. Second, it is important to provide guidance to manufacturers and airlines as they seek to balance a variety of environmental, safety and performance objectives. This is particularly important because of the capital-intensive nature of the industry – roughly $10B for a new airplane development effort -- and because of the long time-scales for development and use. Technology development and deployment may take 10 years, followed by a 20 year production period, followed by as long as 30 years in service. Therefore, airplane technology under development today may still be flying 50 years from now.

### *4.1 Issues with Metrics for Assessing Aviation Climate Impacts*

Estimates of radiative forcing for aviation, such as those produced in IPCC (1999) or Sausen et al. (2005), represent the radiative forcing at a given time due to all prior and current aviation activity (e.g., effects of accumulated $CO_2$ emissions, plus present day, short-lived impacts like contrails). Since some of the effects have very different timesscales, such radiative forcing estimates for either current or projected fleets of aircraft do not capture the relative importance of short-lived and long-lived effects. Further, as discussed earlier, different sources for radiative forcing (e.g., contrails, $CO_2$, $NO_x$ through ozone, and $NO_x$ through methane) produce different levels of temperature change at the surface of the Earth per unit change in radiative forcing. As mentioned earlier, a limitation of considering relative levels of radiative forcing is that the different impacts on temperature are not fully accounted for, although the use of efficacy factors may improve this evaluation.

Thus, climate metrics that integrate over past aviation activities, in of themselves, may not be an appropriate basis for making policy decisions, nor are they an appropriate basis for fully evaluating the relative impacts of various aviation effects. This argument is not new; indeed, it is widely understood and accepted, and a variety of alternative integral measures have been pursued [see e.g., *Forster et al.*, 2006].

### *4.2 Key Challenges and Gaps in addressing Trade-offs among Aviation Climate Impacts*

Extensive discussion at the Workshop highlighted the current uncertainties and difficulties in addressing trade-offs among climate impacts like the examples mentioned above. Based on the information from previous assessments and from more recent published investigations, it was concluded that the scientific community would not <u>currently</u> be able to reach consensus in quantifying the climate impacts, and the associated metrics, associated with the $NO_x$-$O_3$-$CH_4$ impacts or with the contrail and cirrus impacts for the purpose of trade-offs.

Present models are far more capable than those used in the 1999 IPCC assessment, and could be used with the goal of developing a limited set of trade-off metrics. Simulations with present models would still be subject to uncertainties as outlined above, but could be used to develop metrics for aspects such as cruise altitude and routing. For a given fleet and distribution of emissions, it is possible to quantify the response for a change in a single aspect of the fleet, such as a reduction of $NO_x$ emissions. Significant effort would be required to produce and analyze the necessary simulations. It is important that the response to the aircraft emissions and its uncertainty are presented in a manner that takes into account their interdependence. Uncertainty should not be interpreted as representing a normal distribution. For example, the 1999 IPCC assessment did not assume a normal distribution for uncertainties. The quoted uncertainty represented a 2/3 likelihood interval. If present models and tools were used to compare the effects of two "future" fleets, with combined differences in emissions, flight altitude and the latitude distribution of emissions, we are unsure whether current models could represent the statistical significance of the difference. The forcings from changes in $O_3$ and $CH_4$ are expected to have opposite signs, canceling effects would broaden the uncertainty, and even the sign of the net impact might be uncertain. Finally, note that implications for the trade-offs developed based on the present fleet and atmospheric conditions may be potentially different for the future projections. Uncertainty about the changes in the future background atmosphere relative to today adds to the uncertainties described earlier in the Uncertainties and Research Gaps section of this document.

In a more general sense, there are no published studies examining the possible choices, dependencies and problems for metrics suitable for application to aviation, that adequately utilize our understanding of the impact of aviation emissions on atmospheric composition, as reflected in state-of-the-art atmospheric models. Research is needed to examine the effect of different metrics, and the choices within each metric (e.g. time horizon), on evaluating the relative importance of different aviation emissions. Such studies would need to explore the potential of existing metrics and the possibility of designing new metrics.

It was noted that in discussing trade-offs involving contrail-cirrus effects that these effects will depend on latitude, with pronounced regional differences expected. More robust estimates depend on progress in understanding supersaturation and cloud modeling, but also on scenarios of how future flight routes will be distributed. We cannot tell with confidence what these tradeoffs will look like in a future climate, and it will be difficult to develop trade-off metrics for contrail-cirrus and cirrus changes based on existing information.

Although the complexities and uncertainties surrounding trade-off alternative can be perceived as barriers to policy-making, it is important to bear in mind that aircraft manufacturers continue to bring forward new products and the policy-making community must continue to consider environmental policy decisions related to aviation. Climate change metrics are expected to play an important role in this decision-making process.

Research is needed to examine different metrics, and the choices within each metric (e.g. time horizon), on assessing the relative climate impacts of different aviation emissions. It must be stressed that even if agreement on an acceptable metric design was reached, it may be that the current atmospheric models are unable to calculate the input parameters for these metrics with acceptable accuracy. Hence, studies would need to examine the impact of both model and parametric uncertainties on trade-off issues.

### *4.3 Extending the Trade-off Space*

The trade-off concept can be expanded if one attempts to evaluate interdependencies among local air quality, noise and climate impacts due to provisions of addressing the one relative to the other. In 2004 the International Civil Aviation Organization adopted new certification standards for aircraft engine NOx emissions. The new standards represent a 12 percent increase in stringency (tighter standards) to be introduced in 2008 and are designed to mitigate the local air quality impacts of aviation. ICAO estimated the cost of this increase in stringency to be approximately $5 billion. Aircraft and engines designed to meet this standard are likely to have to make compromises on fuel burn and weight, and thus, on climate and noise impacts. Policymakers have also expressed an interest in comparing aviation to other industries (e.g., other transportation systems). The European Union is considering options for including aviation in emissions trading to mitigate climate impacts. These attempts raised many policy questions. The attention of workshop participants was drawn to these interdependencies and trade-offs. However, given the science focus on the aviation-induced climate impacts, there was no further discussion on these issues.

## 5. Research Needs and Prioritized Recommendations

*The workshop identified the need for focused research efforts in the United States to address the uncertainties and gaps in our understanding of current and projected impacts of aviation on climate and to develop metrics to characterize these impacts. This could be done through coordination and/or expansion of existing and planned climate research programs or it may entail new activities.* Such efforts should include strong and continuing interactions between the science community, aviation system operators and policy developers to ensure that the most up-to-date science is readily available to policy considerations and that scientists are aware of the questions and challenges faced by operators and policy developers. These efforts will also require leveraging of ongoing research programs of the climate system.

Substantial progress across the issues will require a long-running science program to be established. The Atmospheric Effects of Aviation Project (AEAP), the NASA led research program during the 1990s, with its numerous European collaborations along with its annual meetings, provides an excellent model. The effect of low-cost, quick-and-dirty approaches to improve scientific understanding is questionable. However, because there are potential needs for near term policy considerations, the new research efforts need to consider short-term as well as long-term research objectives. Each of the three Subgroups at the Workshop addressed both the short-term and long-term research needs and developed a prioritized list of recommendations that should be considered for an aviation-focused research program. The short-term research priorities assumed that an interim assessment of the effects of aviation on climate was needed within the next three (to five) years to meet NGATS objectives.

In establishing the objectives of the focused research efforts, it will be important to consider existing, ongoing research where value-added contributions can be made by additional consideration of the issues associated with the emissions from aviation. To the degree possible, the Subgroups also addressed the ongoing research that should be considered in meeting program objectives. It is also recognized that the short-term and long-term research efforts discussed below will require new or additional research funding.

In the discussion below, the highest priority items for short-term or long-term research are specifically noted. All other items should be regarded as being of medium to high priority.

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

### On-going Research

Aircraft research cannot be decoupled from on-going research in atmospheric chemistry and climate. New efforts that address aircraft issues will benefit from and be enhanced by on-going efforts in climate research.

• *Aircraft impact studies.*

There is significant atmospheric research funded through EU Framework programs focusing on emissions from aircraft and their impact on atmospheric composition and climate. Studies focus on impact in the UT/LS. These studies include the chemical compounds $O_3$, $NO_x$, OH, $CH_4$ and water vapor. Recent EU funded research projects have focused on current and future emissions from aircraft and the impact on atmospheric composition and climate. The TRADEOFF [Sausen et al, 2005] and CRYOPLANE [Gauss et al., 2004] projects included studies of tradeoff options like change in routings (TRADEOFF) and the use of hydrogen as fuel (CRYOPLANE). The SCENIC project investigated impact on the atmospheric composition from introducing a fleet of supersonic aircraft. Current and future aircraft emissions have been updated in connection with the projects. These studies are followed by ongoing research in the Integrated Project (IP) QUANTIFY (2005 – 2010, http://ip-quantify.eu). The goals of QUANTIFY have been expanded over prior programs to include the impact on atmospheric composition and climate from the transport sector (aircraft, ship, land-based transport). Studies include improvements in model performance (transport processes, plume parameterizations, chemistry), and current and future contributions from the different transport sectors to atmospheric composition changes and climate impact (through metrics). Further aircraft impact studies are being performed through the EU-led European Compatible Air-Transport System (ECATS, http://www.pa.op.dlr.de/ecats/) Network of Excellence, where the focus is on technological aspects and the relation to environmental impact. One of the objectives is to improve modeling capability to reduce uncertainties and develop common modeling tools for large-scale studies such as climate impact.

• *Climate Research.*

*SCOUT-O3*. This international program contributes to the understanding of processes in the UT/LS, where the focus is on ozone changes in the LS region, including stratosphere troposphere exchange, convective transport to the UT, chemical processes in the UT/LS and climate-chemistry interactions.

*U.S. agency research programs.* Several U.S. agencies (e.g., NASA, NOAA, DOE, NSF, and EPA) sponsor individual investigator research related to climate concerns. For example, DOE has the Atmospheric Radiation Measurement (ARM) program and NASA sponsors climate research within a number of its programs. NASA also sponsors the development of global three-dimensional models for studying the chemistry and physics of the troposphere and stratosphere though the Global Modeling Initiative (GMI).

*Satellite Measurement Programs including validation campaigns (Aura, AVE, ACE, ENVISAT, etc.)* In the last 5 to 6 years many satellites have been launched to address important questions regarding global air quality, climate and the stratospheric ozone layer (Aura, SCISAT-1 ACE, ENVISAT etc.). Satellite observations and data obtained through their validation programs (e.g. AVE) have contributed to a substantial database of tropospheric, UT/LS, and stratospheric measurements. Instruments such as MLS on Aura measure CO and $O_3$ in this region. ACE measures 10-20 species down to 5 km. In addition, measurements of important species in the free troposphere, such as, for example, CO from MOPITT (EOS-Terra), MLS and TES (both on EOS-Aura) can be used to address issues of tropospheric transport.

*NSF UT/LS-HIAPER.* The NSF community is making a concerted effort to investigate the UT/LS, using the new high altitude research aircraft, Gulfstream V, known as High-performance Instrumented Airborne Platform for Environmental Research (HIAPER). Field campaigns planned for the next 5-10 years have specific foci for UT/LS chemistry, dynamics, and microphysics, including the mixing of chemical constituents in the tropopause region, the role of convective transport in coupling the boundary layer and the UT/LS, connections of chemistry and microphysics, lightning production of NOx. The data obtained in this effort will be interpreted in conjunction with satellite observations using multi-scale models. The set of questions and tools in development for these missions are all highly relevant to aviation specific research. The NASA DC-8, WB-57, and the NOAA P-3 also have key roles in understanding atmospheric chemistry issues relevant to the climate impacts of aviation.

*SPARC CCMval.* The SPARC community has developed a strategy for process-oriented validation of coupled chemistry-climate models (CCMs) termed CCM-Val (Chemical Climate Model Evaluation) [http://www.atmosp.physics.utoronto.ca/SPARC; *Eyring et al.*, 2005/]. The focus has been to develop analysis tools/methods in the areas of radiation, dynamics, transport, and chemistry and microphysics better understanding model processes. The performance criteria and diagnostics developed within this effort will also be applicable to the chemical transport models (CTMs) and serve to assess how well the new generation of models can be used to represent aviation related processes.

### Short-Term Research Needs

The activities below are deemed feasible in the next three years. As pointed out below, some of these efforts will expand ongoing research in the US and other countries, or will involve collaboration with such research.

- **[High Priority]** *Models and Measurements Intercomparison*. A Models and Measurements Intercomparison, emphasizing the UT/LS and free troposphere, could be conducted following similar efforts previously carried out for the stratosphere (e.g., Park et al., 1999), as well as ongoing activities in Europe (ACCENT, SCOUT-O3). It would require: a) detailed definition of modeling experiments testing different model aspects (transport, chemistry), and diagnosing model differences through process oriented model intercomparison; b) compilation of a database of measurements from different platforms, to be used in evaluating model performance; c) identification of model deficiencies through the above process, leading to model improvements and reduction of uncertainty in model predictions. Studies of the UT/LS also need to investigate the effects of higher resolution on representation of constituents and relevant processes in that region.
- *Use of state-of-the-art models to provide parametric relationships between aviation emissions and environmental impact.* Since the aircraft fly in the UT/LS, models with detailed representation of both troposphere and stratosphere are needed. Such models exist (e.g., GMI, MOZART), and continue to be tested with different measurements. A parameter space for aircraft emissions needs to be defined, with appropriate sampling to derive meaningful approximations. This activity needs to be coordinated with the aircraft engineering community. This activity would be most useful if conducted following the Models and Measurements Intercomparison.
- *Vertical transport processes between 2 and 10 km*. Vertical transport processes bring $NO_x$ and other ozone precursors to flight altitudes (e.g., convection), and transport aircraft exhaust downwards (e.g., downdrafts and large-scale downwelling). Lightning is also associated with deep convective regions. Various representations of these processes are used in current models, and all are highly uncertain. Activities in this area should profit from collaboration with ongoing model intercomparison and evaluation by the European ACCENT program.
- *Data analysis and modeling*. A wealth of data has been obtained in the lowermost stratosphere by different aircraft and satellite platforms. A wealth of data has been obtained from past measurement campaigns such as the NASA supported SONEX measure-

ments that have not been fully analyzed for the possible link to aviation activities in the region of the observations. Also, the NASA A-train constellation of satellites, and the European satellites ENVISAT and SCISAT-1 are providing a wealth of data in this region. Different data analysis and modeling groups are currently using these data to constrain the magnitude and seasonality of turnover rates and mixing processes in the lowermost stratosphere. Results from these studies will further reduce uncertainties in the dispersion of aircraft exhaust in this region.

- *Model analyses of chemical and climate impacts.* Re-examine the impacts of aviation in the UT/LS using several of the improved models.

**Long-term Research Needs**

- **[High Priority]** *Field Campaign(s) to address issues with HOx-NOx chemistry in the UT.* As discussed in the "Uncertainty" section, there are significant discrepancies between measured $HO_2$ concentrations and constrained box model calculated values in the upper troposphere. If the measured $HO_2$ values are accurate, this indicates either missing mechanisms in the photochemical scheme, or wrong kinetic parameters. Redundant measurements of OH, $HO_2$, NO, $NO_2$ species are needed to resolve this issue. This is classified as a long-term goal because it requires development and adaptation of instruments to operate on the same aircraft platform. To be useful, the campaign must cover a range of environments – pristine, polluted, moderately polluted, to test non-linearities in the system. It would be important also to sample areas known to have elevated NOx concentrations from aircraft effluents. Such a campaign can also include instruments to examine microphysical processes for contrails and cirrus.
- *Background $NO_x$ and its control via lightning and convection*. Because of non-linearities in the atmosphere, the ozone response from the same amount of $NO_x$ deposited in the upper troposphere by aviation can vary depending on the background concentration of $NO_x$ from non-aviation sources. It is important to derive the background concentrations in the upper troposphere from observations, and to understand the relative importance of the lightning source and transport of $NO_x$ emissions from the boundary layer in understanding these background concentrations. A similar argument could be made for HOx precursors.
- *Relationship between surface reaction efficiencies of heterogeneous chemistry and upper tropospheric aerosol composition.* Heterogeneous reactions on aerosol surfaces transform $NO_x$ species to $HNO_3$ that is removed efficiently by washout processes. Thus, the reaction efficiency plays an important role in determine the residence time of $NO_x$ in the troposphere. The efficiency depends on the chemical composition of the aerosol. It is important to make in situ measurements of aerosol composition and use measured concentrations of trace species to derive reaction efficiency factors.
- *Status of low-temperature kinetic rates.* Many reaction rate constants are measured at higher temperatures and the measured results are extrapolated to lower temperature appropriate for the upper troposphere. Unfortunately, it is not immediately obvious

which reaction(s) is/are responsible for discrepancies between modeled and measured concentrations. Continued efforts are needed to identify those reactions followed by direct measurements of the rate for the appropriate temperature range.

- *Access to high-performance computing*. Computational resources continue to be a limiting factor in performing simulations with the ever finer model resolution required to represent atmospheric processes. There is a need to continuous upgrading of the computer hardware to take full advantage of new developments for maximum throughput. This strategy also turns out to be cost effective, as obsolete equipment inevitably requires higher maintenance cost.

## *5.2 Contrails and Cirrus*

Asterisks indicate areas of research that are being addressed to some degree in current programs.

**On-going Research Projects (and Some Recently Proposed but not yet Supported)**

Projects marked with the # symbol are planned or proposed and not yet funded.

- PARTNER contrail studies (2005-2007). This project being undertaken in PARTNER aims to find relationships between aircraft parameters and the properties of contrails generated by the aircraft under a variety of atmospheric conditions. Large-Eddy Simulation studies are being conducted, initially with simple ice-microphysics and focusing on contrail evolution for the first few minutes. These are complemented by parallel, detailed particle microphysical calculations carried out along representative dilution trajectories. Both types of studies are proposed for longer time periods and further contrail evolution in the future.
- APEX ground-based particle emission studies (2004-2006). A series of field studies have been carried out to measure particle precursors and particles, both volatile and non-volatile, using commercial high bypass ratio turbine engines on ground-based airplanes. This series of Aircraft Particle Emissions Experiments (APEX, JETS/APEX2, APEX3, UNA-UNA), sponsored by a number of U.S. agencies and with broad measurement team representation, has generated results both from dedicated engines tests and from advected plume studies during routine operations at airports. While the tests were carried out at ground level, intermediate engine powers were explored during dedicated engine tests, so that cruise operations might be estimated in the future after altitude chamber measurements are made to develop algorithms for extrapolating static sea level measurements to cruise conditions.
- NASA LaRC CMAI (2006-2008). A study, sponsored by the NASA Cloud Modeling and Analysis Initiative, is underway at NASA Langley Research Center (LaRC) to examine the potential for modeling persistent contrails using high temporal and spatial resolution numerical weather analyses (NWA). Contrail formation, properties, and spreading parameterizations used in the model will be determined empirically based on satellite observations of contrails in the absence of natural cirrus in conjunction with the atmospheric conditions in the NWA. Aircraft will be flown through the model

to form contrails; the results will be used to compute radiative impacts and will be validated using satellite data.

- DLR-IPA PAZI (2004-2007). The project conducted at the Institute of Atmospheric Physics (IPA) and sponsored by DLR concentrates on the effects of particles from aviation and other anthropogenic and natural sources on aerosols, cirrus clouds, and climate. Besides IPA, other Research Centers from the Helmholtz-Society in Jülich, Karlsruhe, and Bremerhaven, the institutes of Meteorology and Chemistry from the Max-Planck-Society and various universities, and partners from France, Sweden, Switzerland, England, and Canada all contribute to this project. Its first funding phase ended in 2003, the results of which have been summarized in the Proceedings of the European Conference on Aviation, Atmosphere and Climate (AAC). Much of the work carried out in PAZIs second funding phase is centered on the direct and indirect effects of aircraft emissions on high cloudiness and their associated climate impact. The project homepage provides more detailed information (including all references that have emerged from PAZI-related studies), and also the first phase summary report can be downloaded from this site (http://www.pa.op.dlr.de/pazi/).
- EU Integrated Project QUANTIFY (2005-10). The main goal of QUANTIFY is to quantify the climate impact of global and European transport systems for the present situation and for several scenarios of future development. The climate impact of various transport modes (land surface, shipping, aviation) will be assessed, including those of long-lived greenhouse gases like $CO_2$ and $N_2O$, and in particular the effects of emissions of ozone precursors and particles, as well as of contrails and ship tracks. The project goal includes the provision of forecasts and other policy-relevant advice, which will be supplied to governments and to international assessments of climate change and ozone depletion, such as the IPCC climate assessments and the WMO-UNEP ozone assessments. Using significantly improved transport emission inventories, better evaluated and hence more reliable models, these new forecasts in QUANTIFY will represent a considerable improvement of current predictions. QUANTIFY work packages include focused field measurements, exploitation of existing data, a range of numerical models, and new policy-relevant metrics of climate change.
(http://www.pa.op.dlr.de/quantify/)
- NASA TC-4 / Costa Rica (2007-8)#. The Tropical Composition, Cloud, and Climate Coupling (TC-4) mission is a proposed NASA Earth Science Enterprise (ESE) investigation. The primary goals of TC-4 are to gain a better understanding of chemical, dynamical, and physical processes occurring in the tropical upper troposphere and in the layer surrounding the tropical tropopause as well as the roles that the anvils of deep convective clouds and tropical cirrus play in humidifying the upper troposphere and lower stratosphere. These issues are relevant to studies involving global climate change, stratospheric ozone depletion, global tropospheric chemistry, and the Earth's radiation balance. While not connected to aviation research, results from TC-4 could help improve understanding and detection of supersaturation in cirrus levels.

- NASA MODIS (2006-)#. The MODIS cloud products contain rich information about the properties of ice clouds. The level-2 MODIS cloud properties (MOD06_L2 for Terra satellite and MYD06_L2 for Aqua satellite) are retrieved on a granule scale, which consist of cloud top physical parameters (temperature, pressure, effective emissivity), cloud phase, cloud optical parameters (optical depth, effective particle radius, water path), cirrus reflectance in the visible band, contrail flag. Of the MODIS ice cloud products, the cirrus reflectance derived from the visible and 1.375-μm bands is quite unique as it is available even for very thin cirrus clouds. The MODIS level-2 products are further integrated into the MODIS level-3 products that have a one-degree resolution in both latitude and longitude. The MODIS level-3 cloud products can be directly applied to climate simulations.
- NASA CALIPSO (2006-). One of the science objectives of the NASA CALIPSO satellite mission is to provide comprehensive measurements of cloud vertical structure. CALIPSO products will include: cloud height (for layers with optical depths $\tau > 0.01$), cloud thickness (for layers with $\tau < 5$), extinction profile, ice/water phase, ice cloud emissivity, and ice particle size.

### Short-Term Research Needs

- **[High Priority]** *In-situ probing and remote sensing of aging contrail-cirrus and aircraft plumes.* A combination of in-situ and remote sensing measurements can be used to characterize the growth, decay and trajectories of contrail ice particle populations in the mid-latitude upper troposphere. In pristine humid air, devoid of ice particles and outside of aircraft flight corridors, a research aircraft would lay out a contrail. It would soon thereafter make a set of measurements in the contrail with ice particle probes to determine the initial state (number concentrations and sizes). Thereafter, the aircraft would climb above the cloud. With a cloud Doppler radar, lidar, and radiometers, it would map out the evolution of particles in the vertical using a combination of radar/lidar (to obtain mean effective radius and ice water content), lidar/radiometers to retrieve mean effective size through the depth of the contrail, and Doppler fall velocity which can be linked to the mean sedimentation velocity of the population. Occasional ascents and descents through the contrail can be used to provide evaluation/validation of the retrieved properties, to determine whether additional ice nucleation is occurring in contrail-cirrus, and to measure vertical motions within the cloud column.

  A similar measurement strategy would be applicable for airborne observations of aging exhaust plumes in the absence of contrails, although it will be much more difficult to track individual plumes for an extended period of time. Such measurements additionally require the detection of relative humidity, $SO_2$, NOx and NOy (which includes the longer lived reservoirs gases like $HNO_3$, to study chemical conversion of nitrogen oxides), $CO_2$ (to infer plume age), and organics in condensed phase. Additional instruments include an aerosol mass spectrometer, aerosol probes to quantify interstitial aerosol properties, and condensation nuclei and ice nuclei counter. To this end, currently available aerosol mass spectrometers need enhanced sensitivity to measure small concentrations and novel IN counter that are under development need to operate in-flight in cirrus conditions. The deployment of instruments detecting single black carbon particles is highly desirable. Such instruments are capable of quantifying number size distributions as well as the mixing state of soot particles (i.e., the degree of coating with soluble matter). Along with accurate supersaturation measurements, the in-situ detection of single soot particles might provide a clue for unravelling the indirect effect.

To increase our understanding of contrail-cirrus development, a set of coordinated regional-scale campaigns should be designed and executed to measure the appropriate variables both with in-situ and passive and active remote sensing instruments. The measurements should cover the cloud-free air prior to contrail initiation through the entire life of the contrail-cirrus until it becomes part of larger natural system or dissipates. In the latter case, the cleared air should be sampled to determine the particulates that remain after the episode is complete. Because contrail-cirrus persistence is highly variable, lasting from a half hour to more than 14 hours, a large number of events should be sampled to gain the needed information. Such regional-scale experiments should ideally be combined with high-resolution space-borne remote sensing, for instance, to address the question of fractional coverage, with obvious benefits for global model validation.

- **[High Priority**] *Initiate regional modeling studies of supersaturation and contrails using weather forecast models that have the potential to include our best physics and the high resolution needed to more accurately predict supersaturation*. Development of these models and associated observational datasets may be the best approach for developing our knowledge in the near term before attempting to use global models.
- **[High Priority**] *Global model studies addressing direct and indirect effects*.* In global climate models (GCMs) that enable the prediction of number and mass of ice crystals in cirrus clouds, it is possible to study the effect of soot aerosols on cirrus formation. These models need some predictive capability for soot particle abundance, both from aircraft and other sources, along with ice nucleation parameterizations that include realistic background cirrus formation scenarios. By their very nature, GCM studies of the indirect effect remain parametric until the freezing properties of aircraft soot and associated plume processing effects are better characterized.

Provided appropriate parameterizations can be developed that are able to track contrail-cirrus as a distinct class of cirrus clouds consistent with the physics already employed in GCM cloud modules, the direct effect of persistent, spreading contrails on cloud cover and radiative forcing can be studied even in the framework of conventional climate models. Even without explicit calculation of supersaturation, such studies will be more realistic than existing GCM estimates and lead to improved prediction of the hitherto poorly quantified global contrail-climate impact.

Both types of studies will yield separate estimates for the direct effect of contrail-cirrus alone and the indirect effect of soot emissions on cirrus properties alone. Interpretation of the resulting global radiative forcing is complicated by the fact that the reference climate changes due to the aviation impact (i.e., the cirrus cloud properties change). A combined treatment of direct and indirect effects is not feasible in the short term.

- **[High Priority**] *Use of existing or upcoming information from space-borne sensors.* A high priority will be the investigation of the optical and microphysical properties of contrail and contrail-cirrus, e.g., the optical thickness and effective particle sizes (two important parameters that are essential to the study of the radiative forcing of these clouds) from space-borne sensors. The satellite-based radiometric measurements facilitate a unique approach to understand the characteristics of contrails and contrail-cirrus on a global scale. Especially, the passive [e.g., the Moderate Resolution Imaging Spectroradiometer (MODIS)] and active [e.g., Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO)] sensors aboard the A-train platforms provide unprecedented opportunity to study aviation-induced and modified high clouds.

  The MODIS sensors on both Terra and Aqua platforms have a strong water vapor absorption channel centered at 1.375 μm. This channel is quite effective for detecting contrails and cirrus clouds because the reflection of sunlight by the surface and lower atmosphere including low-level water clouds is absorbed by water vapor below the clouds. Under contrail and contrail-cirrus cloudy conditions, the radiometric measurements acquired by the AIRS provide the hyperspectral signatures of these clouds, which can be used to effectively infer the properties of these clouds. The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on CALIPSO launched on April 28, 2006 provides new capabilities to study the vertical structures of contrails and contrail-cirrus clouds. The polarization capability of the CALIOP at 532 nm will allow fundamental advances in our understanding of the particle morphologies of ice crystals in contrails and cirrus.

  The research goal of this priority in the next 3-5 years will be the use of synergetic data from the existing passive and active sensors to systematically analyze the global distributions and characteristics of contrail/cirrus clouds. This effort will include the development of robust new algorithms to use the synergetic data sets to detect contrails and contrail-cirrus clouds and to retrieve their properties.

- **[High Priority**] *Evaluation of capability for supersaturation from satellite observations.* As an initial high priority, short-term study, a careful analysis and comparison of all available correlative data on supersaturation at aircraft flight levels are needed. Also on a short-term basis, systematic studies should be undertaken that compare locations of observed contrail-cirrus as detected from satellite or from ground based observations with regions of supersaturation detected from satellite. Such comparisons would be a reasonable first step for assessing the viability of current satellite measurements to accurately detect upper tropospheric supersaturation. On a longer-term basis, studies to improve retrievals for existing instruments and develop new instruments for measuring supersaturation at aircraft flight levels are needed.

- *Correlations between supersaturation fields and contrail-cirrus*. Satellites provide global observations of the atmosphere and clouds. Enhancing techniques for automated detection of supersaturated air parcels and persistent contrails from space-borne passive sensors will lend insight to the global nature of their presence and influence on radiative forcing. Many techniques rely on reflected-solar radiances, which has a limiting influence on the quality of the contrail detection and analysis because: (i) radiance calibration is critical; (ii) the contrails and contrail-cirrus often exhibit self-shadowing attributes that confound the microphysical and radiative-property retrievals; (iii) these retrievals are limited to daytime only. Retrieval techniques are emerging that exploit the influence of ice-particle shape and size on passive multispectral infrared signatures. It is important to place increased emphasis on coupled visible-infrared retrieval techniques that gracefully degrade to infrared-only retrievals at night.

  Developing a truly global day-night contrail detection and analysis capability affords the construction of a contrail-cirrus climatology that provides not only frequency of occurrence but also trends in the diurnal cycle and statistics on radiative forcing changes. Space-based detection of supersaturated air parcels will enhance this climatology. Detecting supersaturated air parcels from infrared and microwave sounders is limited to some degree by the vertical and horizontal spatial resolutions of both the parcels and the satellite observations themselves. However it is possible even in limiting conditions to identify atmospheric water vapor conditions under which supersaturation with respect to ice is likely. Quantifying the frequencies of occurrence of contrail-cirrus with respect to supersaturated air parcels provides critical guidance for parameterizing contrail processes at the sub-grid scales, both spatial and temporal, required by a GCM.

  With the advent of active space-based platforms it will be possible to supplement passive-radiance contrail-cirrus retrievals with active radar and lidar observations, in part to compare and in part to further constrain the retrievals, albeit for only a portion of the total satellite swath. Active lidar/radar and passive visible/infrared radiometer observations from aircraft augment the spaceborne set, and are vital for assessing the atmospheric and contrail state in detail. Aircraft radiance measurements from selected spectral bands can be used to retrieve contrail radiative and microphysical properties that in turn drive radiative flux models. These "retrieved" shortwave and longwave fluxes can then be compared with coincident in-situ broadband flux measurements to ensure that the detailed ice-particle retrievals and associated microphysical models are radiatively consistent with observation.

- *Process studies of plume and contrail development**. A complete relationship has not yet been established between aircraft technology, neither engine characteristics nor airframe configuration, and the resulting aerosol properties of aviation-induced cloud particles. Process studies that explore the role of emitted non-volatile (soot) particles, nucleated volatile particles, and how these aerosols interact with each other and with background ambient aerosols is required to understand how contrails evolve into cirrus-like clouds and how aviation particle emissions perturb the background aerosol in the absence of contrail formation. The role of aircraft configuration (engine placement, wing loading, etc.) may also have impact on the nature and properties of the resulting ice clouds that mediate the radiative impact that aviation imposes. Reliable estimates of the amounts and properties of aerosols and ice clouds generated by aviation requires making a causal connection between the emissions left behind the airplane and those deposited in the atmosphere at the global grid scale.

- *Laboratory measurements of ice nucleation.* Assessing the impact of contrail-cirrus interaction on climate change requires, in addition to field and modeling studies, careful laboratory measurements of respective aerosol-induced processes. Needed are experiments that are sensitive not only to the onset threshold of ice nucleation but also to the number fraction of aerosol particles acting as heterogeneous IN as function of temperature and ice supersaturation. Such data is urgently needed to develop aerosol-related parameterisations of heterogeneous ice nucleation for use in models. Future experiments should focus on the ice nucleation efficiency of representative aircraft-emitted (soot) and natural (e.g., dust) aerosols. Important are systematic variations of soot parameters like the organic carbon content, which are already known from previous studies to influence the ice nucleation efficiency of soot. Another important issue is the impact of particle aging and mixing due to coagulation growth and condensation of less volatile substances like sulfuric acid or organics. Different approaches and methods of IN measurements also need to be compared.

**Long-Term Research Needs**

- The development or improvement of instruments that help establish background concentrations and characteristics of heterogeneous ice nuclei and measure supersaturation accurately, in particular at low water vapor volume mixing ratios (at the 10-50 ppm level at tropopause temperatures and pressures). This includes verification of supersaturation measurements from satellites. More accurate temperature measurements are also needed.
- The development and implementation of new concepts for ice phase-related microphysics, supersaturation, radiation, and cloud fraction, enabling a consistent treatment of aviation effects in the framework of climate and operational weather forecast models. This includes the creation and validation of a number of parameterization schemes, as the crucial processes to be treated will remain unresolved, both spatially and temporally, by global atmospheric models in the foreseeable future.

## *5.3 Climate Impacts and Climate Metrics*

**On-going Research**

Limited efforts are continuing to address the adequacy of the radiative forcing concept as a metric in a general sense for climate change and the use of efficacy within this concept, but these efforts are not focused on aviation.

**Short-Term Research Needs**

*Cloud changes beyond linear contrails*. One of the major uncertain forcings is that from cloud changes. Changes may be caused by spreading contrails (and so they are initiated by the formation of contrails). Changes are also possible in the ice number concentration associated with changes to the ice number concentration from ice nuclei associated with aircraft emissions. The following subprojects are recommended.

- **[High Priority**] *Radiative forcing from all cirrus and contrails.* In addition to previously mentioned studies, specific studies are needed that are aimed at better understanding the radiative forcing from contrails and cirrus. Intercomparisons (model to model) and evaluations (compare model to observations) of radiative transfer models are also needed. Also, studies are needed to analyze the dependence on radiative transfer scheme and on representation of size and shape of ice clouds.
- *Develop cloud scale models with enough physics to predict macroscopic cloud changes*.
- *Chemistry-climate interaction relevant to aviation (future climate)*. Chemistry-climate interactions from aircraft are currently evaluated as being relatively small. However, this may not remain true in future climates. Further model studies of this aspect are recommended.

  More research is needed to determine the efficacy of aviation related climate forcings. Current studies with limited number of models have shown that while climate model sensitivity to forcing varies substantially, that of efficacy (the relative change in temperature to that caused by CO2) is not as variable. More models need to be examined as well as their estimates of radiative forcing. The radiative forcing and response of the models need to be compared to observations as much as possible.

- **[High Priority**] *Systematic model intercomparison of efficacy studies*. Inhomogeneous vertically and horizontally distributed forcing agents. Cirrus changes, ozone changes, CH4, soot. Effect of changes in climate state.

  More research is needed to examine the effect of different metrics on evaluating the relative importance of aviation effects from different emissions. Different metrics can change the relative importance of the different effects from aviation emissions. A metric is needed that faithfully captures the climate impact of different components of aviation emissions.

- **[High Priority**] *Explore different existing and possible new metrics (both integrative metrics and endpoint metrics).* For example, RF, global average surface temperature change, regional temperature changes, precipitation changes, extremes.
- **[High Priority**] *Quantify the reliability in determining various metrics and how uncertainties propagate (both parametric input uncertainties and model uncertainties).*

**Long-Term Research Needs**

- *Experiments designed to not form contrails -- attempt to detect the signature of aerosol emissions along the aircraft track in formation of cirrus.*
- *Evaluate the change of water vapor within the UT/LS associated with aircraft.* Although this forcing is relatively small at present, it may become larger in the future. This issue also involves

the turnover time from the lower stratosphere to the troposphere and is connected with issues affecting the effects of NOx. A coordinated program of model studies in comparison with measurements that includes this aspect is recommended.

- Trend studies of cirrus clouds: what fraction is due to aviation?

  GCMs have not been developed with any capability to predict supersaturation. In addition, cloud fractions within these models are generally diagnostic, not prognostic. Further model development is needed to correct these inadequacies for treating the effects of aircraft on clouds.

- **[High Priority**] Development of forecasting methods for supersaturation (possibly based on commercial aircraft measurements)
- **[High Priority**] Development of methods to prognostically calculate cloud fraction within GCMs.

### *5.4 Research for Trade-off Studies*

Trade-off studies need to be placed in context of the research priorities above. All of these studies will have a high priority for policy considerations; however, research first needs to focus on of the identification, development and evaluation of metrics that can relate various climate impacts due to aviation.

Besides the scientific research interest in analyzing the net effects of potential trade-offs, there is also a policy need to understand the benefits of emission reductions due to various interventions as a result of air technology, operations and policy options. Model intercomparison studies can be used to establish how well we can evaluate various trade-offs. Trade-offs need to be evaluated using the various metrics established in research discussed above. Some of the possible trade-offs to consider for additional evaluation include:

- Engine NOx reduction technology versus fuel efficiency (i.e., $CO_2$ emissions)
- noise abatement versus fuel efficiency
- Changing cruise flight altitudes (which is also affected by aircraft design)
- Changing future geographical distributions of fleet (e.g., more flights to Asia)
- Flight re-routings (daytime vs. night-time flights; avoiding regions of super-saturation; avoiding certain regions, e.g. polar routing, with specialized chemistry or within or outside existing cirrus)
- Calculations of the long-term $O_3$ and $CH_4$ changes due to aviation. These calculations are needed for metrics studies, and are related to studies recommended above.
- Studies of the co-dependence of physical impacts (e.g., ozone and methane effects are inter-related, not independent) and resulting metrics and methods used in trade-offs considerations.

Climate change metrics are expected to play an important role in these analyses. There is currently no study in the peer reviewed literature that can be cited to justify, based on the scientific understanding of the impact of aviation emissions, the possible choices of metrics suitable for trade-off application. Research is needed to examine the effect of different metrics, and the choices within each metric (e.g. time horizon), on evaluating the relative importance of different aviation emissions. Such studies would need to explore the potential of existing metrics and the possibility of designing new metrics. It must be stressed that even if there is a philosophical agreement on an acceptable metric, current atmospheric models may not be able to calculate these metrics with acceptable accuracy.

## 6. Next steps

Following this Workshop, there are a range of possible next steps that could be taken. Most participants felt strongly that a solid, quantitative evaluation of climate change impacts for a range of aviation technological, fuel, operational and policy related options would be desirable. For the sponsors, there are additional steps that could be taken to make the results more useful for decision-making. For example, a smaller group of science and other aviation experts could be brought together to take the outcome of this Workshop as a starting point towards addressing issues such as:

- Ranking and prioritizing research needs across all three subgroups based on the ability to contribute toward answering the practical needs faced by aviation community (operators, manufactures, regulators and policymakers).
- Establishing a forum for dialogue between the science and aviation (manufacturers, operators, and regulators) communities to provide input to the prioritization process.
- Identifying what existing research activities can be leveraged toward meeting practical needs.
- Identifying how long it would take to achieve the identified practical needs with "business as usual" research investment.
- Identifying investment required to achieve meaningful progress toward addressing key questions based on specific timelines (e.g., 3, 5 and 10 years).
- Creating a roadmap with identified roles and responsibilities of various participating agencies and stakeholders.
- Establishing a peer review process to gather input on analyzing the climate impacts of aviation within the perspective of other environmental impacts such as noise and air quality.

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# Appendices

## Appendix 1

## Workshop Agenda

# Workshop on the Impacts of Aviation on Climate Change

June 7-9, 2006

Boston, MA

June 7

| | |
|---|---|
| 8:00 - 9:00 a.m. | Registration and Breakfast* |
| 9:00 - 9:10 a.m. | Mohan Gupta – Welcome and logistics |
| 9:10 - 9:25 a.m. | Lourdes Maurice – Motivation and Vision for the Workshop: JPDO/NGATS/FAA Context |
| 9:25 - 9:40 a.m. | Malcolm Ko – The EIPT-S/M Panel charge to the workshop |
| 9:40 - 10:15 a.m. | Don Wuebbles – Science overview, workshop goals & objectives, expected outcomes and format |
| 10:15 - 10:30 a.m. | Break |
| 10:30 - Noon | Charge to subgroup leaders: Key questions by the subgroup leaders and general discussion<br>Don Wuebbles – Discussion leader |
| 10:30 - 11:00 a.m. | Anne Douglass – UT/LS and Chemistry Effects |
| 11:00 - 11:30 a.m. | Bernd Kärcher – Contrails and Cirrus Clouds |
| 11:30 - Noon | W.-C. Wang – Climate Impacts and Climate Metrics |
| Noon - 1:00 p.m. | Lunch |
| 1:00 - 3:00 p.m. | Parallel subgroup meetings<br>**Focus:** Review the present state of scientific knowledge and key underlying uncertainties |
| 3:00 - 3:15 p.m. | Break |
| 3:15 - 5:15 p.m. | Plenary session: Updates from each subgroup with discussions, (approx. 40 minutes each)<br>Don Wuebbles – Discussion leader |
| 5:15 - 5:30 p.m. | Don Wuebbles – Summary and charge for the next session |

<u>June 8</u>

| | |
|---|---|
| - 8:00 a.m. | Breakfast* |
| 8:00 - 10:00 a.m. | Parallel subgroup meetings<br>**Focus:** Explore the metrics of aviation emissions relative to other emissions. Discuss the aviation-related trade-off issues. Identify the gaps in aviation-related research needs. |
| 10:00 - 10:15 a.m. | Break |
| 10:15 - 11:45 a.m. | Plenary session: Updates from each subgroup with discussions, (approx. 30 minutes each)<br>Don Wuebbles – Discussion leader |
| 11:45 - Noon | Don Wuebbles – Summary and charge for the next session |
| Noon - 1:00 p.m. | Lunch |
| 1:00 - 3:00 p.m. | Parallel subgroup meetings<br>**Focus:** Identify short- and long-term priorities of aviation needs. Identify the ongoing and already planned future research programs and make recommendations on how to leverage upon them to meet aviation needs. |
| 3.00 - 3.15 p.m. | Break |
| 3:15 - 4:45 p.m. | Plenary session: Updates from each subgroup with discussions, (approx. 30 minutes each)<br>Don Wuebbles – Discussion leader |
| 4:45 - 5:00 p.m. | Don Wuebbles – Summary and charge for the next session |

<u>June 9</u>

| | |
|---|---|
| - 8.00 a.m. | Breakfast* |
| 8:00 - 10:00 a.m. | Parallel subgroup meetings<br>**Focus:** Develop final consensus on all issues. |
| 10:00 - 10:15 a.m. | Break |
| 10:15 - 12:30 p.m. | Plenary session: Updates from each subgroup with discussions, (approx. 45 minutes each)<br>Don Wuebbles – Discussion leader |
| 12:30 - 12:55 p.m. | Discussion on publication of the final report, involvement of attendees, review and overall schedule.<br>Don Wuebbles – Discussion leader |
| 12:55 - 1:00 p.m. | Concluding remarks – Mohan Gupta, Malcolm Ko, Don Wuebbles |
| 1:00 p.m. | Adjourn |

# Appendix 2

## Workshop Participants/Authors for Each Subgroup

**Workshop Chair:** Don Wuebbles, Univ. Illinois - Urbana Champaign

## Subgroup 1: Emissions in the UT/LS and Resulting Chemistry Effects

Anne Douglass, GSFC NASA : Subgroup Leader
Ivar Isaksen, Univ. Oslo, Norway
Daniel Jacob, Harvard Univ.
Jennifer Logan, Harvard Univ.
J. McConnell, York Univ., Canada
Dan Murphy, CSD/ESRL NOAA
Laura Pan, NCAR
Michael Prather, Univ. California-Irvine
Jose Rodriguez, GSFC NASA

### Subgroup 2: Contrails and Cirrus

B. Kärcher, IPA/DLR, Germany : Subgroup Leader
Steve Baughcum, Boeing Co.
Robert P. d'Entremont, AER, Inc.
Andy Dessler, Texas A & M Univ.
Paul Ginoux, GFDL NOAA
Andy Heymsfield, MMM/ESSL NCAR
Sanjiva Lele, Stanford Univ.
Rick Miake-Lye, Aerodyne Res. Inc.
Pat Minnis, LaRC NASA
Dave Mitchell, DRI
Karen Rosenlof, ESRL NOAA
Ken Sassen, Univ. Alaska
Azadeh Tabazadeh, Stanford Univ.
Ping Yang, Texas A & M Univ.
Fangqun Yu, SUNY-Albany

### Subgroup 3: Climate Impacts and Climate Metrics

Wei-Chyung Wang, SUNY-Albany : Subgroup Leader
Redina Herman, Western Illinois Univ.
Joyce Penner, Univ. Michigan
Robert Sausen, IPA/DLR, Germany
Keith Shine, Univ. Reading, UK
Ian Waitz, MIT
Don Wuebbles, Univ. Illinois - Urbana Champaign

# Appendix 3

## Other Attendees at the Workshop

Nathan Brown, FAA
Mohan Gupta, FAA
Curtis Holsclaw, FAA
Brian Kim, Volpe Center DOT
Malcolm Ko, LaRC NASA
Joel Levy, NOAA
Karen Marais, MIT
Lourdes Maurice, FAA
Chris Roof, Volpe Center DOT
Saleem Sattar, Transport Canada