A Report on the Way Forward

Based on the

Review of Research Gaps and Priorities

Sponsored by the Environmental Working Group of the U.S. NextGen Joint Planning and Development Office

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Preface

Projections indicate that the demand for aviation will increase by a factor of 2-3 over the next two decades. Although rising and volatile fuel prices are slowing demand at present, expansion of aviation is likely to continue and, as in the past, could outpace economic growth. To meet future aviation capacity needs, the United States is developing and implementing a dynamic, flexible and scalable Next Generation Air Transportation System (NextGen) that is safe, secure, efficient and environmentally sound. In the absence of mitigating actions increased aviation activities are expected to increase noise and emissions and, hence, associated environmental impacts. Consideration of current operational trends and environmental impacts indicates that future environmental impacts will be the principal constraint on the capacity and flexibility of NextGen unless these impacts are effectively managed and mitigated in a timely manner. The Environmental Working Group (EWG) of the NextGen Joint Planning and Development Office (JPDO) is responsible for the development of the NextGen environmental strategy with the objective of environmental protection that allows sustained aviation growth. The environmental strategy is at the heart of NextGen.

One of the stated NextGen environmental goals is to limit or reduce the impacts of aviation emissions on global climate. A report to the U.S. Congress in 2004 on 'Aviation and the Environment" prepared by the FAA-NASA-Transport Canada sponsored Center of Excellence PARTNER (the Partnership for AiR Transportation Noise and Emissions Reduction) clearly stated that among the environmental impacts of aviation, the greatest uncertainty and contention is associated with climate impacts. There is a need to better characterize non-CO_2 aviation climate impacts and their associated uncertainties in order to formulate realistic goals and actions to mitigate these impacts. Mitigation actions will likely be combinations of technological innovation (inclusive of engine, aircraft and fuel), operational and market-based measures, and regulatory intervention. No single action will likely achieve all targeted goals. Mitigation options generally come with tradeoffs and interdependencies that must be properly understood before optimally balanced cost-beneficial options can be designed and implemented.

The Intergovernmental Panel on Climate Change (IPCC) 1999 report on 'Aviation and the Global Atmosphere' and the recent IPCC Fourth Assessment Report 'Climate Change 2007' both stated that the levels of scientific understanding for non-CO_2 climate impacts of aviation range from medium to very low. In response, the Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA) jointly sponsored a workshop on the 'Impacts of Aviation on Climate Change' in 2006 under the auspices of NextGen/JPDO EWG. This workshop concluded that there is a need for focused research efforts in the U.S. to address uncertainties and gaps in our understanding of impacts of aviation on climate. Similar recommendations for the research efforts in the international community were suggested during the International Civil Aviation Organization (ICAO)-sponsored international workshop on 'Assessing current scientific knowledge, uncertainty and gaps quantifying climate change, noise and air quality aviation impacts' in 2007.

Under the auspices of the EWG and as a part of its five-pillar plan to meet NextGen environmental goals, the FAA has developed the Aviation Climate Change Research Initiative (ACCRI) with participation from NASA, the National Oceanic and Atmospheric Administration

(NOAA) and the Environmental Protection Agency (EPA). These federal agencies are also key contributors to the U.S. Climate Change Science Program (CCSP). The main objective of ACCRI is to identify and address key scientific gaps and uncertainties regarding climate impacts while providing timely scientific input to inform optimum mitigation actions and policies. The ACCRI approach to meet this objective is to support aviation-specific climate change research that is policy-relevant and solution-focused and to coordinate and link its research needs and activities with related national and international climate change research efforts.

To develop its research plan, ACCRI openly solicited and supported national and international science teams to develop 8 subject-specific white papers (SSWPs) dealing with various scientific aspects of the climate impacts of aviation as stated in Appendix A. The SSWPs were designed to provide a review of the latest state of knowledge, uncertainties, analyses capabilities, and gaps as well as to develop key research recommendations for goals that can be achieved within the short- and long-term time horizons consistent with the EWG needs. The SSWPs also provided recommendations on how the current state of science and analyses capabilities can be best used today to assess the current and future climate impacts of aviation.

To solicit inputs from the scientific and stakeholder communities, ACCRI convened an international science meeting February 25-27, 2008. More than 90 experts from various disciplines attended the meeting. This report summarizes the findings and recommendations of this meeting. In particular, the recommended way forward presented in Chapter 6 of this report is expected to be implemented as part of the ACCRI program.

We gratefully acknowledge support from the FAA Office of Environment and Energy that made it possible to initiate the ACCRI program and to achieve the program's goals to date. We thank all the participants who attended the meeting and their organizations for supporting their participation. We thank the session co-chairs who also served as the coordinating authors for their respective session chapters, and Guy Brasseur of the National Center for Atmospheric Research (NCAR) who served as the Lead Coordinating Author. We thank Clay Reherman of the U.S. DOT Volpe Center for helping us through the SSWP solicitation process and for organizing the ACCRI meeting. Finally, and not least, we thank Barb Petruzzi, Executive Assistant to Guy Brasseur, for her tireless help in communicating with authors and reviewers throughout the report preparation and review period, and for compiling and editing all the report chapters.

We sincerely hope that the research plan developed through this inaugural ACCRI meeting will help us advance the scientific basis that will ultimately inform the decisions to ensure that the NextGen climate impact challenges are tackled the right way and its ambitious environmental goals are met.

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Executive Summary

Environmental protection is at the heart of the U. S. Next Generation Air Transportation System that is being implemented to meet projected growth in aviation. A well developed scientific basis of the climate impacts of aviation emissions constrained by reduced uncertainties is needed to inform the mitigation actions so that a balance can be achieved between the economic as well as transport benefits of aviation and its environmental impacts. Under the auspices of the Environmental Working Group (EWG) of the NextGen Joint Planning and Development Office (JPDO) and as a part of its five-pillar plan to meet NextGen environmental goals, the FAA has developed the Aviation Climate Change Research Initiative (ACCRI) with participation from NASA, NOAA and EPA. The main objective of ACCRI is to identify and address key scientific gaps and uncertainties while providing timely scientific input to inform optimum mitigation actions and policies. The ACCRI approach to meet this objective is to support aviation-specific climate change research that is policy-relevant and solution-focused, and to coordinate and link its research needs and activities with related national and international climate change research efforts. This summary outlines the key findings and recommendations for research priorities and the way forward that were developed during the ACCRI science meeting that will help to shape future directions for the ACCRI program.

While operating and cruising the skies, aircraft engines release considerable amounts of gases and particles, which are diluted in their wake and progressively mix with the surrounding air. The largest fraction of the aircraft emissions takes place in the flight corridors throughout the upper troposphere and lowermost stratosphere (8-13 km altitude). The main aircraft emissions include carbon dioxide (CO_2), water vapor (H_2O), nitrogen oxides (NO_x), sulfur oxides (SO_x), hydrocarbons (HC) and soot. At present, aviation accounts for approximately 2% of the worldwide CO_2 emissions and 12% of the CO_2 from all transportation sources.

The release of nitrogen oxides contributes to enhanced photochemical production and loss of tropospheric ozone and methane (CH_4) respectively. In addition, the water vapor released by engines triggers the formation of condensation trails (also called contrails) in sufficiently cold air masses. Contrails may persist for hours and increase cirrus cloudiness in ice-supersaturated air masses.

Progress requires that an appropriate strategy be developed to reduce scientific uncertainties regarding chemical, dynamical, microphysical and radiative processes in the upper atmosphere and lower stratosphere region (UTLS). Among the major questions to be addressed are (1) the accurate measurement of relative humidity in the UTLS, (2) the generation of cirrus clouds by persistent contrails (contrail cirrus) or modifications of existing cirrus, and the role of soot in upper tropospheric ice formation, (3) the exact nature of the chemical cycles involving NO_x, HO_x, and halogens in the UTLS and the scavenging of chemical compounds by ice particles from these atmospheric layers, including the role of heterogeneous chemistry (aerosol and ice phase).

1. Contrails and Induced Cirrus

Contrails form at temperatures of about -40^{o}C and below, depending on altitude, ambient humidity, fuel properties, and engine propulsion efficiency. Initially, the aircraft's water vapor is rapidly converted to ice as ice crystals are nucleated and environmental humidity is taken up. Emissions of soot particles composed mainly of black carbon, along with sulfur compounds influence the number of ice particles formed and may impact the properties of contrails and contrail-induced cirrus clouds., In addition, particle emissions may change the formation and properties of cirrus clouds regardless of emitted inside or outside contrails.

Whether contrails shrink and disappear or develop into contrail cirrus is dependent upon the environmental relative humidity with respect to ice. In an ice supersaturated atmosphere, contrails persist. Contrail crystals develop and extract excess environmental water vapor. Optical and microphysical properties of contrails differ from those of natural cirrus, but with age, they may become similar. The transition of line-shaped contrails into cirrus-like clouds, however, is not well understood nor well represented in climate models.

Integrated usage of satellite remote sensing observations, from polar-orbiting and geostationary platforms for example in correlation with traffic data, can enhance the accuracy of contrail detection, complement studies of the aerosol indirect effect and of contrail cirrus, provide necessary input parameters to radiative transfer models, and extend the spatial coverage of contrail observations to the global scale. But this approach still needs improvement in increasing geographical and temporal coverage and in resolving difficulties in detecting line shaped contrails.

Current climate model estimates of contrail radiative forcing are limited to line-shaped contrails. The parameterizations of contrail radiative properties, which are used in radiative transfer schemes embedded in climate models, are essentially proxies developed on the basis of observations and simulations carried out for natural cirrus clouds. Contrails generally heat the atmosphere-earth system on average, especially in high traffic density areas. The most recent model investigation suggests that the radiative forcing for the year 1992 is 3.5 mWm^{-2} for a visible (optical depth>0.02) contrail coverage of 0.06% and for a total contrail coverage of 0.1%. The best estimate of global radiative forcing due to line shaped contrails for the year 2000, which was inferred from two independent model integrations, is 10 mWm^{-2}, but with a large uncertainty. The amount of aviation induced cirrus has been estimated from cirrus trend studies to be of order 0.25% globally in the year 2000. The radiative forcing of aviation induced cirrus is not well known. Its value may be far larger than that of line-shaped contrails.

2. Chemistry and Transport Processes in the Upper Troposphere and Lower Stratosphere

Quantitative understanding of coupled NO_x ($NO+NO_2$) and HO_x (OH and HO_2) chemistry is essential for quantifying the ozone budget in the upper troposphere and lower stratosphere (UTLS), and the impact of NOx aircraft emissions on ozone. Serious discrepancies remain, however, between observed and calculated concentrations of chemical species particularly when NO_x levels are high. For example, under these conditions, the measured concentrations of HO_2 are considerably larger than those calculated by constrained photochemical models.

3. Recommendations for Future Research

General recommendations serving all aircraft related research efforts: The global distribution of ice supersaturation should be further evaluated. More and better observations of ice supersaturated areas with high accuracy, and high vertical and horizontal resolution are urgently needed. In the *near-term*, the global distribution of ice supersaturation should be further evaluated using radiosonde, airborne and satellite-based data on upper tropospheric relative humidity.

Microphysics of Contrails and Induced Cirrus: In order to better characterize the effects of contrails on climate, a strategy towards the development of better observational datasets is needed. There is a need to expand the current database of in-situ cirrus microphysical observations with recently developed instruments and methods that correct or filter for instrument errors. Laboratory studies of exhaust soot and targeted field studies focusing on soot effects on cirrus are needed. A fresh analysis of past observations in contrail cirrus should be performed. Better observational datasets for contrails should be produced

Optical properties of Contrails and Induced Cirrus: The development of contrail-cirrus clouds should be investigated on the basis of cloud resolving models with supersaturation capability while exploring the use of sensors on commercial aircraft to improve water-vapor/contrail relationships. Aerosol indirect effect on ice clouds should be studied on the basis of in-situ and satellite data, and the extent and impacts of aircraft-aerosol induced cirrus should be estimated.
In the *near-term*, it is recommended to (1) develop datasets representing contrail particle single-scattering properties from existing light scattering models, which will use realistic shapes and sizes of ice crystals observed in these clouds, (2) parameterize the radiative properties of contrails and contrail-cirrus for use in global and regional climate models, (3) accurately determine contrail coverage, optical properties, and radiative forcing from a variety of satellite datasets, and (4) carry out a small-to-medium scale contrail/contrail-cirrus field experiment in an air traffic corridor to support optical property and radiative forcing calculations and remote sensing validation.

Modeling on Contrail's Impact on Climate: The global radiative forcing due to contrails and contrail cirrus can only be evaluated using Global Climate Models. Up to now only one approach estimating the climate effect of line shaped contrails has been used. Sensitivity experiments estimating the climate impact of line-shaped contrails should be conducted. A process based parameterization is urgently needed that would enable a more realistic simulation of line shaped contrails and for the first time the simulation of contrail cirrus. General model improvements are needed to ensure that climate predictions are based on increasingly sound foundations. Large-scale models should incorporate more accurate representations of (1) ice supersaturation and cirrus development, (2) ice cloud microphysics, and (3) cirrus and contrail optical properties. Independent studies and sensitivity experiments estimating the climate impact of line-shaped contrails should be performed. Global climate models with process based cirrus coverage and ice microphysical schemes should be used to study the predictive capabilities and radiative forcing effects of contrails and contrail-cirrus.

Chemical Composition of the Upper Troposphere and Lower Stratosphere: Further analysis of space observations will increase our knowledge of the current background atmospheric composition and to help quantify ozone production and loss that can be ascribed directly to aircraft emissions. The discrepancies that remain between modeled and observed HO_x species at high NO_2 values in the region where subsonic aircraft emissions represent the most significant perturbation to chemistry, need to be resolved. Improved parameterizations of deep convection and lightning production of NO_x need to be developed and verified in multi-scale models, in order to better constrain the relative contributions of different emissions to the NO_y budget in the UTLS. Improved multi-scale models are needed to investigate the corridors aspect of the aircraft emissions and the transition (e.g., dispersion and transport) to regional scale climate impacts. Evidence is mounting that abundances of inorganic bromine in the UT are significantly larger than previously believed, presumably due to efficient transport of short-lived bromine sources to the UT. The balance between ozone production by high NO_x and ozone destruction by halogen species needs to be studied with high-resolution measurements and models. Finally, the changes that could result in the future atmosphere under a different climate regime, and specifically the impact of aviation under these conditions should be assessed.

In the *near-term*, chemical transport models and chemistry-climate models should address selected issues related to chemical processes in the UTLS assess a set of scenarios describing the impact of aircraft emissions on atmospheric ozone. An inter-comparison exercise of the participating models should be conducted. ACCRI should support important activities (e.g., field campaigns) initiated by other agencies that would help addressing issues relevant to ACCRI.

Climate Impact Metrics for Aviation: Climate change mitigation policies generally require a way of quantifying the present and future climate impact of various anthropogenic activities as well as the expected effects of mitigation strategies. To inform these decisions simple analytical tools - or metrics - can be used to quantify the ultimate climate impact of specific activities, such as aviation emissions. Metrics can also be useful to guide decisions concerning future aircraft design and operations to minimize the climate impact. The use of the radiative forcing metric has already been of substantial value in evaluating the climate impact of aviation emissions and operations and in placing the contributions of aviation in a quantitative framework with global emissions from other sectors. However, the limitations of radiative forcing as a metric have been widely acknowledged and it should not by itself be used to evaluate emissions. It is therefore recommended at present to use only global emissions-based metrics when evaluating the effect of global emissions on global response, including continuing to use and evaluate Global Warming Potential (GWP) and Global Temperature Potential (GTP) metrics. Comprehensive global climate models should be further developed since all useful metrics ultimately depend on such models. Finally, it would be advisable to adapt common metrics across sectors, and to develop new well-evaluated socioeconomic metrics.

4. **The Way Forward**

With a clear programmatic vision and a plan for sustained research, the new aviation/environment program (ACCRI) should be able to bring in *pro bono* (or at minimal cost) the aircraft and ground-based measurement community, the satellite analysis community, the chemistry and climate modeling communities, along with the international research community to participate in specific projects. The program needs to position itself to benefit from the atmospheric chemistry and climate research programs funded by other domestic and international agencies, while providing dedicated support to aviation specific analyses and initiating activities. ACCRI needs to be a multi-year priority driven research program with responsibility to deliver realistic outcomes scheduled to match NextGen decision-making as well as international scientific evaluations and assessment of climate and ozone depletion (IPCC, WMO/UNEP).

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1.
Introduction

Today, approximately 23,000 aircraft operated by more than 2,000 airlines carry more than 2.2 billion passengers annually, and serve about 3,750 airports in the world. The demand in air transport is primarily driven by the economic growth. In fact, trends indicate that the demand in aviation has generally outpaced the economic growth over the past 4 decades and is expected to continue to do so over the next two decades (ICAO, 2007). At present, aircraft emissions contribute about 3% to the global climate change (Fig. 1.1). However, aviation emissions and their contributions to climate change are likely to increase in future with the projected annual increase in global demand of 4.6% during 2005-2025 (ICAO, 2007). The change in emissions and resulting climate impacts due to this projected growth in aviation will be governed by the mix of future aircraft fleet as well as implementation of engine and fuel technological advances, efficient operational procedures, market based options and regulatory interventions.

There is a need to maintain an appropriate balance between growth of aviation, economic benefits and environmental consequences. Towards meeting this objective, the U.S. is transforming its aviation system in the form of dynamic, flexible and scalable Next Generation Air Transportation System (NextGen) to meet future aviation demand while being responsive to continuously evolving social, economic, political and technological changes (Joint Planning and Development office (JPDO)/NextGen, 2008). The environmental strategy is at the heart of NextGen with an objective of environmental protection that would allow sustained aviation growth. On the climate front, the NextGen environmental goal is to limit or reduce impact of aviation greenhouse gas emissions.

While operating and cruising the skies, aircraft engines release considerable amounts of gases and particles, which are diluted in their wake and progressively mix with the surrounding air. The largest fraction of the aircraft emissions takes place in the flight corridors throughout the upper troposphere and lowermost stratosphere (8-13 km altitude). A relatively smaller amount of emissions take place in the vicinity of airports and contribute to local air pollution. To some extent, cruise altitude aircraft emissions could also potentially affect the surface air quality. The main aircraft emissions include carbon dioxide (CO_2), water vapor (H_2O), nitrogen oxides (NO_x), sulfur oxides (SO_x), hydrocarbons (HC) and soot. At present, aviation accounts for approximately 2% of the worldwide CO_2 emissions and 12% of the CO_2 from all transportation sources. This relative contribution from aviation to CO_2 emissions is subject to revision based on how robustly emissions from other transportation sources, particularly marine transport, are quantified. The release of nitrogen oxides contributes to enhanced photochemical production and loss of tropospheric ozone and methane (CH_4) respectively. In addition, the water vapor released by engines triggers the formation of condensation trails (also called contrails) in sufficiently cold air masses. Contrails may persist for hours and increase cirrus cloudiness in ice-supersaturated air masses.

Figure 1.1 (lower panel) shows the radiative forcing associated with global aviation. Excluding the effects of cirrus cloud changes, the aviation total is of the order of 50 mWm^{-2}, about 3% of the total radiative forcing resulting from all human drivers (upper panels). Including cirrus changes, the range of uncertainty reaches from 30 – 130 mWm^{-2}, or 2-8 %. The diagram in Figure 1.1 (lower panel) shows different estimates of the radiative forcing produced by aviation representative of year 2005. Besides the direct greenhouse effect associated with CO_2 emissions, an additional positive forcing of equivalent magnitude is produced by NO_x-generated ozone, with a slightly smaller in magnitude negative forcing due to the reduction in the methane concentration. The direct radiative effects resulting from the engine emissions of water, sulfur compounds and soot are estimated to be small. For all these effects, the level of scientific understanding is only low to medium. The quantification of the direct climate effect of line-shaped contrails has improved in recent years, but large uncertainties remain. Even less understood is the role of cirrus clouds that are produced or modified by persistent contrails under certain atmospheric conditions. Another uncertainty is the potentially important role played by aircraft-generated soot particles, which could act as ice nuclei in the vicinity of air corridors. Therefore, it is required to better understand the microphysical and radiative effects associated with cirrus clouds (i.e., ice particles) in the upper troposphere.

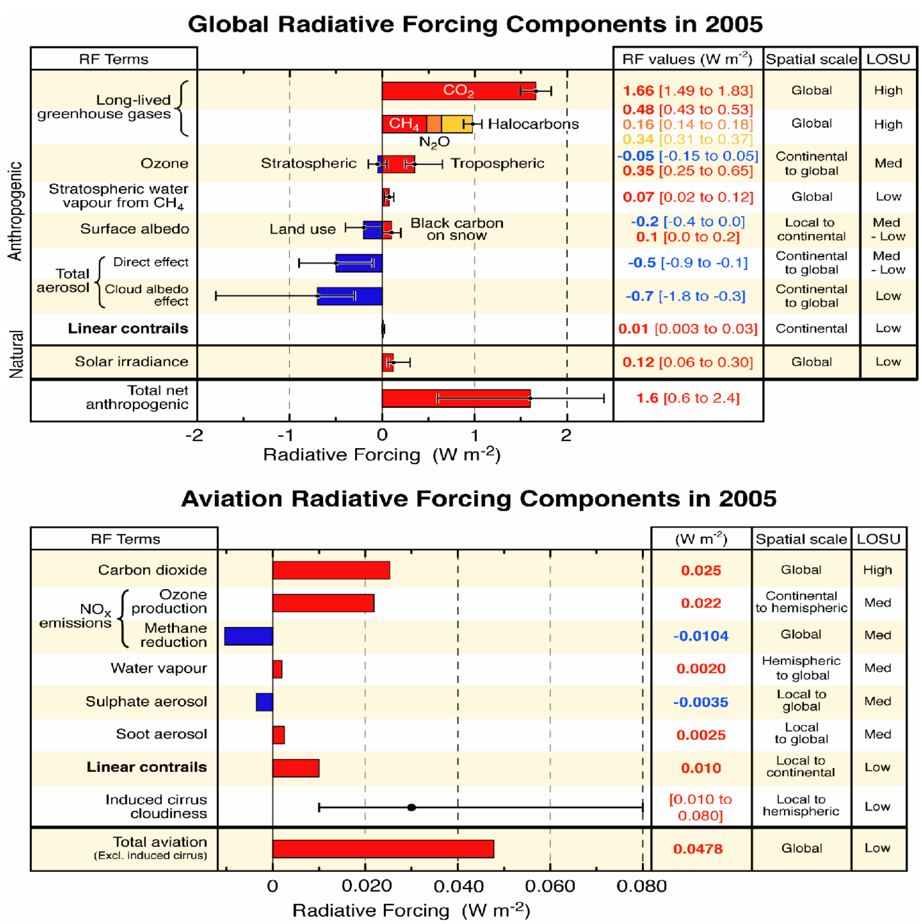

Figure 1.1: Top panel) Global mean radiative forcing (RF) components for the period 1750 to 2005 from Forster *et al.* (2007). The components implicitly include all aviation emissions and effects except linear contrails, which are shown as a separate term. (Bottom panel) Global mean RF components for aviation emissions and effects as evaluated for 2005, based on Sausen *et al.* (2005). Note that the linear contrail components in the two panels are equal. In each panel the columns display the RF spatial scales and the levels of scientific understanding. Note that the total aviation induced radiative forcing does not include radiative forcing due to induced cirrus cloudiness due to low level of scientific confidence.

The assessment of the effects of aviation on climate requires specialized models that accurately treat the chemical and microphysical processes controlling the perturbation caused by aircraft, as well as related atmospheric processes that govern the evolution of climate (impact of greenhouse gases and aerosols, atmospheric dynamics, water cycle). These processes need to be accurately represented and validated. Because many effects occur on spatial scales that are unresolved by climate models (e.g., cirrus cloud changes, plume processing of emissions), such assessments require the development and use of suitable parameterization schemes that are consistent with the model processes acting on the resolved scales. Numerical simulations are then performed on the basis of scenarios for present and future aircraft fleet emissions. Unfortunately, these model projections are still subject to significant errors, which reflect in part, a lack of understanding of certain fundamental processes as well as those that specifically govern the interaction of aircraft exhaust with the atmosphere on range of spatial and temporal scales. Therefore to understand and predict aviation impacts, process studies must be conducted to improve our knowledge of the mechanisms that affect the dynamics, chemistry and microphysics of the troposphere and lower stratosphere. Model improvement requires that information provided by observational datasets be analyzed and understood. The model projections can serve as the basis to assess environmental impacts and to make sound policy decisions. The different elements that contribute to a comprehensive environmental assessment of the impact of aviation on climate are shown in Figure 1.2. Improvements in the model predictions and more generally in the assessment of aircraft impacts on climate require that important, yet insufficiently understood processes, first be investigated.

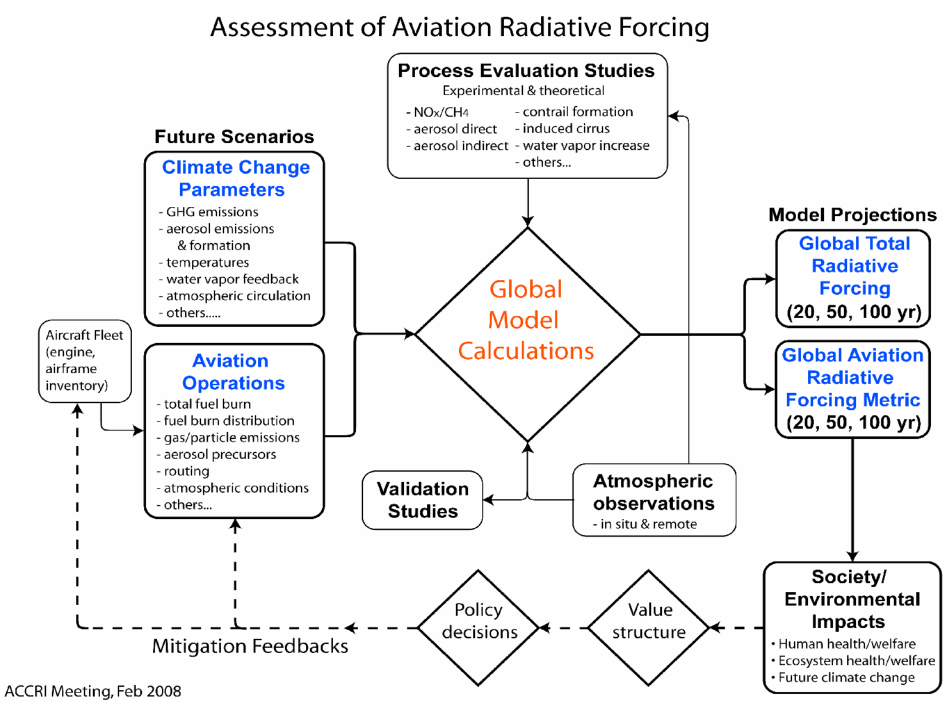

Figure 1.2. Schematic description of the different elements that will lead to an integrated assessment of the effects of aviation on climate. (D. Fahey, personal communication)

Almost ten years ago, the Intergovernmental Panel for Climate Change (IPCC) conducted a detailed assessment of the impact of aviation on the global atmosphere (http://www.ipcc.ch). Under the auspices of NextGen/JPDO Environmental Working Group, an international workshop held in 2006 on the impact of aviation on climate change reviewed the state of the science, highlighted uncertainties and provided recommendations on the research needs (http://www.faa.gov/airports_airtraffic/environmental_issues/media/Aviationclimworkshop-final.pdf). Following the recommendations of this workshop, Aviation Climate Change Research Initiative (ACCRI) was developed with an objective to improve the state of scientific knowledge and address key knowledge gaps while making the best practical use of available science and modeling capability to quantify the climate impacts of aviation. The major steps of ACCRI are sequential, with prior steps setting direction and framing expectations for subsequent steps. Under Step I, ACCRI provided support to develop subject-specific whitepapers (SSWPs) on key issues related to climate impacts of aviation as listed under Appendix I. Under Step II, ACCRI convened a science meeting in February, 2008 which was attended by about 100 domestic and international experts from academia, industry and research agencies. The purpose of this ACCRI meeting was to discuss the findings of SSWPs at the broader scientific forum and to develop recommendations on the key research priorities and the way forward for the next ACCRI steps.

The current report presents an overview of key findings and direction for the way forward developed during the science meeting proceedings that could drive the ACCRI program. The different aspects that will be addressed in this document include (1) Contrail and induced cirrus: Formation, Microphysics and Lifecycle; (2) Contrail and induced cirrus: Optics and Radiation; (3) Chemistry and Transport processes in the upper troposphere and lower stratosphere; and (4) Climate Impacts and Metrics. Each Section will provide a brief overview of our current understanding, highlight some key research needs, and make specific recommendations for short-, intermediate and long-term research activities that would rapidly enhance our ability to reduce uncertainties and answer key questions by the government and the aeronautical industry.

Progress requires that an appropriate strategy be developed to reduce scientific uncertainties regarding chemical, dynamical, microphysical and radiative processes in the upper atmosphere and lower stratosphere region (UTLS). Among the major questions to be addressed are (1) the accurate measurement of relative humidity in the UTLS, (2) the generation of cirrus clouds by persistent contrails (contrail cirrus) or modifications of existing cirrus, and the role of soot in upper tropospheric ice formation, (3) the exact nature of the chemical cycles involving NO_x, HO_x, and halogens in the UTLS and the scavenging of chemical compounds by ice particles from these atmospheric layers, including the role of heterogeneous chemistry (aerosol and ice phase). An important first step is to develop a global climatology (including variability and trends) of line-shaped contrails detectable with remote sensing methods with information on their associated optical properties. A more realistic representation of contrails/cirrus needs to be implemented in the most advanced climate models.

Recommendations for a research program that will address key questions posed by industry and government will be outlined in the following Sections. In the long-term, the science will greatly benefit from new and systematic observations of chemical, physical, microphysical, and radiative processes in the UTLS, and specifically experimental studies that focus on the development and fate of aircraft plumes in flight corridors. Field campaigns that address such issues in the UTLS are planned by different institutions in the world, and could benefit the ACCRI Initiative. The development of regional/global climate models that account for the radiative effects of contrail cirrus and assess the indirect radiative effects of NO_x released by aircraft engines is another priority for the future. In the short-term, useful information on contrail coverage and optical properties could be obtained from a detailed analysis of existing satellite observations. The discrepancies in UTLS water vapor measurements could be resolved or at least considerably reduced. New parameterizations for contrail and cirrus optical properties could be developed and included in climate models. A reliable model prediction of ice super-saturation could be achieved in order to better determine the regions in which contrails form and persist in different atmospheric layers at any time. The chemical cycles in the UTLS could be more accurately quantified and the differences between observed and calculated concentrations of fast-reacting species like OH and HO_2 could be resolved; the effects of aerosol and cloud-related heterogeneous processes could be better quantified.

Aviation's impacts on climate change and ozone depletion occur through a range of atmospheric perturbations that are often different from the primary anthropogenic driving forces, viz, greenhouse gases and halogenated gases, respectively. In addition to the major questions listed above, it is therefore also important to assess whether the standard metrics now used in climate change (RF, GWP, GTP) or ozone depletion (equivalent chlorine loading, ozone hole recovery time) can be fairly used to compare the impacts of aviation among its various emission types, with other transportation sectors and indeed other human activities. There is clearly a need to be able to differentiate between the various options for future aviation scenarios using a range of metrics.

Finally, it should be realized that such an effort requires that the science community organize itself through a multiple agency cooperative effort, adequate budgets, international cooperation, and a strong partnership between the scientific community, industry and government.

2.
Contrails and Induced Cirrus Microphysics and Climate Impact

2.1. Current Understanding and Issues

Thermodynamics is the controlling factor for contrail formation, whereas the physics and chemistry of the emitted particles is secondary. Theory indicates that for jet aircraft flight altitudes, contrails form at temperatures of about -40°C and below. The thermodynamic conditions for contrail formation can be incorporated in large-scale models. Initially, the aircraft's water vapor is rapidly converted to ice as ice crystals are nucleated and environmental humidity is taken up. These ice crystals are quickly captured and transported downward by the vortex pair generated by the aircraft.

Whether contrails shrink and disappear or develop into contrail cirrus is dependent upon the environmental relative humidity with respect to ice. In an ice supersaturated atmosphere, contrails persist. Contrail crystals develop and extract excess environmental water vapor (Fig. 2.1). Optical and microphysical properties of contrails differ from those of natural cirrus, but with age, they may become similar. The transition of line-shaped contrails into cirrus-like clouds, however, is not well understood nor well represented in climate models. These models do not commonly incorporate detailed ice cloud microphysics or resolve supersaturation.

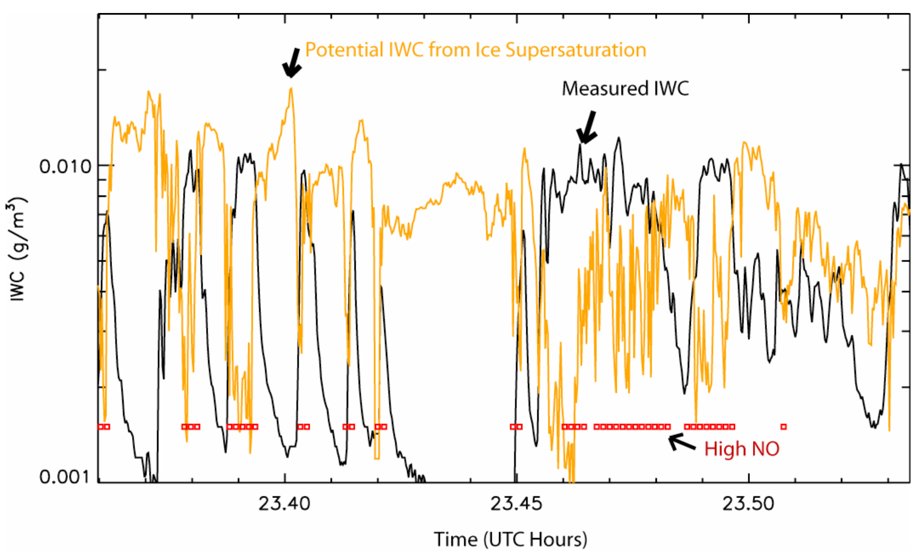

Figure 2.1. Ice water content (IWC) measured and estimated from the ambient ice supersaturation during sampling of a contrail and ambient environment from the NASA SUCCESS field campaign. The dark line is the ice water content measured by a counterflow virtual impactor probe. These are contrail crystals: they are associated with high NO (red symbols in lower part of figure). Outside of high NO regions, crystals are virtually nonexistent but ice supersaturations are high. The orange line, representing the potential IWC, which is high outside of the high NO regions, is the difference between the measured (ambient) air vapor density and that for ice saturation at the ambient temperature. It represents the IWC that would have been squeezed out by contrail crystals had they been produced in those regions.

To date, only a few field campaigns, including SUCCESS (Toon and Miake-Lye 1998) and SULFUR 1-7 (Schumann et al 2002), have been devoted to *in situ* measurements of the microphysical and chemical properties of contrails and contrail-cirrus clouds. As a result, the current understanding of contrail properties, as well as the aerosol indirect effects associated with aircraft emissions, is still extremely limited. The available observations show that water saturation must be reached in the exhaust plume in order to form a visible contrail, which, given the cold temperatures, imply that homogeneous freezing of water condensed on soot particles is a dominant process leading to ice formation. Moderate heterogeneous ice nucleation of fresh soot emissions cannot be ruled out. Contrail ice number concentrations are initially of order 10^4-10^5 cm^{-3} and sizes of order 1 μm. During the vortex phase, descent of the contrail decreases the concentrations by several orders of magnitude, to the order of 10-100 cm^{-3}. Mean sizes increase up to 10 μm. Descent of the contrail decreases the ice water content and the smaller ice particles may sublimate if the plume humidity decreases below ice saturation. Continued evolution of the size distribution depends upon the ambient relative humidity. Habits of the largest contrail ice crystals in ice supersaturation environments are similar to those for similar natural cirrus—bullet rosettes; those of the majority of smaller ice crystals is less clear due to the difficulty to measure shapes of particles below some tens of μm. Measurements of particle size distributions in aged contrails and contrail cirrus when crystals of several hundred microns and above are present are now under scrutiny. There is a growing consensus that small ice crystals can be produced by shattering of crystals on the microphysical probes' inlets. It is therefore now difficult to differentiate the particle size distributions (PSD) in cases where large crystals exist in contrails, and that the time and transition toward natural cirrus properties is not well defined based on current data.

Ice crystals in contrails and contrail-induced cirrus are bullet rosettes and irregular shapes (e.g., Gayet *et al.* 1996). One study found that in young contrails, the ice crystals were quasi-spherical droxtals with sizes ranging from 1 to 5 μm (Strauss 1994). Figure 2.2 shows examples of scanning microscope images of ice crystals in contrails (Goodman *et al.* 1998), including hexagonal plates, columns, and triangular plates. Using microphotographs taken from airborne particle sampling in a young contrail (aged 3-4 min) at altitudes between 8 and 9 km and temperatures between –49°C and –53°C, Weickmann (1945, 1949) found a few large (~100 μm) hollow prisms typical of highly ice-supersaturated conditions, but noted that the hollow prisms are "under no circumstances to be considered as typical for contrails." Sussmann (1997) presented photographs of a 120^o parhelion and a 22^o parhelion within persistent contrails. These optical phenomena could be accounted for by 0.1 to 1% of the population with hexagonal plate-like shapes, with sizes somewhere in the range of 100 microns to several mm (Bréon and Dubrulle, 2004). Heymsfield *et al.* (1998) observed the development of ice crystals from contrail formation through to their fallout from contrail cirrus. Crystals falling out of the contrail cirrus were bullet rosettes.

Soot particles emitted by aircraft jet engines may perturb cirrus properties and alter cirrus coverage, regardless of whether a contrail forms. Aircraft engine exhaust may be a source of enhanced aerosol particle number concentrations in cirrus formation regions. Ice formation by black carbon particles and competition with natural ice nuclei remains poorly understood

(Kärcher *et al.*, 2007). Until this issue is resolved, model studies addressing soot-induced cirrus can only provide preliminary information on the effects of soot on cirrus properties.

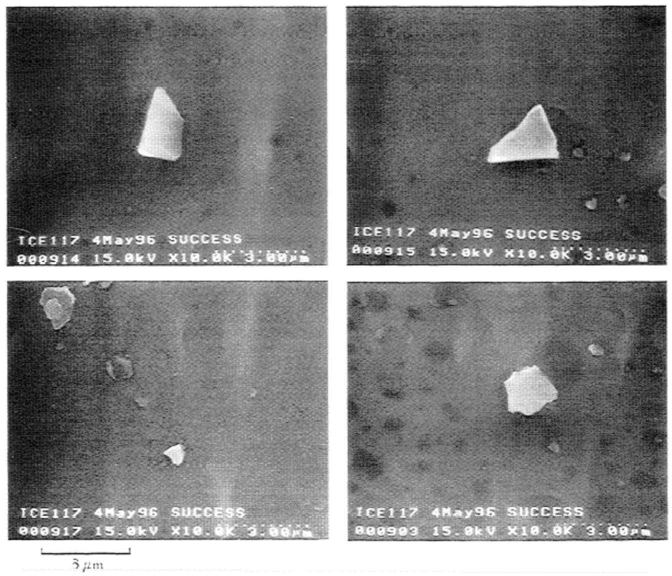

Figure 2.2. Scanning microscope images of small crystals as captured with an ice replicator (Goodman *et al.*, 1998).

Current climate model estimates of contrail radiative forcing are limited to line-shaped contrails. The parameterizations of contrail radiative properties, which are used in radiative transfer schemes embedded in climate models, are essentially proxies developed on the basis of observations and simulations carried out for natural cirrus clouds. Contrails generally heat the atmosphere-earth system on average, especially in high traffic density areas. A few global model studies have inferred coverage and global radiative forcing due to line-shaped contrails using a simple parameterization for coverage and ice water content that is based on scaling to regional satellite observations. One model estimated the ice water content in contrails. From these studies it is estimated that global radiative forcing due to line shaped contrails for the year 2000 is 10 mWm^{-2} (Sausen *et al.*, 2005). This value is scaled from simulations of Marquart *et al.* (2003) and Myhre and Stordal (2001) for the year 1992. The former study estimated radiative forcing to be 3.5 mWm^{-2} (fig. 2.4) for a visible (optical depth>0.02) contrail coverage of 0.06% (fig. 2.3) and a total contrail coverage of 0.1%. These estimates cannot be simply scaled to future air traffic scenarios since a significant part of the increase in air traffic will happen outside the currently most frequented routes, among other issues. Current studies concentrate on the mid latitudes. In addition, contrail cover may scale with either flight distance or fuel consumption or other aviation parameters.

There exists no accepted best estimate of global radiative forcing due to contrail cirrus (apart from line- shaped contrails) and aircraft soot effects on cirrus, though estimates of changes to cirrus clouds exist (Stordal *et al.*, 2005). Validation of simulated contrail coverage requires improved quantification of detection thresholds in the observations. Airborne measurements of contrails suffer from the poor characterization of the habit of small ice crystals typical for contrails. Parameterizations of contrail radiative forcing use little of the existing in situ measurements of young contrails.

2.2. Research Needs (Long-Term Objectives)

For a realistic estimation of the climate effect of contrail formation, persistence and evolution, the microphysical and optical properties of contrail cirrus need to be well represented by regional and global models. Chapter 3 discusses optics and radiation aspects of contrails and contrail cirrus in more detail.

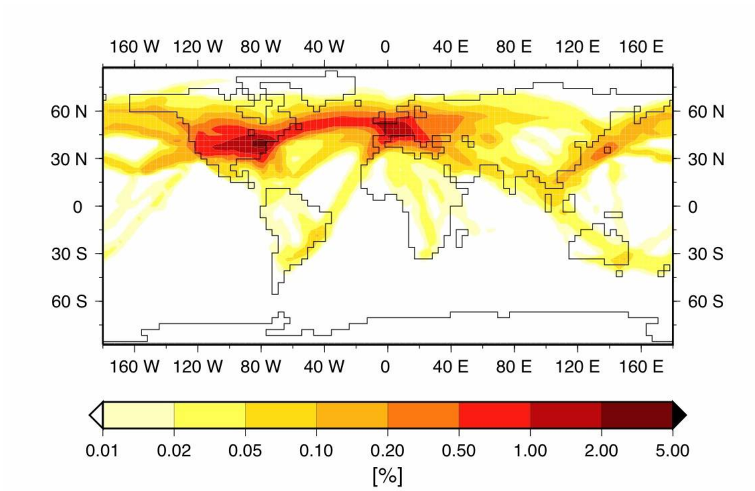

Figure 2.3. Annually averaged coverage of line shaped contrails with an optical depth exceeding 0.02 (%) for 1992 aviation as simulated by the ECHAM4 climate model. The corresponding annual global mean is 0.06 % (Marquart *et al.*, 2003).

2.2.1. Microphysics

Reliable measurements of contrail and cirrus microphysical properties and their parametric representations are needed for radiative flux divergence estimates and modeling. Small particles below 50 µm diameter, as prevalent in contrail cirrus, dominate light scattering behavior, but the concentration of larger crystals increases over the contrail cirrus life time. *There is a need to expand the current database of in-situ cirrus microphysical observations with recently developed instruments and methods that correct or filter for instrument errors (ice particle shattering).*

Cirrus changes due to the emission of soot particles from aircraft jet engines are uncertain because the ice-nucleation behavior of aging soot emissions is not known. Progress in this area requires *laboratory studies of exhaust soot and targeted field studies focusing on soot effects on cirrus*.

2.2.2. Contrail Radiative Forcing

For model validation, *more and better observations of ice supersaturated areas with high accuracy, and high vertical and horizontal resolution are urgently needed*. Regional modeling may help in this respect. Regular and accurate humidity measurements from commercial aircraft in cruise and humidity corrected data from radiosondes would help to improve the climatology and forecast of ice supersaturation.

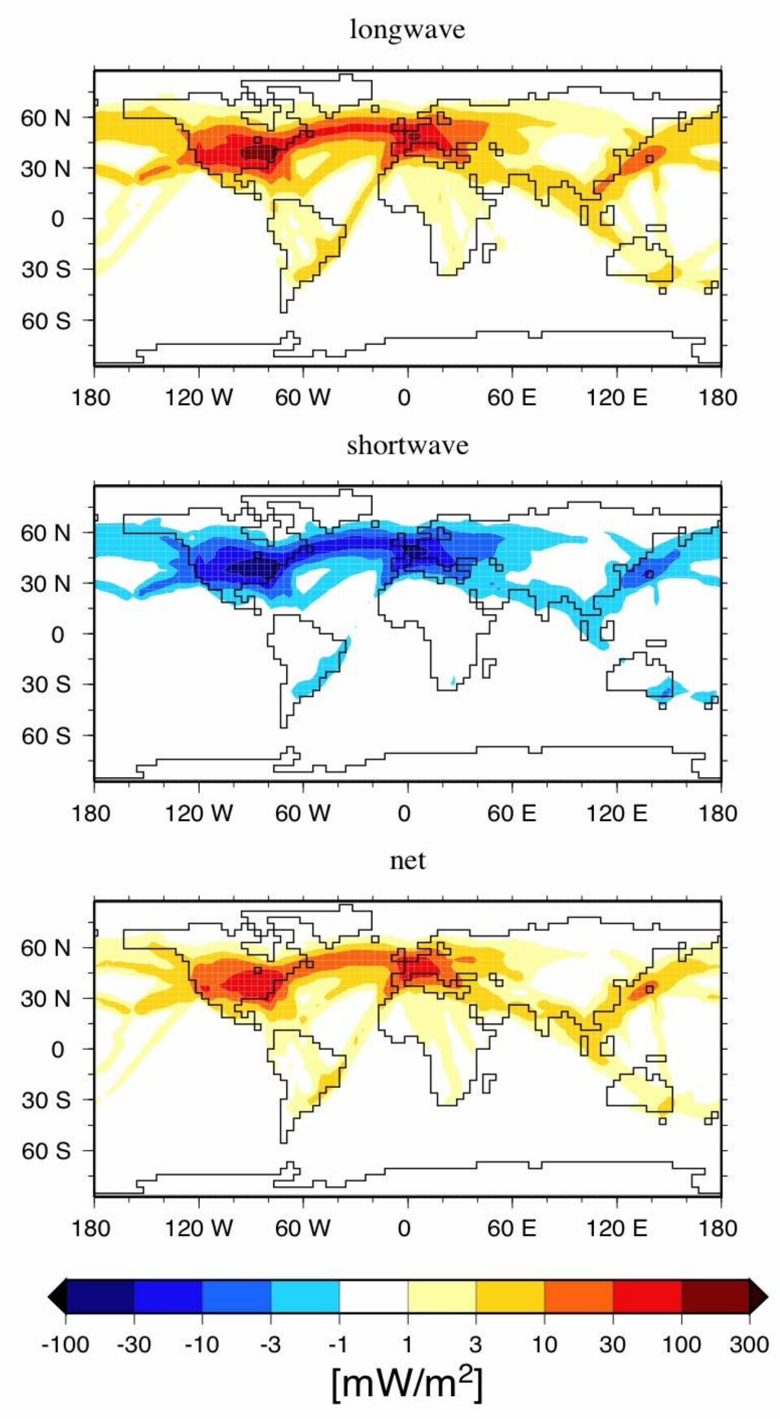

Figure 2.4. Annually averaged radiative forcing of line shaped contrails (mWm^{-2}) for 1992 aviation as calculated from in the ECHAM4 climate model. The corresponding global net value is $3.5 mWm^{-2}$ after correcting the longwave forcing for the effect of missing longwave scattering in the ECHAM4 radiation scheme (Marquart et al., 2003). (Source: S. Marquart, personal communication)

Several approaches for regional and global model simulations of radiative forcing due to aircraft-induced cirrus should be pursued for a robust estimate. Approaches include bulk modeling with detailed microphysics and modeling bulk contrail or individual contrail evolution. Contrail modeling in global models may be based on parameterizations of ice supersaturation. More observations of the microphysics of aged contrail cirrus with a focus on improved measurements of small ice particles are needed to constrain such estimates. High resolution regional models may simulate the transition from young to aged contrail cirrus.

2.3. Short-Term Research Recommendations

2.3.1. Microphysics

Given that the distribution of ice supersaturation is among the primary factors in determining the direct and indirect effects of contrails on climate, *the global distribution of ice supersaturation should be further evaluated using radiosonde, airborne and satellite-based data on upper tropospheric relative humidity and ice supersaturation*. This is critical for evaluation of forecast and climate models. Implementing new parameterizations will require comparisons and validation with existing data sets. Beyond field program *in situ* data, it is desirable to take regular water vapor measurements on high-altitude commercial aircraft similar to MOZAIC or the TAMDAR system (Moninger *et al.*, 2004). Those measurements could be complemented by onboard aft-viewing video cameras or coincident satellite analyses to record contrail occurrence.

Most subscale processes controlling contrail cirrus development are not represented in current large-scale models. *There is a clear need to incorporate into large-scale models more accurate representations of (1) ice supersaturation and (2) ice cloud microphysics.*

A fresh look at past observations in contrail cirrus is needed to separate data sets that can be corrected for crystal shattering artifacts, from those that have no artifacts and from those that cannot be corrected. This also supports the design of future airborne campaigns aiming at probing evolving contrail cirrus.

2.3.2. Contrail Radiative Forcing

The representation of cirrus and contrail optical properties in large-scale models needs to be improved, making use of information available from in situ measurements and recent observations from active (lidar) and passive satellite observations. Radiative transfer schemes have to be adapted in order to deal with particle size distributions and shapes commonly found in contrails and use a realistic cloud/contrail overlap in combination with information on the inhomogeneity of the optical properties.

Independent studies and sensitivity experiments estimating the climate impact of line-shaped contrails are necessary so that proper error bars of contrail radiative forcing can be inferred. Studies should sample the possible parameter space of persistent contrail properties.

Better observational datasets for contrails are necessary for constraining climate model parameterizations of line-shaped contrails and model validation. A globally homogeneous data set of line-shaped contrail coverage together with the associated detection thresholds and efficiencies should be produced from satellite retrievals.

Combined satellite and Lidar observations and contrail prediction tools in numerical weather prediction models may assist in validating global models, in developing regional contrail predictions, and in contrail mitigation strategies.

3.
Contrails and Induced Cirrus Optics and Radiation

3.1. Current Understanding and Issues

Due to substantial increases in air traffic over the globe, soot particles composed mainly of black carbon, along with sulfur compounds and water vapor, have infiltrated the upper atmosphere, causing increased frequency in the occurrence of contrails and contrail-induced cirrus clouds (Liou *et al.* 1990; Minnis *et al.* 2004). Figure 3.1 shows that, based on surface observations and satellite data, there is an upward trend of cirrus cloud cover over the past 50 years near U. S. flight corridors, and that this increase corresponds to the rising trend of jet fuel consumption. Although the coverage of contrails and contrail-cirrus clouds is much less than that of naturally formed cirrus clouds, their radiative effects are not negligible, particularly near flight corridors where they are frequently observed.

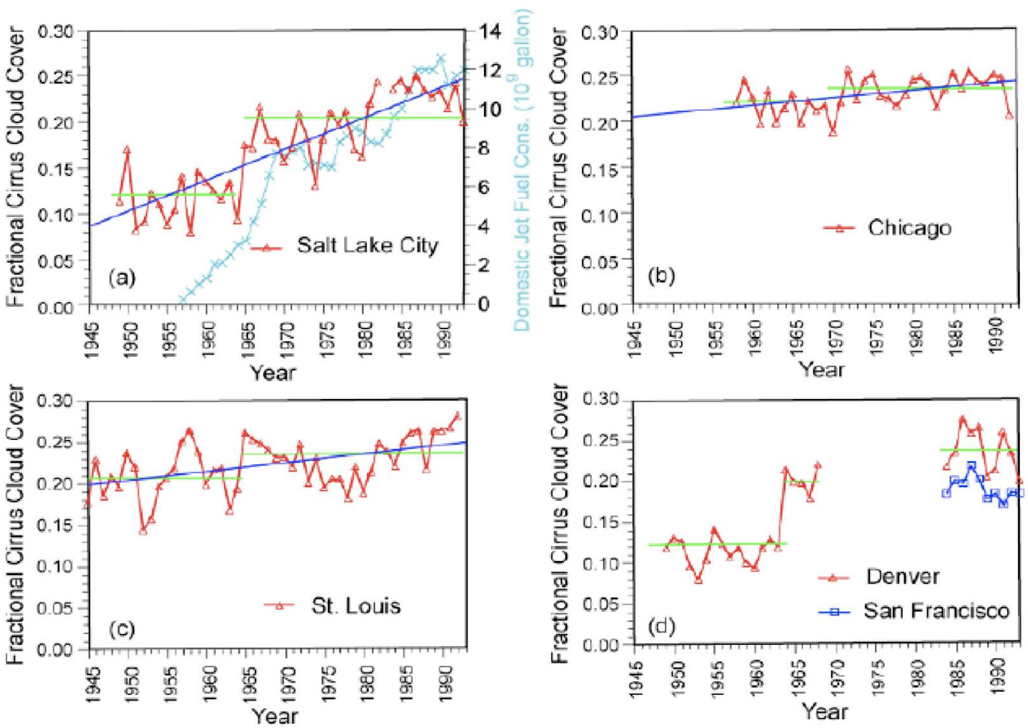

Figure. 3.1 Mean annual cirrus cloud cover over Salt Lake City from 1948 to 1992 (upper left) and domestic jet fuel consumption (after Liou *et al.* 1990). The two solid lines are the linear regression fits for cirrus cloud cover for 1948-1964 and 1965-1992. The linear regression trend for the entire period is shown by the heavy line. Cirrus cloud cover from 1945 to 1992 is shown in the other three panels for several midlatitude U. S. cities.

Satellite remote sensing provides a valuable alternative approach for contrail studies. Integrated usage of satellite observations can improve the accuracy of contrail detection, complement studies of the aerosol indirect effect, provide necessary input parameters to radiative transfer models, and extend the spatial coverage of contrail observations to the global scale. But this approach also has limitations. Very young contrails and older contrails that no longer have the characteristic linear shapes are quite difficult to detect. For this reason, most existing contrail radiative forcing studies have been focused on linear contrails that are distinguishable from natural cirrus. Although very young contrails are expected to have a negligible effect, the results of those studies only represent the baseline climate impact because undetected older contrails were not included (Minnis *et al.* 2004). Moreover, the commonly used split-window technique may misidentify natural cirrus clouds as contrails (Minnis *et al.* 2005). Obviously, there is an urgent need to improve the detection of contrails from satellite observations, and to develop effective algorithms to infer contrail optical thickness and particle sizes.

3.2. Research Needs

As stated in Section 2.1, there have been few field programs designed to study contrails over their life cycle. The optical properties of contrails, optical depth, effective radius, and ice crystal shape, vary with contrail age. As noted in Section 2.1, there have been few characterizations of contrail crystal shape, especially during their initial stages. Fig. 2.2 shows the only example of ice crystal shapes obtained within tens of seconds of the generation of a contrail.

Figure 3.2 (adapted from Liou *et al.* 2000) illustrates the importance of cirrus ice particle nonsphericity for radiative processes. Specifically, the solar albedos for cirrus clouds, calculated by assuming particles are plates/columns or spheres, are compared with in situ measurements from a field campaign. The shaded area indicates the range of the results based on equivalent spheres. Neglecting nonsphericity will lead to underestimation of cirrus solar albedo, a parameter critical for determining the effect of cirrus clouds on the radiant energy budget. For contrails, the shapes and sizes of the ice particles are also key factors in determining the optical properties of these particles and, consequently, the bulk radiative characteristics of contrails and contrail-cirrus clouds.

To reduce uncertainties in the radiative forcing assessment of contrails and contrail-induced cirrus clouds, there is an urgent need to determine the single-scattering properties for, at least, the predominant particle habits in these clouds. These optical properties should serve as the basis for parameterizations of radiation fields from contrails and contrail-induced cirrus clouds for use in global and regional climate models and, at the same time, can be used in retrievals of contrail properties from satellite observations. After a survey of existing light scattering computational methods/models, a combination of the following approaches could be followed for ice crystals in contrails and contrail-induced cirrus: the finite-difference time domain (FDTD) technique (Yee 1966; Yang and Liou 1996a), the discrete dipole approximation (DDA) method (Purcell and Pennypacker 1973), the T-matrix method (Mishchenko and Travis 1994), and the geometric optics method (Takano and Liou, 1989a,b; Yang and Liou 1996b; Liou *et al.* 2000).

Contrail particles have been found to contain soot. Soot within or on an ice particle affects the refractive index of the particle, and hence influences the scattering properties. In turn, this may result in differences in radiative forcing. Different practical and existing mixing treatments for ice particles containing soot inclusions have been applied to investigate the optics of ice clouds in climate models (e.g., Jacobson, 2006). However, these mixing treatments are based on the assumption of spherical ice particles. More realistic optical properties of ice particles containing soot need to be computed for nonspherical habits.

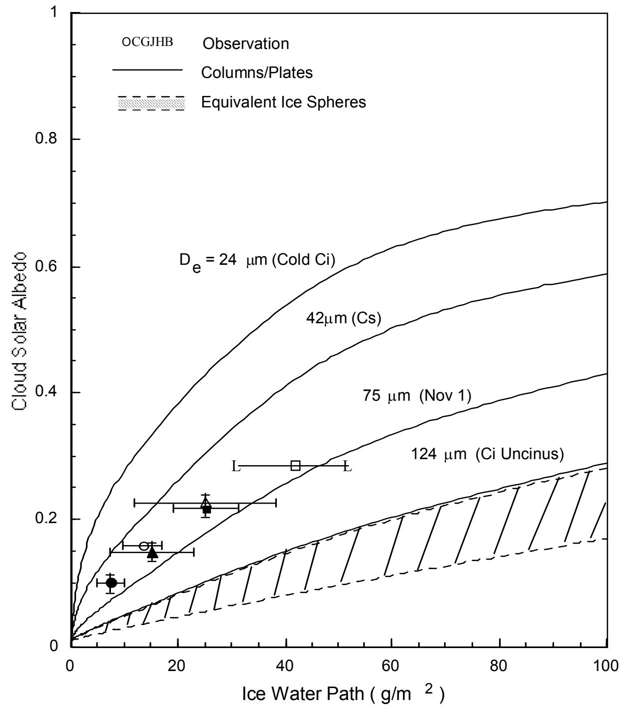

Figure 3.2. Solar albedo as a function of ice water path determined from broadband flux observations from aircraft for cirrus clouds that occurred during the FIRE experiment, Wisconsin, November-December, 1986. The solid lines represent theoretical results computed from a line-by-line equivalent solar model using observed ice crystal sizes and shapes for a range of mean effective ice crystal sizes. The dashed lines are corresponding results for equivalent spheres. Adapted from Liou *et al.* (2000).

Since most, if not all, climate models contain radiation parameterizations only for natural cirrus clouds, development of new parameterizations of contrail and contrail-cirrus bulk radiative properties are necessary for realistically portraying contrails in the radiative transfer schemes used in regional and global climate models. The parameterizations could be developed based on the single-scattering properties of contrails and contrail-induced cirrus clouds, which will be derived from the first prioritized task. The parameterizations should be validated by comparing the model simulations of radiation fluxes with measurements (e.g., the CERES data and DOE-ARM ground radiometric measurements).

Existing and past satellite sensors that measure narrowband (e.g., MODIS, AVHRR, GOES), broadband (CERES) and polarized (POLDER) radiances, high-resolution interferometers (AIRS), and multi-viewing angle sensors (MISR), as well as active sensors such as lidars (CALIPSO, ICESat), provide an unprecedented opportunity to observe contrails and contrail-cirrus clouds. While it is clear that 1.375-µm reflectances and 8.55, 11, 12-µm brightness temperatures are effective for detecting thin and high clouds including contrails, separating natural and aircraft-generated ice clouds remains a large source of uncertainty. Thus, additional study of the spectral properties of contrails is required to determine the potential for distinguishing contrails from nearly linear cirrus clouds in current and future satellite imagers. It is highly recommended that existing and ongoing satellite datasets should be used synergistically to quantify the extent of contrails and contrail-cirrus clouds climatologically on both global and regional scales.

3.3. Recommendations for Short- and Long-Term Research

An adequate evaluation of the radiative forcing of contrails and contrail-cirrus clouds hinges on improving the microphysical, macrophysical, and chemical properties of these clouds. To this end, four near-term priorities have been identified for the best use of the currently available tools to reduce uncertainties in assessing the climate impact of contrails and contrail-cirrus clouds. Specifically, it is recommended to (1) develop datasets representing contrail particle single-scattering properties from existing light scattering models, which will use realistic shapes and sizes of ice crystals observed in these clouds, (2) parameterize the radiative properties of contrails and contrail-cirrus for use in global and regional climate models, (3) accurately determine contrail coverage, optical properties, and radiative forcing from a variety of satellite datasets, and (4) carry out a small-to-medium scale contrail/contrail-cirrus field experiment in an air traffic corridor to support optical property and radiative forcing calculations and remote sensing validation.

For the medium-to-long-term priorities, it is recommended to (1) use coupled meteorology and chemistry models (e.g., Zhang, 2008) with ice microphysical and spectral radiative transfer modules to study the predictive capabilities and radiative forcing effects of contrails and contrail-cirrus, (2) understand the development of contrail-cirrus clouds (mid-term) on the basis of numerical models with supersaturation capability while exploring the use of sensors on commercial aircraft to improve water-vapor/contrail relationships, and (3) study aerosol indirect effect on ice clouds (mid-term) on the basis of satellite data, estimate the extent and impacts of aircraft-aerosol induced cirrus, an issue addressed in Chapter 2.

4.
Chemistry and Transport Processes in the Upper Troposphere and Lower Stratosphere

4.1. Current Understanding and Issues

Since the IPCC report (1999) there has been significant progress in understanding and modeling atmospheric chemistry in the Upper Troposphere/Lower Stratosphere (UTLS). Quantitative understanding of coupled NO_x ($NO+NO_2$) and HO_x (OH and HO_2) chemistry is essential for quantifying the ozone budget in the UTLS. Recent measurements (e.g., Ren *et al.*, 2008) have greatly improved our understanding of this issue but serious discrepancies remain, particularly at high levels of NO_x, where the measured concentrations of HO_2 are much larger than those calculated by constrained photochemical models (cf., Figure 4.1). Another important component of the NO_x/HO_x puzzle is the quantitative understanding of the NO_x budget in the UT. The major sources of NO_x in the UT are delivery of NO_x from the PBL by large scale convection and also from lightning. PBL sources of NO_x include combustion of fossil fuel, biomass burning in the tropics and burning of boreal forests (cf., Table 4.1). Unfortunately the fraction of PBL-NO_x that is transported to the UT by large scale convection is not well characterized and the fraction likely depends on season and continent (cf., Schumann *et al.*, 2000; Singh *et al.*, 2007). Likewise the contribution to the UT-NO_x budget from lightning (Martin *et al.*, 2007; Schumann and Huntrieser, 2007 Table 4.1) is likely comparable to that transported from the PBL. Removal of NO_y[1] from the UT occurs through transport by the resolved circulation to loss regions in the stratosphere, as well as regions of wet removal in the troposphere. Our knowledge of the resolved circulation is continually improving but some removal processes remain difficult to quantify. Uptake of HNO_3 and other NO_y species, such as PAN, on sedimenting ice in the UT may lead to the vertical redistribution of NO_y while "rain-out" in large convection towers can locally impact the NO_x distribution. Observations of NO_x and HNO_3 in the UT (Bertram *et al.*, 2007) have indicated the deviation from equilibrium may be taken as a measure of their time from convective activity and hence may provide a means of assessing convective parameterizations in models.

OH can attack methane, which is a greenhouse gas. Thus if tropospheric ozone were to increase, as a result of increased NO_x, (to which aviation would contribute several percent) it is expected that OH would increase leading to a decrease in CH_4. Thus, as noted in Penner *et al.* (1999), there will be compensating effects in terms of radiative forcing, positive from ozone increases and negative from methane decreases. However, due to their differing lifetimes, the ozone effect will be more regional whereas the methane impact will be global in extent. The compensating effects are quite model dependent and perhaps the underlying uncertainties relate to the differing spatial distributions of NO_x in models and how that feedbacks on O_3 generation and OH production.

[1] NOy = NOx + other nitrogen containing compounds such as NO_3, N2O_5, HNO_3, HNO_4, HONO, $ClNO_3$, $BrNO_3$, PAN

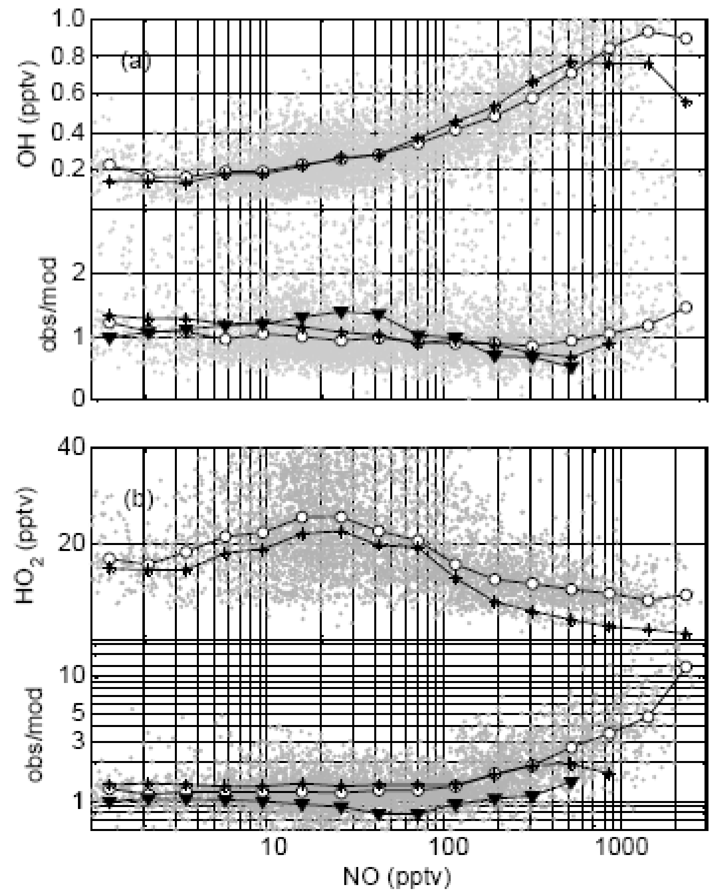

Figure 4.1 (a) Comparison of NO dependence for observations of OH (upper panel) and the ratio of measured-to-modeled OH (lower panel). (b) Comparison of NO dependence for observations of HO_2 (upper panel) values and the ratio of measured-to-modeled HO_2 from INTEX-A (circles), TRACE-P (stars) and PEM Tropics B (triangles). Individual INTEX-A 1-minute measurements are shown (gray dots). All lines show the median profiles (from Ren *et al.*, 2008).

The NO_x/NO_y fraction in the UT is important since, as mentioned above, it governs, along with HO_x, the UT production of ozone. This fraction is determined by gas-phase chemistry, removal of HNO_3, and by heterogeneous chemistry on aerosols, contrails and cirrus clouds. In the UTLS the NO_x/NO_y fraction may also be impacted by heterogeneous hydrolysis reactions involving halogen species which, while converting water to HO_x, and reservoir halogen to active halogen, can also result in the conversion of relatively active NO_x and related species to HNO_3. This process is quantitatively understood in the LS but in the UT the extent of its impact is uncertain.

The chemical and climate impact of aircraft is assessed via models. However, aircraft create emissions in plumes of a size much smaller that is resolvable by current global models, and whose processes may not be well represented. For example, NO_x may be converted to HNO_3 reducing the efficiency of O_3 production from NO_x. Current plume studies suggest this depends quite critically on the background atmosphere (Meilinger *et al.*, 2005). In addition, a recent global modeling study by Søvde *et al.* (2007) that included aerosol processes, including an assessment of the impacts of plumes and persistent contrails, suggests a reduction in the efficiency of ozone production by NO_x emissions in the upper troposphere relative to previous studies. Furthermore, their study predicts ozone losses in the lower stratosphere due to heterogeneous reactions, where previous studies predicted ozone production.[2]

Oxidation of various short-lived organic species, as well as the reaction of water vapor with $O(^1D)$, represents important sources of HO_x in the UT. In addition, important contributions to the UT ozone budget come from stratospheric/tropospheric exchange (STE) which, along with NO_y and other species, supplies about 500 MT-O_3 comparable to the net photochemical O_3 tendencies in the troposphere. Water is also important for formation of contrails and cirrus (see chapters 2 and 3), which influence atmospheric composition by providing surfaces for heterogeneous reactions that enhance ozone depleting forms of halogens. There are continuing discrepancies of ~30% and larger amongst in situ measurements of water vapor in the UTLS which is larger than the reported accuracies that are especially critical near the tropopause, where specific humidities are very low and heterogeneous reactions could impact the sign of ozone tendencies. Uncertainties in temperature of a degree or two become important for defining the extent of supersaturation often observed in the UT, a prerequisite for prescribing the background state into which aircraft exhaust represents a major source of contrail-forming water vapor and condensation nuclei that can flip the local state of the atmosphere from one that is predominantly ozone-producing (e.g., high NO_x) to one that is ozone-destroying (low NO_x, high active chlorine). While it is generally believed that temperature measurements are accurate to 1^oC, it is important that uncertainties in H_2O and T be considered together in any treatment of aircraft-related issues in the UTLS.

Recognition of a more important role for exhaust-influenced aerosols and heterogeneous chemistry in the UTLS, and for larger NO_x sources from the PBL by convective transport suggest that aircraft emissions could have a smaller impact on ozone production than previously believed, even changing the NO_x impact from production to destruction in some regions. These issues should be resolved by the next generation of research activities.

4.2. Research Needs

- Analyses of satellite data, such as MIPAS on ENVISAT, ACE-FTS and MAESTRO on SCISAT-1 and MLS and HIRDLS on AURA, and observations from extensive in situ sampling programs like MOZAIC, CARIBIC and IAGOS, have benefited our understanding of the UTLS region and these studies should continue to be supported along with the surface-based monitoring programs such as AERONET and SHADOZ (Thompson *et al.*, 2003). Further analysis of other measurements would increase our knowledge of the current background atmospheric composition and help to quantify ozone production and loss that can be ascribed directly to aircraft emissions (e.g., enhancements or losses of ozone in flight corridors)

- Important discrepancies that remain between modeled and observed HO_x species (primarily HO_2) at high NO values in the region where subsonic aircraft emissions represent the most significant perturbation to chemistry (Ren *et al.*, 2008) need to be resolved.

[2]Although no directly relevant to this study, the study also suggests reduced ozone loss or even ozone production attributable to aerosols generated by aircraft flying ~ 20 km.

- Improved parameterizations of deep convection and lightning production of NO_x need to be developed and verified in multi-scale models, in order to better constrain the relative contributions of different emissions to the NO_y budget in the UTLS.

- Improved multi-scale models are needed to investigate the corridors aspect of the aircraft emissions and the transition (e.g., dispersion and transport) to regional scale climate impacts. It is also important to characterize the feedbacks resulting from rapid conversion of NO_x to HNO_3 in plumes and persistent contrails, possible redistribution of aircraft emitted or background NO_x and dehydration (e.g., from sedimentation of HNO_3-containing ice particles), and the influence of aircraft emissions on halogen activation by heterogeneous reactions.

- Evidence is mounting that abundances of inorganic bromine in the UT are significantly larger than previously believed, presumably due to efficient transport of short-lived bromine sources to the UT. One modeling study has shown that heterogeneous reactions of bromine in aircraft corridors can lead to significant denoxification. At the same time, high abundances of NO_x transported from the PBL can deactivate the inorganic halogen species. The balance between ozone production by high NO_x and ozone destruction by halogen species needs to be studied with high-resolution measurements and models (as fine as 100 m in the vertical).

- Also of concern is what may happen in a future atmosphere under a different climate regime. Important issues involve atmospheric dynamics in the stratosphere and troposphere and the strength of the Brewer-Dobson circulation in the future. Changes in STE are likely to alter the delivery of ozone from the stratosphere to the troposphere. We have already noted the important role of convection in transporting NO_x to the UT while also generating lightning NO_x.

Table 4.1 Global NO_x sources (MT-N/year) for 2000 (IPCC, 2001) and 2030

Global NO_x sources	2000	Above 7 km	2030*
Fossil Fuel	33.0		40-50
Aircraft	0.7	0.6	1.5†
Biomass Burning	7.1	??	7.1
Soils	3.0**		3.0
Lightning	5(3-8)*	3.6	5(3-8)
Stratosphere	0.7***	0.7	0.7
Total	50.5		

* Schumann and Huntrieser (2007)
** Jaeglé *et al.*, 2005.
*** Olsen *et al.*, 2001 (and text)
† Sutkus *et al*. (2003). The amount shown is for 2020.

In a future climate, the strength of convection may change the balance and amount of NO_x production and PBL sources in the UT. Furthermore, in addition to increasing aviation emissions by a factor of 2 to 2.5 in the next 20 to 30 years (Table 4.1 and Sutkus *et al.*, 2003), estimates of surface anthropogenic and "natural" emissions (e.g. Stevenson *et al.*, 2006 and references therein) suggest a similar increase but with a possibly different spatial distribution from contemporary emission patterns. In the tropics, convection often appears to feature as an important aspect of the Madden-Julian Oscillation (MJO) and this along with transport into the stratosphere via the TTL may change. These concerns suggest that it will be important to assess future aviation impact using CTMs with meteorological fields derived from future climate simulations and including adequate representation of both the troposphere and the stratosphere. In addition, coupled chemistry-climate models (CCMs) need to be incorporated in future assessments.

What is common among the various chemistry-transport needs is a focus on process studies and these need to be pursued to reduce uncertainties in order understanding of the workings of the current atmosphere and their projection into the future.

4.3. Short-Term Research Recommendations

- Given the cruise altitude of aircraft, and the recent improvements in CTMs and CCMs, such models could be used in the short term (about 18 months) to assess a set of scenarios, such as those used for the IPCC 1999 report. They could also be used to address selected specific issues noted in part 1 above. For example, modeling studies of the sensitivity of ozone balance and atmospheric oxidation (e.g., trace-gas lifetimes) (both troposphere and stratosphere) to heterogeneous processes should be carried out. Focused model experiments should be undertaken to explore the impact of a specific uncertainty by incorporating 'simple' prescribed parameterizations (e.g., HNO_3 uptake and redistribution by sedimentation, heterogeneous chlorine and bromine chemistry, uncertainties in HO_x/NO_x chemistry, and errors in water vapor and supersaturation).

- The formulation of an appropriate list of questions to be addressed in the "short term" could be defined by a working group including the communities involved, viz., atmospheric modeling (CTM, CCM, and multiscale models), members of the satellite and aircraft measurements community and industry. This activity should not be done in isolation. There are many other modeling projects which, although not directly aligned with aviation effects, would necessarily have useful information. For example, the HTAP model comparison for interhemispheric transport of (surface) pollution and the CCMVal intercomparison (e.g., Eyring *et al.*, 2006). Also during the timeline of this part of the program there will be aircraft campaigns such as POLARCAT, ARCTAS associated with the IPY, and supported by satellite measurements and modeling.

- Within the next two to three years, one can envisage a Model Measurement Exercise, designed for the UTLS, similar in structure to that used for the NASA High Speed Research program. This could consist of assembling a database of suitable observations that could help provide important constraints on STE, convective transport and associated lightning production, and water vapor. This could cover some of the scope of the IPCC 1999 report. This data as well as associated diagnostics such as "observed" STE values and correlations could be used to help in rating the reliability of models. In addition, it is clear that this work would be of importance to the "metrics" subgroup models.

- Further planning for long-term activities should include a consideration of the best approach for model development. There is a hierarchy of models (e.g., box, plume, regional, CTMs and GCMs) necessary to provide the best constraints of uncertainties due to processes that range in importance from local to global, incorporation of plume processes and contrail-cirrus chemistry into regional/global models, defining new large-scale measurements campaigns to answer specific aircraft-related questions not addressed by existing data, continuation of satellite measurements, and the use of coupled chemistry-climate models to define climate impact of aviation and potential feedbacks. A high priority should be placed on addressing the potential importance of resolution (vertical layering and plume/contrail horizontal scales) and development and use of multiscale models. As can be seen in Figure 4.2, taken from a high resolution global variable model, the spatial structure of the atmospheric fields (in this case ozone) are quite detailed, challenging measurements from space and from slow-response instruments deployed on aircraft.

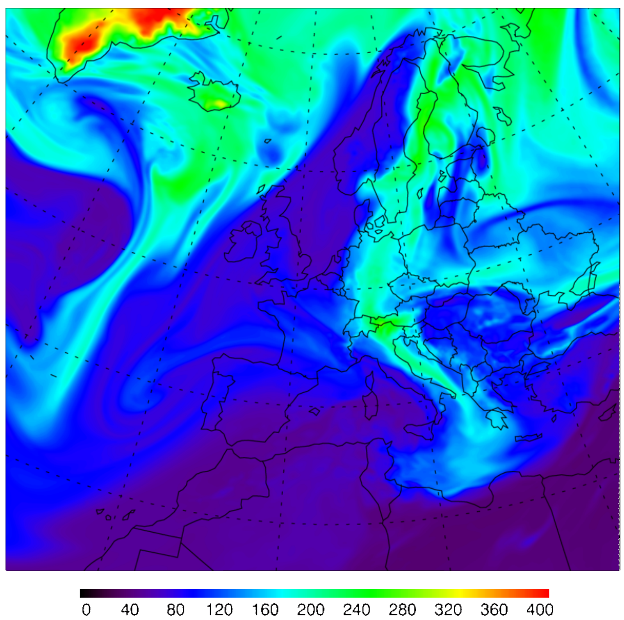

Figure 4.2. Ozone distribution (units 10 ppbv) at ~ 220 hPa over eastern Atlantic and Western Europe calculated using a global variable resolution model (courtesy of J. Kaminski, 2008) at 15x15 km^2 resolution in the core.

- It is highly recommended that a new ACCRI program that follows the near- and medium-term approach outlined above also promote and support, where possible, important activities initiated by other agencies (e.g., major NASA, NSF, and DOE). In particular, an ACCRI program could advocate for the importance of examinations of issues such as accuracies and representativeness of measurements of temperature and pressure, water vapor, HO_x, and halogens. Limited funds for medium-term, focused studies (for example characterization of supersaturation, HO_x, NO_x, and halogen chemistries, particle sizes and habits, and instrument performance, in plumes and persistent contrails), could pay big dividends in the long-term, if carried out with focus and in collaboration with the modeling studies outlined above. Small, focused studies with research aircraft and balloon could respond quickly to input provided by the modeling teams engaged in the near- and medium-term studies. For example, the question of how important is redistribution of NO_y in a persistent contrail could be assessed in a small, focused campaign involving measurements of particles, ice-water content, and nitric acid in and around persistent contrails that are observed frequently over the Rocky Mountains, whereas emission indices of NO_x and particles could be assessed by a series of measurements within contrails and heavily traveled flight corridors.

5.
Climate Impact Metrics for Aviation

5.1. Background

Climate change mitigation policies such as the Kyoto Protocol are already being implemented throughout much of the world and much more consideration is going into new policy development. Such policies generally require a way of quantifying the present and future climate impact of various anthropogenic activities as well as the expected effects of mitigation strategies. To inform these decisions simple analytical tools - or metrics - can be used to quantify the ultimate climate impact of specific activities, such as aviation emissions (IPCC, 1999; Forster and Rogers, 2008; Wuebbles *et al.*, 2008; Forster *et al.*, 2006). Metrics simplify consideration of the effects of aviation on climate by policymakers as in other sectors. Metrics can also be useful to guide decisions concerning future aircraft design and operations to minimize the climate impact.

Aviation is currently a small but important contributor to climate change. It affects climate through various mechanisms and a range of processes that occur on different spatial scales and time scales; quantification of many of these effects is still uncertain (see IPCC, 1999; Sausen *et al.*, 2005; IPCC 2007; as well as Figure 5.1.). The global radiative forcing of aviation is small compared to other anthropogenic terms that, taken together, are contributing to climate change as noted in surface temperatures and the daily temperature range in the U.S. and elsewhere. For aviation as well as other sectors, it is desirable to have a metric that is as closely as possible related to the climate impact of concern. Yet as shown in Figure 5.1, the uncertainties increase as we move from quantifying aviation emissions and radiative forcing to quantifying temperature and precipitation changes or trying to estimate the socioeconomic impacts.

When choosing a metric for climate impacts of emissions from aviation, some fundamental questions must first be answered (O'Neill, 2001; Fuglestvedt *et al.*, 2003), such as: What are the policy questions under consideration and what is the context for the application? What is the function or purpose of the metric? Can the metric be applied to various scenarios and forcings? What is the effectiveness of the metric for the user, whether it is for technology or policy considerations? Is the metric flexible enough to easily incorporate advances in scientific understanding? What is the timescale for the evaluation of potential climate impacts? In addition, the most useful metrics will be applicable to other transportation and /or energy sectors.

Ideally, a metric is scientifically well grounded, simple to use, and easy to understand by scientists and policymakers alike. It must be an effective tool for communication between scientists, industries, and policymakers. One main concern with developing new metrics is the need to weigh the applicability of the metric against ease in understanding the results. So, the best metrics will be simple and include uncertainties that reflect the state of knowledge in order to give users confidence in the scientific quality of the metric (Fuglestvedt *et al.*, 2003). On the other hand, aviation metrics must account for regional effects, since aviation is concentrated in a rather narrow latitude band.

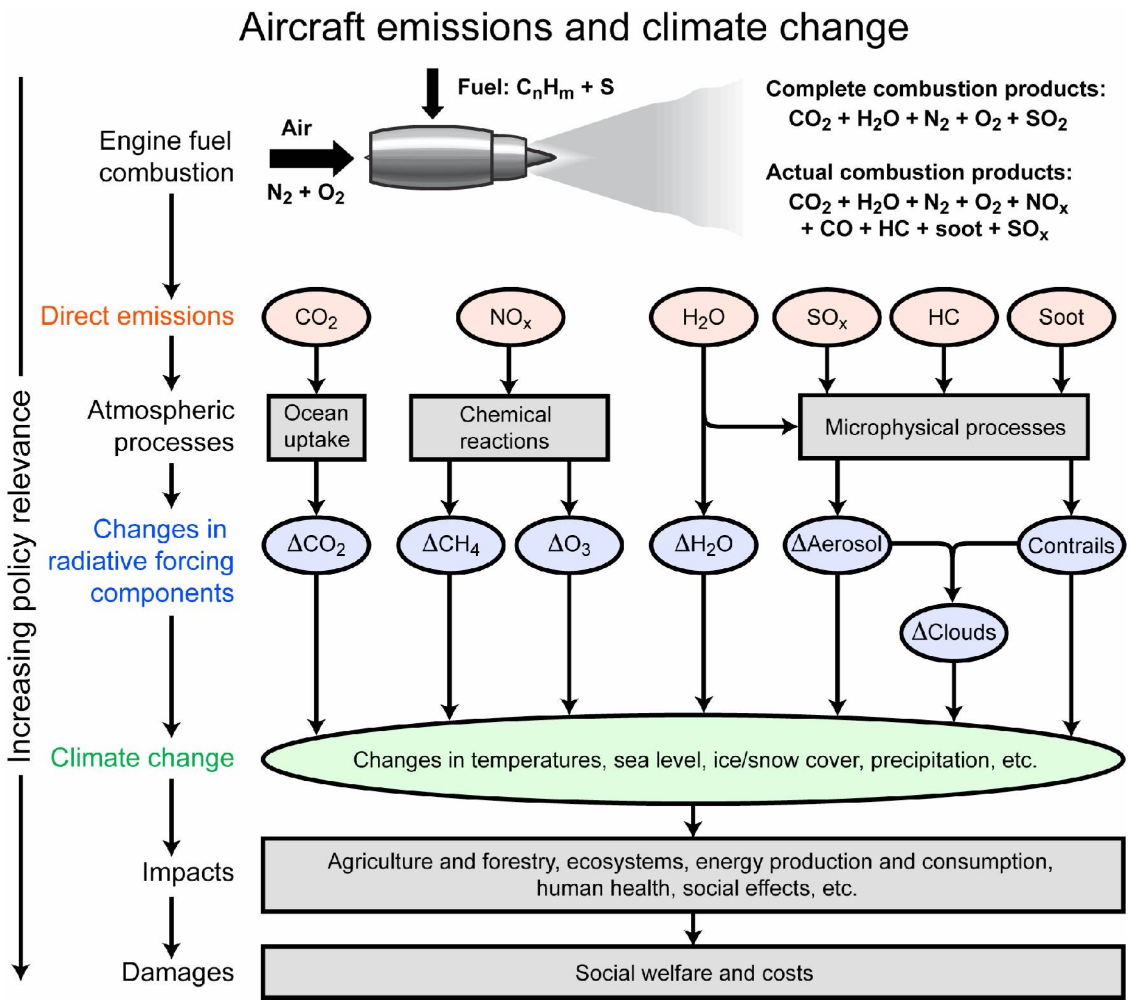

Figure 5.1. Aircraft emissions and their resulting potential impacts on climate change and welfare loss (developed for new report for CAEP, but adapted from Wuebbles *et al.*, 2007, based on IPCC, 1999 and Fuglestvedt *et al.*, 2003).

5.2. Evaluating Contemporary Metric Options

Development of meaningful metrics for climate change requires a reasonably accurate capability for the evaluation of the effects of human-related and natural factors affecting climate. Such capabilities require complex state-of-the-art models that include representations of, and interactions among, the atmosphere, its chemical composition, the oceans, biosphere, cryosphere, etc. They also require large computer resources and considerable expertise to perform calculations and to diagnose results from the large amount of output that they produce. Several of the key metrics and policy-oriented tools that are most under consideration for studies of aviation impacts on climate are described below.

5.2.1. Radiative Forcing

The most widely used metric as a proxy for climate change has been globally averaged annual mean stratospheric adjusted radiative forcing (RF) at the tropopause (which is the same as the RF at the top of the atmosphere after stratospheric adjustment.) For this metric, globally averaged annual mean surface temperature is assumed to be equal to the RF multiplied by a climate sensitivity factor. While this method works well for well-mixed greenhouse gases, solar irradiance, surface albedo, and homogeneously distributed non-absorbing aerosols, the linear relationship between RF at the tropopause and global mean surface temperature may not hold for forcing agents that have a strong response near the surface but very little response at the top of the atmosphere (Joshi *et al.*, 2003; Hansen *et al.*, 2005). This relationship also breaks down if the forcing agent is not homogeneously distributed. The classical definition of RF also applies best for global-mean climate response and does not account for regional climate change. In addition to the RF, we must also consider the efficiency of a particular forcing agent in causing climate change. This "efficacy" is not considered in current RF calculations using the traditional definition of RF.

5.2.2. Global Warming Potential (GWP)

The GWP is the most widely used emission metric in evaluating the potential of climate change from a forcing agent (IPCC, 1990; 2007). The GWP represents the radiative forcing for either pulse or sustained emissions above the current background levels by integrating the forcing over a specific time interval, usually 100 yrs as adopted by the Kyoto Protocol, and comparing to the forcing from an equal mass emission of reference material, usually carbon dioxide (CO_2). The use of a GWP for aviation has limitations because the radiative forcings do not all rely on emissions alone (*e.g.,* contrails, aerosols), the lifetime of some effects are short (<<100yrs), and the distribution of forcings is inhomogeneous in the atmosphere. The GWP concept can be modified to account for differences in efficacy between the various components (Fuglestvedt *et al.*, 2003; Berntsen *et al.*, 2005).

5.2.3. Global Temperature Change Potential (GTP)

The GTP has been proposed as an alternative to the GWP in order to avoid some of its limitations (Shine *et al.*, 2005; Shine *et al.*, 2007). The GTP ratios the surface temperature change for either pulse or sustained emissions that will occur at a chosen point in time, to the temperature change for equal mass emission of reference material, usually carbon dioxide (CO_2). The GTP requires essentially the same inputs as the GWP, but also takes into account the thermal inertia of the climate system. Thus it provides a different perspective on the relative importance of emissions of different species and how this changes over time. Additionally, because it considers temperature change, the GTP is further down the cause and effect chain from emissions to impacts and may therefore have a higher relevance. It is also easier to understand than the somewhat abstract concept of integrated RF. The GTP concept can include efficacies for the various components.

5.2.4. Simplified Climate Models

As an alternative to comprehensive global climate models, linearized-response and other simplified models can be used to estimate the response of the climate system to pulsed or sustained emissions (Marais *et al.*, 2007; Lee *et al.*, 2006; Shine *et al.*, 2005; Sausen and Schumann, 2000). Simplified models are tuned to reproduce key responses found in comprehensive global climate models and then are used to explore a range of emission scenarios with less computational resources than the guiding global climate models. Importantly, they have the capability of including information about future scenarios both of aviation and other emissions. The more sophisticated of these models have the potential to include information on regional scales. However, treatment of many of the processes remains too uncertain to trust some aspects of these models' response. Sophisticated global climate models are rarely used for metric evaluation as the higher computational cost of increased complexity currently precludes multiple calculations to assess uncertainties; further, it is probably not worthwhile given current poor understanding of processes such as cirrus cloud modification.

5.2.5. Socio-economic Damage Models

The evaluation of the climate impact of aviation emissions can be taken a step beyond quantifying RF or temperature changes to the evaluation of the socioeconomic damages. Economists and others argue that damages and abatement costs must be included in climate change metrics in order to make valid comparisons of abatement options and consequences across emissions types and geographic regions. Socioeconomic damage models are designed to provide such metrics, which potentially can be of direct policy relevance (e.g. Hammitt *et al.*, 1996; Kandlikar, 1996; Manne and Richels, 2001; Marais *et al.*, 2007). However, the current understanding of the links between climate change, aviation emissions effects, and damages are not well defined enough in general, to adequately quantify these. These models may however provide insight and be useful for exploring scenarios and various policy options.

5.3. Recommendations

The use of the radiative forcing metric has already been of substantial value in evaluating the climate impact of aviation emissions and operations and in placing the contributions of aviation in a quantitative framework with global emissions from other sectors. However, the limitations of radiative forcing as a metric have been widely acknowledged. Recommendations for the use and development of metrics appropriate for aviation are the following:

- *At present use only global metrics when evaluating the effect of global emissions on global response.* Currently we have an insufficient quantifiable understanding of how regional emissions affect both regional and global response or even how global emissions affect local response. Further, too few climate models have assessed aviation efficacies to currently justify their use in policy. We expect this situation to improve over the next 5-10 years as both our understanding and modeling capability improves.

- *Continue use, evaluation and development of the GWP and GTP metrics.* The GWP and GTP are the most usable metrics for aviation at present, even for short-lived emissions such as NO_x. However, simplified models also appear to be promising for policy studies and development of new metrics should also be pursued. Existing metrics have limitations, so we suggest evaluating a range of metrics so not to introduce bias.

- *Continue development of global climate models.* All useful metrics ultimately depend on comprehensive climate models, directly or indirectly. Improving the representativeness and accuracy of these models will directly improve the quality of metrics for aviation and other climate change perturbations. With improved models, efficacies, and regional forcing and responses can be addressed. Regional metrics will be less simple, but can be included in analyses with varied scenarios and mitigation options.

- *Attempt to adapt common metrics.* The value of metrics for aviation climate impact would be increased if they were applicable to emissions from other sectors, *e.g.*, surface transportation.

- *Continue development of socioeconomic metrics.* Socioeconomic metrics are not yet suitable to use in policy development for aviation impacts given current uncertainties in their derivation. Instead, socioeconomic metrics are best viewed as a long-term research goal to assess the climate impact of both aviation emissions and the emissions of other sectors.

- *Develop an aviation metrics working group.* An international working group could identify and formulate metrics for aviation climate change impacts. In addition to atmospheric scientists and users, the group would include stakeholders in the aviation industry and economists. In group dialog, the context for application of aviation metrics could be defined and the fundamental questions about metrics as posed above could be addressed.

6.
The Way Forward

The Aviation Climate Change Research Initiative (ACCRI) has the stated objective of reducing key scientific uncertainties in quantifying aviation-related climate impacts while providing timely scientific input to inform mitigation actions and policies. In defining climate impacts, the scientific community recognizes climate change and the climate system as including far more than just global mean warming. It extends to changes in water resources, air quality, and ecosystems, to name a few. It includes changes occurring from the globe down to sub-continental scales and from decades to centuries. In evaluating aviation's climate impacts we need to consider how it may alter this climate system.

In assessing the role of aviation on the global environment, the way forward must combine the disparate needs for advances in scientific understanding with those for timely evaluations needed for decision making. A short-term, closed-end research program has a strong likelihood of becoming a contracted-services program that will neither generate new research nor new scientific knowledge about the impacts of aviation. Previous programs in the U.S. and Europe were initiated to assess aviation impacts and delivered useful information to the decision making community (e.g., FAA's CIAP & HAPP; NASA's AESA & AEAP, EU's QUANTIFY & ATTICA). They have amply demonstrated the successful link between scientific research and delivery of applied knowledge. Like these programs, the new ACCRI program needs to be seen by the community as a multi-year, research-driven program that has the responsibility to hold timely programmatic meetings and deliver assessment reports scheduled to match decision making.

With a clear programmatic vision and a plan for sustained research (although there is no guarantee of long-term funding), the program may be able to generate the excitement of developing innovative science in service to society. With such an initiation, the new aviation/environment program should be able to bring in *pro bono* (or at minimal cost) the aircraft and ground-based measurement community, the satellite analysis community, the chemistry and climate modeling communities, along with the international research community to participate in specific projects (see below). The ACCRI program needs to position itself to benefit from the atmospheric chemistry and climate research programs funded by other domestic and international agencies, while providing dedicated support to aviation specific analyses and initiating activities. Given the anticipated resources, there will be difficult decisions to be made as to how to balance the program while maintaining critical effort in those scientific areas that are essential to understanding aviation impacts: these decisions can be best addressed with a single science program manager being given the ACCRI mandate. This research program must deliver quantifiable results that feed directly into the international scientific evaluations and assessments of climate and ozone depletion (IPCC, WMO/UNEP).

Planning for a successful aviation/environment program needs to include a concrete research plan along a timely schedule with appropriate prioritization, regularly scheduled program meetings and specific focused meetings that are timed to the needs of the funding agencies. For example, in addition to the annual scientifically oriented program meetings, a summer 2011 program meeting would be planned to synthesize the results to date for the 2nd Generation Input on aviation climate impacts and metrics to the Environmental Working Group of NextGen/JPDO. Specific focused meetings (e.g., satellite data analysis of contrails and cirrus, analyses of climate/chemistry model simulations of aviation impacts, a models and measurements intercomparison) would be scheduled separately, but related to the timeliness requirements. Involving industry and funding agencies at meetings/workshops to set scientific research priorities and at annual meetings allows integration of the program across science and stakeholders. A quarter of the annual program meeting is devoted to topics and questions raised by this user community, with the remaining three quarters is devoted to new science. Such a model maintains the excitement level and interest of both the international science community and the policy community. This model has been very successful in previous NASA aviation-environment programs.

Many ideas have been put forward through the white papers and during the ACCRI science meeting. Below we highlight some of them. At some point the program manager and funding agencies will need to make a preliminary decision as to which of these will be included in the Joint Research Announcement. Inclusion will not necessarily guarantee funding of a specific topic, since it will be up to the community to write compelling proposals as to how work in that area will produce notable advances. Research areas that deliver early results will be given high priority, but investment in preparatory work for a few critical areas must also be included to give balance and vision to the program. Examples of focused research:

Models and Measurements (M&M) in this case describes a critical, objective evaluation of the models used to predict aviation impacts. The program should complete an M&M3 (the 3rd such modeling and analysis project similar to those supported earlier by NASA) within the first 2 years. M&M3 will focus on a wide range of key observations about the upper troposphere and lower stratosphere (UTLS) region. Different from earlier exercises, M&M3 will concentrate on trace species and processes keyed to the perturbation caused by aviation (e.g., NO_x, O_3, soot, H_2O, contrails) and include topics of highest uncertainty in the current modeling of aviation impacts (e.g., deep convection, lightning, cirrus, supersaturation, stratosphere-troposphere exchange). It will be driven in part by the measurement community and include: (i) development of a set of independent tests of the transport and chemistry involving water vapor, trace gases, aerosols, and cirrus; (ii) an objective set of grading criteria for model performance, and (iii) a standard aviation perturbation to be run in parallel with the model evaluation. Support will be provided for developing the key data sets and for model participation. The core criteria for M&M3 are that we have models that can be used to calculate aviation's perturbation and that can be tested against a prescribed set of observations.

A unified global data set for contrails and cirrus, with well characterized accuracy, is possibly within reach using existing satellite observations. Support will be available for several investigators to augment the ongoing NASA EOS satellite teams and be limited to efforts to integrate all satellite observations (and possibly ground-based observations) into quantifiable climatologies of contrails and cirrus cloudiness, as well as water vapor and ice water content. A key element of these efforts will be to evaluate the current physical properties (i.e., optical depth) and radiative forcing by contrails with uncertainty ranges.

Many aircraft campaigns are planned over the next few years that include detailed measurements in the UTLS region over a wide range of environments, but they are directed with a scientific objective different from that of evaluating aviation. This is an opportunity for ACCRI to augment these campaigns at marginal cost by funding the addition of another instrument or post-flight analysis focused on aviation/environment issues. Previous campaigns (such as SUCCESS, SONEX, INTEX etc.) need additional post-flight analysis with a focus on issues of relevance to aircraft assessment. There are several U.S. and European (e.g. with HALO in Germany, starting in the second half of 2009) campaigns currently being planned, and ACCRI should promptly gather a list of these, including key contacts, to enable participation with an aviation-related focus. Support for both mission planning and instrument development intended for a program-specific campaign should be pursued. The ability to independently stage such a campaign would require an expansion of the program and this may not occur in the first three years of the program. Such foresight is an essential program element.

Soot particles may act as ice nuclei and thus alter natural cirrus. Given the uncertainty and potential importance of this impact, the program should define a strategy for determining the relative importance of aviation soot through either ice-cloud nucleation or possibly heterogeneous chemistry, although this is seen as a lower priority. This effort might include analysis of aviation and non-aviation sources of UTLS aerosols from models and measurements, laboratory studies, or a focused in situ campaign to measure the activity of aviation soot. As noted above, such a campaign might only be done in the first three years (see above) as a low-cost, piggy-back participation, but might become the prime campaign of an extended program.

Climate Modeling is a core element of ACCRI, since we must simulate the perturbations to the global environment caused by aviation – past, present and future. These impacts center on climate change and thus the program must include climate models as the core of such assessments. Given that aviation's perturbation to the climate system is currently evaluated to be at most 10% of the total anthropogenic perturbation, the assessment of aviation's impacts must develop and select appropriate and relevant measures that quantify the impact of aviation and afford a direct comparison against the much larger transport and industrial sectors. The program has the responsibility to provide metrics comparable to the IPCC climate assessments in order to compare options for the next generation of aircraft.

Other topics of importance to ACCRI, but not at the same level of effort or responsibility to the program as those above, include: work with the weather operational models to improve treatment of RH and water vapor so that the resulting meteorological fields can be used in contrail/cirrus assessments; improve knowledge of the radiative properties of ice clouds (contrails and cirrus); develop and evaluate parameterizations of plume processing that include the range of meteorological conditions; identify, if possible, robust observational approaches that independent of global models are able to quantify aviation impacts on atmospheric composition, clouds, or climate; develop a strategy including metrics for evaluating (or not) regional climate impacts, air quality, and their (water and ecosystem) impacts. For studies involving the current atmosphere, we will need better access to air traffic data through help from FAA and its international partners (e.g. EUROCONTROL in Europe). We will also need help from industry and governments in developing future aviation scenarios.

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Appendix I

List of ACCRI Subject Specific Whitepapers (SSWPs)

SSWP I UT/LS chemistry and transport by D. Toohey, L. Avallone and M. Ross (http://www.faa.gov/about/office_org/headquarters_offices/aep/aviation_climate/media/ACCRI_SSWP_I_Toohey.pdf)

SSWP II UT/LS chemistry and transport by J. McConnell, W. Evans. J. Kaminski, A. Lupu, L. Neary, K. Semeniuk, K. Toyota (http://www.faa.gov/about/office_org/headquarters_offices/aep/aviation_climate/media/ACCRI_SSWP_II_McConnell.pdf)

SSWP III Contrails and contrail-specific microphysics by A. Heymsfield, D. Baumgardner, P. DeMott, P. Forster, K. Gierens, B. Kärcher, A. Macke (http://www.faa.gov/about/office_org/headquarters_offices/aep/aviation_climate/media/ACCRI_SSWP_III_Heymsfield.pdf)

SSWP IV Climate impact of contrail and contrail cirrus by U. Burkhardt, B. Kärcher, H. Mannstein and U. Schumann (http://www.faa.gov/about/office_org/headquarters_offices/aep/aviation_climate/media/ACCRI_SSWP_IV_Burkhardt.pdf)

SSWP V Contrail/cirrus optics and radiation by S.C. Ou and K.N. Liou (http://www.faa.gov/about/office_org/headquarters_offices/aep/aviation_climate/media/ACCRI_SSWP_V_Ou.pdf)

SSWP VI Contrail/cirrus optics and radiation by P. Yang, A. Dessler and G. Hong (http://www.faa.gov/about/office_org/headquarters_offices/aep/aviation_climate/media/ACCRI_SSWP_VI_PING.pdf)

SSWP VII Metrics for comparison of climate impacts from well mixed greenhouse gases and inhomogeneous forcing such as those from UT/LS ozone, contrails and contrail cirrus by P. Forster and H. Rogers (http://www.faa.gov/about/office_org/headquarters_offices/aep/aviation_climate/media/ACCRI_SSWP_VII_Forster.pdf)

SSWP VIII Metrics for Climate Impacts by D. Wuebbles, H. Yang and R. Herman (http://www.faa.gov/about/office_org/headquarters_offices/aep/aviation_climate/media/ACCRI_SSWP_VIII_Wuebbles.pdf)

Appendix II

ACCRI Science Meeting Agenda

Aviation Climate Change Research Initiative (ACCRI)
Science Meeting
Feb. 25-27, 2008

Sheraton Oceanfront
3501 Atlantic Ave.
Virginia Beach, VA

Meeting Schedule

Day I Feb. 25, 2008

07:00-08:00am	Registration and Breakfast
08:00-08:20am	ACCRI: Vision, Goal and Objectives
	Mohan Gupta, Malcolm Ko, John Murray and David Fahey
08:20-08:35am	ACCRI Science Meeting Report: Focus
	Guy Brasseur: Lead Coordinating Author
08:35-08:45am	Preview of the session on The Way Forward
	Michael Prather and V. Ramaswamy
08:45-08:50am	***Contrail and induced cirrus A: Formation, Microphysics and Lifecycle***
	Co-chairs: Brian Toon and Andrew Gettleman
08:50-09:35am	SSWP Presentation III: Heymsfield *et al.*
09:35-10:20am	SSWP Presentation IV: Burkhardt *et al.*
10:20-10:40am	AM Break
10:40-10:45am	***Contrail and induced cirrus B: Optics and Radiation***
	Co-chairs: Pat Minnis and Harshvardhan
10:45-11:30am	SSWP Presentation V: Steve Ou and K.N. Liou
11:30-12:15pm	SSWP Presentation VI: Ping Yang and Andy Dessler
12:15-01:15pm	Lunch
01:15-02:40pm	Breakout Session: *Contrail and induced cirrus A*

01:15-02:40pm	Breakout Session: *Contrail and induced cirrus B*
02:40-03:00pm	PM Break
03:00-04:00pm	Discussion (Plenary): *Contrail and induced cirrus A*
	Co-chairs: Brian Toon and Andrew Gettleman
04:00-05:00pm	Discussion (Plenary): *Contrail and induced cirrus B*
	Co-chairs: Pat Minnis and Harshvardhan
05:00pm	Next Day Agenda

Day II Feb. 26, 2008

07:00-08:00am	Breakfast
08:00-08:05am	***UT/LS Chemistry and Transport***
	Co-chairs: Jose Rodriguez and Ivar Isaksen
08:05-08:50am	SSWP Presentation I: Darin Toohey *et al.*
08:50-09:35am	SSWP Presentation II: Jack McConnell *et al.*
09:35-09:55am	AM break
09:55-11:55am	Discussion
11:55-12:55pm	Lunch
12:55-01:00pm	***Climate Impacts and Metrics***
	Co-chairs: Dave Fahey and Jan Fuglestvedt
01:00-01:45pm	SSWP Presentation VII: Piers Forster and Helen Rogers
01:45-02:30pm	SSWP Presentation VIII: Don Wuebbles
02:30-02:50pm	PM Break
02:50-04:50pm	Discussion
04:50-05:10pm	Summary of findings: *Contrail and induced cirrus A: Formation, Microphysics and Lifecycle*
	Brian Toon and Andrew Gettleman
05:10pm	Next Day Agenda

Day III Feb. 27, 2008

07:00-08:00am	Breakfast
08:00am	***The Way Forward***
	Co-chairs: Michael Prather and V. Ramaswamy
08:00-10:00am	Discussion
10:00-10:20am	AM Break
10:20-11:30am	Discussion and Summary
11:30-11:50am	Summary of findings: *Contrail and induced cirrus B: Optics and Radiation*
	Pat Minnis and Harshvardhan
11:50-12:10pm	Summary of findings: *UT/LS Chemistry and Transport*
	Jose Rodriguez and Ivar Isaksen
12:10-12:30pm	Summary of findings: *Climate Impacts and Metrics*
	Dave Fahey and Jan Fuglestvedt
12:30-01:30pm	Lunch
01:30-01:45pm	ACCRI Science Meeting Report: Process and Schedule
	Guy Brasseur: Lead Coordinating Author

01:45-02:15pm	Final Discussion with Federal Agency Panel Lourdes Maurice, John Haynes, Malcolm Ko, David Fahey and Cindy Newberg
02:15-02:25pm	Concluding Remarks
02:25pm	Adjourn

Appendix III

List of ACCRI Science Meeting Participants

A. Lupu	York Univ.
Andrew Gettleman	NCAR
Andy Dessler	Texas A&M Univ.
Andy Heymsfield	NCAR
Anne Douglass	NASA GSFC
Anuja Mahashabde	MIT
Bernd Kärcher	DLR, Germany
Bill Brune	Penn State Univ.
Bob d'Entremont	AER, Inc.
Brian Toon	Univ.Colorado, Boulder
Bruce Anderson	NASA LaRC
Bruce Carmichael	NCAR
Bruce Doddridge	NASA LaRC
Cindy Newberg	EPA
Clay Reherman	DOT Volpe Center
Dan Bulzan	NASA GRC
Darin Toohey	Univ.Colorado, Boulder
Darrel Baumgardner	Universidad Nacional Autónoma de México
Dave Fahey	NOAA
Dave Mitchell	DRI
David Duda	NASA LaRC
David Lee	MMU, UK
David Travis	Univ. WI-Whitewater
Don Hagen	MST
Don Wuebbles	UIUC
Dorothy Koch	NASA GISS
Eric Jansen	NASA ARC
Fayette Collier	NASA
Gang Hong	Texas A&M Univ.
Gloria Kulesa	FAA
Gregg Flemming	DOT Volpe Center
Guy Brasseur	NCAR
Hermann Mannstein	DLR, Germany
Harshvardhan	Purdue Univ.
Hukam Mongia	GE
Ian Waitz	MIT
Ivar Isaksen	Univ. Oslo, Norway
Jacek Kaminski	York Univ.
Jan Fuglestvedt	CICERO, Norway
Jimy Dudhia	NCAR
John Brown	NOAA
John Haynes	NASA HQ
John Kinsey	EPA
John Mc Connell	York Univ.

John Murray	NASA LaRC
Jordan Wilkerson	Stanford Univ.
Jose Rodriguez	NASA GSFC
Joyce Penner	Univ. Michigan
K. N. Liou	UCLA
Karen Rosenlof	NOAA
Klaus Gierens	DLR, Germany
Lackson Murufu	NASA LaRC
Lin H. Chambers	NASA LaRC
Linnea Avallone	Univ.Colorado, Boulder
Lourdes Maurice	FAA
Malcolm Ko	NASA LaRC
Mark Jacobson	Stanford Univ.
Martin Stuefer	Univ. Alaska Fairbanks
Michael Prather	UCI
Mohan Gupta	FAA
Pat Minnis	NASA LaRC
Paul DeMott	CSU
Phil Rasch	NCAR
Piers Forster	Univ. Leeds, UK
Ping Yang	Texas A&M Univ.
Rich Stolarski	NASA GSFC
Richard Wahls	NASA LaRC
Rick Miake Lye	Aerodyne Research Inc.
Robert Howard	AEDC-ATA
Roberta C. Dipasquale	NASA LaRC
Saadat Syed	Pratt & Whitney
Shyam Lal	PRL, India
Steve Baughcum	Boeing
Steve Ou	UCLA
Steven Pawson	NASA GSFC
Terry Keating	EPA
Tom Land	EPA
Toshi Matsui	NASA GSFC
Ulrich Schumann	DLR, Germany
Ulrike Burkhardt	DLR, Germany
V. Ramaswamy	NOAA
W F J Evans	York Univ., Canada
Xiaohong Liu	DOE PNL
Xiaowen Li	NASA GSFC