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Aviation and the Global Atmosphere: The State of the Science and Future Research Needs

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Environmental concerns can constrain aviation growth. The topic of greatest uncertainty & contention is the impact of aviation on climate change. Immediate, focused action is required to address the climate impacts of aviation & reduce uncertainties to levels that enable appropriate action.

Global Commercial Flights

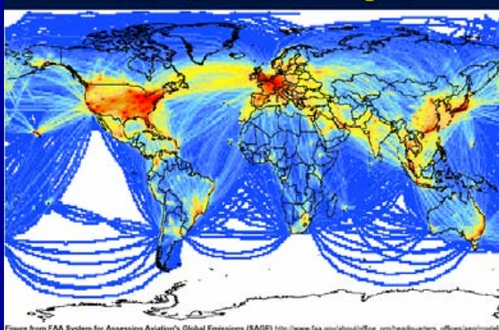
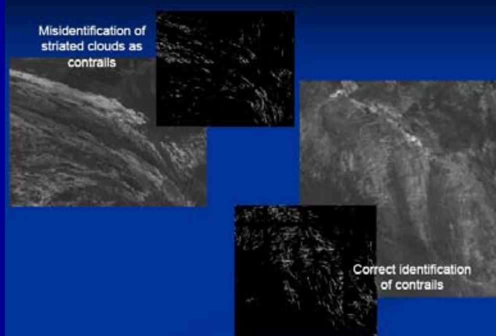


Figure from FAA System for Assessing Aviation's Global Emissions (SAGE) http://www.faa.gov/about/office_org/headquarters_offices/aep/models

Fuel burn/ CO2 emissions for year 2000 commercial flights

Contrail Masks versus Satellite Data



Radiative Forcing from Aircraft

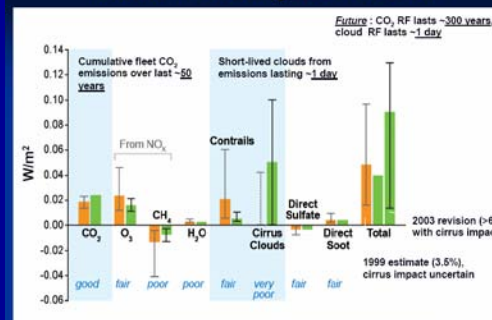


Figure adapted from IPCC (1999) with additional data from Schumann (2003)

"Further work is required to reduce scientific and other uncertainties, to understand better the options for reducing emissions, to better inform decision-makers, and to improve the understanding of the social and economic issues associated with the demand for air transport."

Aviation and the Global Atmosphere, IPCC 1999

Remaining Issues

Significant progress has been made in key areas since the IPCC report. The work done has answered many important questions and has helped to focus attention on the remaining open issues:

- particle emission characterization,
- contrail models,
- cloud models, and
- climate modeling

Potential New Projects

Enhance interaction with Climate Science community

- Improve models of long term contrail evolution (coagulation, sedimentation, interaction with atmospheric shear & turbulence)
- Understand transformation of contrails to cirrus clouds
- Assess satellite data to characterize contrails
- Improve understanding of what controls supersaturation & cirrus formation
- Enhance inventory of particulate matter & sulfate aerosols
- Acquire real world measurements from field studies
- Assess aviation signature within climate models

Aircraft Emissions in the Atmosphere

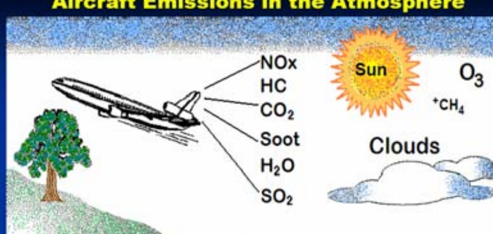
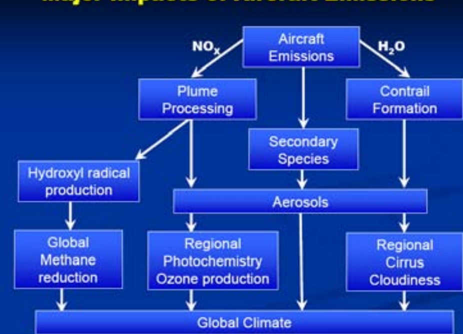


Figure adapted from 1999 Atmospheric Effects of Aviation Project NASA /FAA /EPA Partnership poster

Aircraft emissions consist of nitrogen oxides (NOx), hydrocarbons (HC), carbon dioxide (CO_2), soot (aerosols), water vapor (H_2O), and sulfur dioxide (SO_2). The degree aircraft emissions exert an influence on the atmosphere is determined by the magnitude and effect of the perturbations on critical chemical and/or climate processes. The resulting climate influence (greenhouse effect) occurs from increased ozone and carbon dioxide concentration in the upper troposphere, methane removal and increased cirrus clouds.

Major Impacts of Aircraft Emissions



Ice Cloud Microphysical Model

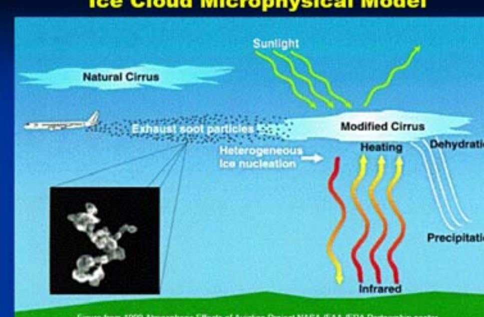


Figure from 1999 Atmospheric Effects of Aviation Project NASA /FAA /EPA Partnership poster

Cirrus have been identified as the most uncertain part of the climate modeling puzzl (IPCC FAR)

Aviation & the Global Atmosphere: The State of the Science & Future Research Needs

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Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER) is a Center of Excellence sponsored by FAA, NASA, & Transport Canada,

http://partner.aero

Advancing the Understanding of Aviation's Global Impacts

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Advancing the Understanding of Aviation's Global Impacts

A discussion of research after the IPCC report on Aviation and the Global Atmosphere

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1.1. Introduction and History

A proposed supersonic transport in the 1970s first piqued interest in the global environmental impact of aviation. A program was initiated by the US Department of Transportation, called the Climatic Impact Assessment Program (CIAP), which studied the effects of a fleet of Supersonic Transports (SSTs) on the atmosphere [CIAP; 1975; NRC, 1975]. Due to a variety of economic, environmental, and business issues, only a small number of supersonic commercial transports were built by a European consortium. The impact of the just over a dozen operational Concorde airplanes was never a global concern, but the groundwork was laid for studying how the emissions from airplanes might perturb the chemistry of the upper atmosphere.

In the 1990s, NASA and US industry concluded that significant technological advances had been made since the SST program was cancelled in the US and, that using technology then available, a more economically feasible supersonic transport could be considered. NASA launched a High Speed Research (HSR) Program to provide the research basis for the required technologies, and devoted an important element of the project to understand the potential environmental impact. The primary concern for this advanced supersonic airplane was the potential to chemically alter, via NO_x emissions, the ozone layer in the stratosphere, which had been getting much attention then due to damage from chlorofluorocarbons (CFCs) and due to the discovery of the ozone hole. The environmental impact element of HSR was dubbed the Atmospheric Effects of Stratospheric Aircraft (AESA) and was a collaboration of NASA Aeronautics and NASA Atmospheric Science research efforts [AESA, 1995, NRC 1999].

AESA soon was subsumed in a larger effort, the Atmospheric Effects of Aviation Project (AEAP), since it was realized that in order to understand the proposed supersonic fleet, the impact of the existing subsonic fleet needed to be understood. Thus AEAP had both AESA and the Subsonic Assessment (SASS) elements, exploring the impact of existing and future fleets on the atmosphere. In Europe, similar projects had already been started, after AESA but before SASS, examining the impact of the subsonic fleet, with prime examples being AERONOX [1995] and POLINAT [POLINAT, 1997, 1999]. The combined international effort greatly furthered the understanding of the impacts of cruising commercial airplanes on the atmosphere and went far beyond the initial motivating questions of ozone impact by a fleet of supersonic airplanes.

Many research articles and technical presentations at scientific meetings resulted from all of this activity, and this garnered the attention of a broader community, including international policy makers. Consequently, the International Civil Aviation Organization (ICAO) and the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer made a formal request to have these recent advances in understanding synthesized to "identify and characterize options for mitigating future impacts". This formal request was addressed to the Intergovernmental Panel on Climate Change (IPCC), which operates under the World Meteorological Organization and the United Nations Environment Programme to assess scientific information and to provide expert advice through their publications.

A major publication was written in response to this request to IPCC, with authors from the broad community of aviation and atmospheric science, many of whom were in the various international research programs already mentioned. ***Aviation and the Global Atmosphere*** [IPCC, 1999] was a complete and thorough documentation of the state of understanding at that time of how emissions at cruise altitudes affects the atmosphere. A much used resource, the contents of that report have guided the ensuing research and have begun to have influences with international policy making.

Indeed, further research has followed on the heels of the IPCC report, and additional understanding has been obtained, refining estimates and reducing uncertainties. However, the size of the research effort within the US fell abruptly not long after the

IPCC report was released, as NASA's HSR and Advanced Subsonic Technology (AST) programs concluded. In Europe, progress did not slow as abruptly, but partly through decreased EU research funding and partly through lack of synergies with the parallel US programs, overall activities in advancing understanding of the environmental impact of aviation diminished.

Notwithstanding the decreased activity since 1999, a number of significant advances have been made by the active research groups in the intervening years. The remainder of this report will summarize some of the key results that have been obtained in the past five years. Some of the attention of the research community has shifted to begin to include the environmental impacts of aircraft at ground level in and around airports. Where understanding in these local air quality impacts overlaps with the global atmospheric concerns, they will be included here, but there are a growing number of studies that focus on airport aircraft emissions that will not be addressed by this report.

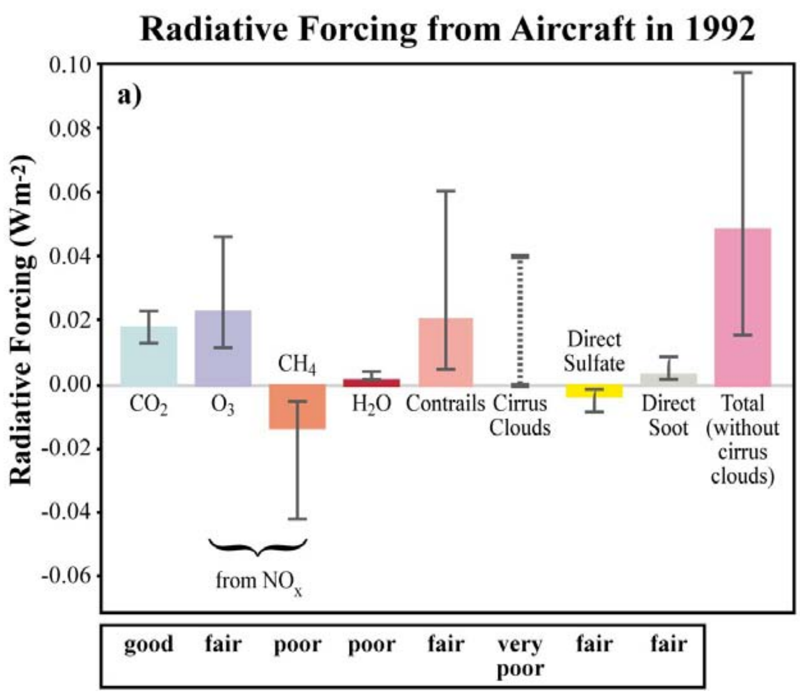
In the next section, a very brief summary will be given of the extensive set of conclusions contained in the IPCC report, emphasizing those areas where significant uncertainties were identified and those where significant progress has since been achieved. In the following sections, subsequent progress will be discussed, drawing especially on the proceedings of several international meetings held in Germany (A^2C^3 in 2001 and AAC in 2003) and in France (ISAIE in 2004), as well as on AEAP results as presented there or elsewhere.

IPCC Report Highlights and Uncertainties

The IPCC Report is a compendium of a wide range of technical work devoted to understanding the influence of aircraft emissions at altitude on chemical and radiative processes in the atmosphere. It covers:

- ozone chemistry
- emitted particles and cloud processes
- atmospheric modeling to include aviation impacts
- climate change calculations
- aircraft technology related to emissions
- emissions as determined by fleet operations
- current and future emissions inventories
- regulatory and market-based mitigation strategies

The report opens with a "Summary for Policymakers", which outlines the contents and main conclusions. In addition to being a brief tutorial on the subject and a statement of the potential problem that cruise emissions from aircraft may represent, a concise graphic captured the current scientific understanding of aircraft emissions. The estimated impacts due to various emissions and the degree of confidence in the estimates of their impacts was presented and has been since quoted often. Figure 2 of the "Summary for Policymakers" is reproduced here:



1.1.1. Figure 2 from Summary for Policymakers of the IPCC Report

The environmental perturbations due to emissions of CO_2, NO_x, H_2O, and particles (both soot and sulfate particles) were estimated for a representation of the fleet in 1992. The currency for comparison among the various emissions is radiative forcing, which quantifies the change in global radiative energy balance attributable to each emission. In addition to providing uncertainty estimates for these emissions as error bars, an evaluation was made of the relative appraisal of the scientific understanding used to make the estimate and provide the error bar. The situation as of the 1999 IPCC report indicates that there were many degrees of imperfection in the ability to quantify the impact from airplane emissions.

This figure shows the total radiative forcing in 1992 resulting from the accumulated CO_2 of all historical aviation operations prior to 1992, as well as the effects of contrails, induced-cirrus, NO_x and particulate matter, which have varying lifetimes much shorter than CO_2. There are three aspects of these estimates of radiative forcing that are important to recognize. First the impacts on surface temperature of these different radiative forcing sources differ by a factor of 3. Second, from an economics perspective they are "sunk costs" and thus are not an appropriate basis for making decisions on future actions. Evaluating marginal impacts of future actions is required. Third, only a small fraction of the total effects of CO_2 are represented (the first 10's of years of a 300 year cumulative impact). Because of the third item, when one looks to the future and evaluates the marginal future impacts of new aircraft operations (i.e. the impacts we can influence with new policies and technologies) a very different picture emerges. The relative importance to society of temperature changes due to the various emissions depends on the valuation of change at different times in the future. However such a future perspective, whether it is for a single flight or for the entire activity of a new aircraft over its life-time, appears likely to increase the relative importance of the emissions with the longer time-scale.

CO_2: The ability to predict environmental change due to CO_2 emissions is good and the uncertainties are small. This is due to the fact that efficient combustion in aircraft engines allow very reliable estimates of the emission levels based on fuel consumption and that CO_2's effect on radiation forcing is very well understood.

NO_x: While NO_x emissions levels can be estimated very well based on engine performance calculations and certification data, NO_x influences atmospheric chemistry through both ozone and methane, and this complicates the resulting overall radiative forcing. For ozone impact, airplane emissions can produce ozone when the emissions are in the troposphere and destroy ozone (via H_2O and sulfate) when in the stratosphere. For methane, NO_x reduces methane, but in a globally distributed sense. This is in distinction to the local production of ozone in flight corridors. Also methane sources and sinks in the atmosphere are not well understood, limiting the confidence in this impact of NO_x. In addition, contributions from lightning sources to the NO_x budget are not well understood and complicate the interpretation of the aviation source.

H_2O: Water vapor from aircraft can be estimated reliably and its deposition in the atmosphere is well understood, but atmospheric processing of water near the tropopause where airplanes fly is not well understood. The budget of water vapor depends on very different lifetimes for water in the troposphere (short) and in the stratosphere (long), and on transport across the tropopause. Though the estimate of H_2O emissions is accurate, the appraisal of the impact is still considered poor.

Particles: Emitted particles have a number of potential impacts on the atmosphere. Direct radiative effects due to the suspended particles themselves are fairly well understood and modest in magnitude compared to other emissions. The situation is complicated by the fact that particles can serve as nuclei for condensation, either immediately upon emission as a condensation trail, *i.e.* contrail, behind the airplane or later as a seed for the formation of a cirrus cloud roughly at flight altitudes. The physics of contrail formation is fairly well understood, but the radiative impact and frequency of occurrence still has many uncertainties. This results in a very large error bar for the contrail estimate. Contributions to this uncertainty include: lack of knowledge of the amount and nature of the particle emissions from airplane engines, their ability to act as condensation nuclei, their evolving nature in the atmosphere, the frequency with which contrails form in the atmosphere, and the radiative properties of the resulting ice crystal clouds.

The situation is even more uncertain for cirrus clouds. The dotted range for cirrus clouds in the Figure is meant to indicate that the understanding is insufficient to provide either an estimate or an uncertainty, but rather a range of possible best estimates is given. And this range is as large as the largest uncertainty of all of the emissions: that of contrails. Thus it can be clearly stated from the IPCC report that the biggest uncertainties associated with emissions from airplanes are due to possible impacts from particle emissions (both contrails and clouds). Additional uncertainties are associated with impacts due to NO_x as it affects ozone and methane.

The "Summary for Policymakers" also discusses the resulting climate effects for the current fleet, the trends as projected growth is accounted for, and various possible options for mitigating the impacts. These are important and very relevant aspects of the IPCC report, especially for policymakers. Any uncertainties in estimating the impacts will propagate on through the estimates for future scenarios and any mitigation strategies. Thus, for the purposes of this report and discussing advances in reducing uncertainties in scientific understanding, these other important aspects of addressing the potential future impact of aviation emissions will not be considered further herein.

Progress After the IPCC Report

The conclusions of the IPCC Report were used to guide research in both the US and Europe in the years after its release. Not surprisingly, issues of particle emissions and their potential impact on contrail and cloud processes became a research focus due to the large potential impacts, possibly exceeding those of CO_2, and due to the larger uncertainties relative to gaseous emissions impacts. Significant progress has been made on a number of specific questions, as will be highlighted below. On the other hand, due to decreases in overall support internationally, the rate of progress has not been as rapid as in the preceding decade. While AEAP had annual meetings, each showing great progress and accomplishments, the international community has been meeting on a semi-annual basis: in Seeheim, Germany in 2001 for a conference entitled Aviation, Aerosols, Contrails, and Cirrus Clouds [A^2C^3, 2001], and in Friedrichshafen, Germany in 2003 for Aviation, Atmosphere, and Climate [AAC, 2004]. The conference proceedings from these meetings provide very useful summaries and references to the research progress over the years since the IPCC report was completed.

Engine Emissions Characterization: Experimental programs to measure the particle emissions from aircraft engine technology have proceeded on both sides of the Atlantic. Both full engine, on-wing measurements and rig measurements were carried out. On-wing measurements were carried out in two NASA sponsored activities, called EXperiment to Characterize Aircraft Volatile Aerosol and Trace species Emissions (EXCAVATE in 2002) and Aircraft Particle Emissions eXperiment (APEX in 2004). Rig measurements were carried out in NASA/QinetiQ collaborative program in 1999 and 2001, and in a EU collaboration called PartEmis in the same years, shifted a few months later, following in the footsteps of NASA/QinetiQ.

NASA/QinetiQ [2002] was designed to explore the evolution of particles and particle precursor gases as they are transported through the turbine and nozzle of the engine. Results from measurements made at the combustor exit and subsequently at the engine exit measured the variation in particle properties and suggested growth of the particles. Further, variations in the gaseous emission HONO along the post combustor flow was consistent with chemical kinetic modeling, providing increased confidence in our understanding of oxidative chemistry of precursor gases. The following study carried out by an EU collaboration, PartEmis, [PartEmis, 2004] expanded on the NASA/QinetiQ results and interpreted the changes in particle processes between the combustor and the (simulated in the case of PartEmis) engine exit to be within limit of reproducibility of engine conditions (and measurements). These two independent studies accentuate the difficulty in making precise measurements of particle processes, and emphasize that probe sampling issues and sampling handling are extremely important when attempting to make quantitative comparisons, especially between widely different thermodynamic environments.

Both NASA/QinetiQ and PartEmis provide reinforcing evidence that the carbonaceous aerosol and other gaseous emissions are largely independent of the fuel sulfur content (FSC). These studies also indicate that less than 3% of the fuel sulfur is emitted in the higher oxidation state, S(VI) (SO_3 and/or H_2SO_4), depending on temperature. The majority is emitted at SO_2. While this constraint is becoming a very robust experimental conclusion, the variation of fuel sulfur conversion to S(VI) across engine technologies and across operating conditions for a given engine technology has only been explored by models and experimental verification of the calculated trends is still lacking, due to the difficulty in quantifying the emitted sulfate in a wide variety of engine measurements.

PartEmis had a wider range of measurement techniques deployed than NASA/QinetiQ and was able to distinguish a large effect of fuel sulfur on the increased hygroscopicity of the emitted particles, and thus on their CCN activity. This is important for understanding their involvement in contrails and cloud processes, and has been explored in laboratory studies as well. PartEmis results also indicated that organic emissions decrease with higher power conditions, which reinforces similar conclusions for a wider range of engine conditions explored in on-wing measurement programs.

EXCAVATE [2004] and APEX [2004] both focused on looking at on-wing engines across a range of engine powers for fuels with various fuel sulfur levels (and differing aromatic content for APEX). APEX hosted a very wide range of measurement technologies, partly to evaluate the merits of the participating instruments and partly to ensure the most reliable conclusions could be obtained through redundant, overlapping measurements. In both tests, the focus was on obtaining measured EIs for particles and condensable gases versus engine power, fuel type, and distance behind the engine.

As a result of these studies, the characterization of particle emissions from the two engines employed has been accomplished to a unique degree of completeness. The engines are representative of engines in the commercial fleet, yet how these results are applicable to fleet assessment is still to be determined. Because of the completeness of these studies, many results are still forthcoming. However, many significant conclusions are already evident.

First, the emissions of carbonaceous particles (soot) are strongly increasing at the highest engine power conditions. Both the number and size of the particles increase as power increases, and the characteristics of the carbonaceous, nonvolatile emissions do not evolve from the engine exit to distances of several 10s of meters behind the engine. That is to say, the nonvolatile particles created in the combustor do not evolve significantly after leaving the combustor, as long as only the nonvolatile component is being considered. On the other hand, several classes of condensable gaseous emissions do condense on these nonvolatile particles as the temperatures drop in the plume due to the mixing of ambient air with hot exhaust.

In EXCAVATE, the first evidence was obtained that engine lubrication oil could participate as a component in the condensed organic fraction in the downstream plume particles. The speciation of hydrocarbons in the gas phase at the engine exit plane and in the particles was explored more fully in APEX and it is possible that engine oil contributes to the downstream particles also for that engine, but the relative role is still being resolved. Other contributions from partially oxidized fuel components may also play an important role, and the relative contributions and their implications will be an area for active future research.

In both EXCAVATE and APEX, sulfate is found to condense in the plume, contributing to condensed mass both on the nonvolatile particles and in newly formed volatile particles, which are much smaller in size than the nonvolatile carbonaceous particles. The amount of sulfate is not as strongly dependent on engine power as the nonvolatile particle emissions and the possible role of organic emissions in forming and adding to these volatile particles is being studied, based on APEX data. Interestingly, gaseous organic emissions drop dramatically as power increases from the lowest power settings, while the condensed organic fraction in the plume does not decrease in the same way. For the engines used in EXCAVATE and APEX, the condensing gaseous species are being deposited in the 10s of meters behind the engine, with significant effects evident at 25 – 30 m. To what degree these condensation processes are complete at 30 m and how the particulate matter further evolves at larger downstream distances is still an open question.

Additional aviation emissions studies were carried out late in 2004, at a major North American airport (airport study UNA-UNA), and in the second half of 2005 (JETS/APEX2 in Oakland, California, and a planned mission in Cleveland, APEX3). In these studies, both dedicated engine tests, like EXCAVATE and APEX, and airport runway studies measuring in service airplanes during routine operation were carried out. Analysis and reporting of these studies is currently ongoing and will contribute significantly to the initial studies already carried out.

Laboratory Studies of Carbonaceous Particle Properties: Starting with laboratory studies during SASS [1997], the chemical and microphysical properties of carbonaceous aerosol has been explored. SASS results have demonstrated that carbonaceous particles do not act as a catalyst for ozone reactions and, in fact, soot reactivity with ozone decreases with time. On the other hand, sulfate particles do interact chemically, perturbing NO_x and ozone levels, and thus we need to know the conversion fraction of SO_2 to sulfate for aviation technologies, as well as the size of the particles providing the sulfate surfaces for reactions (e.g., condensed on soot particles versus forming new, smaller particles – and what is available as particle surfaces for heterogeneous reactions).

A wide variety of results, including PartEmis (mentioned above) and Popovicheva [AAC] and Möhler [AAC, ISAIE], demonstrate that condensed sulfate enhances the ability of carbonaceous particles to act as condensation nuclei for water condensation in contrails or clouds. However, the absence of sulfate does not completely preclude hygroscopic behavior, and the possible role of the properties of the carbonaceous surfaces is being explored. Possible factors include reactivity of the surface providing bound oxygen or sulfur as nucleation sites or condensed organic species offering opportunities for water condensation, although perhaps at a reduced level compared to that due to a sulfate coating. In addition to cloud condensation nucleation properties, ice nucleation is important for understanding the transition of a contrail to cirrus-like properties. Initial work on the impact of sulfate on ice nucleation is demonstrating that sulfur enhances ice nucleation as well [Möhler, ISAIE].

Plume and Contrail Studies: Chemistry and condensation that occurs immediately behind the airplane can change the emissions in important ways. Global models that calculate the impact of emissions cannot resolve processes that are much smaller than the grid used in the calculations, so it is important to track the emissions' evolution until they are dispersed on a global grid scale. From the point of view of chemistry, two assessments have recently been done [Kraabøl, 2000; Plumb et al., 2004] to determine whether the changes in the plume are important relative to simply applying the engine exit plane chemical composition to the global grid at the appropriate concentration. Consensus has not yet been achieved on this question, since the results range from very small effects (3%) to significant effects (~20% or more).

From the point of view of contrails, the processes occurring in the plume are paramount and have explicit global consequences. Studies have begun examining the effects that aircraft technology has on contrail production. For example, the propulsion efficiency can affect the precise temperature at which contrails form [Schumann, A^2C^3; Detwiler and Jackson, 2002]. Application of such effects in detailed modeling studies is now possible. Tools have been developed to simulate the flow and various levels of detail in chemistry and, particle microphysics using Large Eddy Simulation (LES) [Dürbeck, 1996; Lewellen and Lewellen, 2001; Chen and Lin, 2001; Paoli, 2004; Garnier, 2004]. These models have been applied to both the aircraft-influenced near field and the late contrail dispersion phase. While the importance of contrail processes is indisputably important to global assessments, details ranging from airplane technology effects, through particle emission details, to evolution to cirrus-like properties have yet to be fully explored to identify the critical contrail parameters that affect the global impact.

In the absence of an accurate simulation of the evolution of a contrail to a cirrus-like cloud, satellite data has been used to estimate the contributions of contrails and the resulting clouds to changes in the radiative forcing. Overall, the current best estimates of the radiative forcing from contrails have been reduced relative to what was reported in IPCC, but the uncertainties have increased [Schumann, AAC]. Additional work in analyzing satellite data is ongoing, with widely ranging estimates of the net radiative impact [Minnis, AAC; Mannstein, AAC]. The increased uncertainty found in the current assessment lies in the calculation of the radiative impact from contrails. But within this range of uncertainty, Minnis et al. [2004] have suggested that warming of the troposphere, and the resulting effects on surface temperature, over the U.S. between 1975 and 1994 can be attributed to contrails. This has become something of a controversial claim, and further studies will be required to support or refute whether this large an impact from contrails has already become manifest. Clearly, a strong research program is required to assess whether aircraft could be already perturbing the environment at a level that is suggested by this extreme prediction.

Cloud Studies: The impact that particle emissions from airplanes have on cirrus clouds is an area of on-going active research. At all of the recent international meetings, cirrus clouds have been an essential subject. The basic microphysical properties of the emitted particles, as examined in laboratory studies, are primary inputs to understanding their impact on clouds, but many environmental factors also contribute to cloud formation. Discerning the difference that is made by aviation emissions at cruise altitudes requires determining the way all of these factors interact.

The contribution of condensation nuclei by airplanes needs to be considered in the context of other biogenic and anthropogenic aerosol in the atmosphere where the airplane deposits its particles. While soot is an important constituent of the aerosol near the tropopause, the contributions from aviation and from biomass burning in the tropics have not been fully resolved [Baumgardner, AAC]. In addition, the physical properties of aviation emissions and the transported surface emissions may be quite different, for fresh aircraft emissions. The possibility of heterogeneous nucleation of ice on these particles will determine their ultimate impact, yet modeling of such processes is just beginning.

Beyond the nucleation capability of particles, other aspects of cloud formation still require a better understanding as well. The relative humidity of the local environment determines formation and persistence of both contrails and cirrus clouds, and the humidity is determined by local water vapor concentrations. Clouds form and exist at scales smaller than the few degrees latitude/longitude and few km altitude grid that global models use. Thus the processes that affect clouds are "sub-grid scale", that is smaller than what the global models can resolve. The fine scale features of the water concentration also make the relevant water budget difficult to determine by satellite measurements or field studies due to the high resolution required. This discrepancy of scale has become an important part of recent studies, such as EU's MOZAIC and PAZI, and NASA's CRYSTAL-FACE, which have identified significant small scale features in the water distribution and local anomalies of supersaturation. These are important advances in understanding what drives contrail and cloud processes, however work is still required before this understanding can be applied to reducing uncertainties in global impacts.

Modeling of Global Impacts: The General Circulation Models (GCMs) used in IPCC included the transport and chemistry of gas phase species and heterogeneous reactions on aerosol surface area. Soot impact on cirrus formation was not yet in those models at that time. Initial calculations are now being performed that include emitted particles influencing cirrus formation [Penner, AAC; Hendricks, AAC], and they suggest that aviation particles may be significant. However, at this early stage, it remains unclear whether the radiative impact is positive or negative (more nuclei may make more smaller cloud particles, reducing the radiative effect). Clearly, much more needs to be done, determining how to include relevant particle emissions parameters, to represent sub-grid scale plume processing, and account for variations in the water concentration field, among others.

Beyond the inclusion of particles in GCMs, a number of issues related to the uncertainties in effects already in GCMs still need to be addressed. The uncertainties in NO_x forcing of ozone and CH_4 reported in IPCC are smaller than those due to cirrus and contrails, yet the disparate effects on ozone (local) and methane (distributed) as well as differences in their lifetimes, require improvements in our understanding there. Especially important from the point of view of aviation, the details of transport between the troposphere and stratosphere across the tropopause affect how NO_x affects ozone and methane, and this transport occurs where airplanes typically fly. Also, the NO_x emitted by airplanes adds to the overall NO_x budget in the atmosphere, yet the contributions from natural lightning sources are not well known and are distributed in the atmosphere unlike ground sources. These and other contributions to the uncertainties in NO_x radiative forcing estimates have continued to be addressed since IPCC, and are still being analyzed. Similarly, determinations of all of the chemical kinetic rates used in GCMs is regularly being assessed and updated to increase the accuracy of the GCM chemical calculations.

The uncertainties in particle impacts and NO_x effects in GCM calculations are being addressed in ongoing research, but it is also important that these studies are examining not only the instantaneous forcings, but also accounting for the Absolute Global Warming Potential of specific emissions. So, while there are few uncertainties in the radiative impact of CO_2 and attention is focused on reducing uncertainties in NO_x and particle impacts, the long lifetime of CO_2 in the atmosphere must be accounted for in assessing the relative contributions of engine emissions and possible tradeoffs between them in mitigation strategies that may be considered [Ko, 2004]

1.2. Suggested Future Directions

Significant progress has been made in key areas since the IPCC report. The work done has answered many important questions and has helped to focus attention on the remaining open issues. These can be categorized as being related to:

- particle emission characterization,
- contrail models,
- cloud models, and
- GCMs and climate models

Particle Emissions Characterization: Many important advances have been made in understanding particle emissions from aircraft engines. However, unlike gaseous emissions, many parameters are needed to quantify the particle emissions, and several of the resulting particle parameters evolve rapidly soon after emission. Thus more understanding is required to apply all of the knowledge recently obtained. There is a need to fully characterize particle emissions from representative aircraft engines (and refine gaseous emissions inventories as needed) and begin to develop a database for a wide range of engine technologies. Special attention should be focused on condensable species that play a role in microphysical processes that may impact cirrus clouds, like sulfuric acid and any relevant condensable hydrocarbons. In particular, it is important to be able to quantify what fraction of the fuel sulfur participates in particle processes immediately after emission and which condensable organics play a role in coating soot and forming new particles. Further, a basic understanding needs to be developed to interpret the emissions database in terms of the breadth of atmospheric conditions in which airplanes fly.

Laboratory studies of carbonaceous particles, their interaction with condensable sulfate and organic species, and their ability to condense water vapor and nucleate freezing have progressed significantly since the IPCC report. However, as characterization of the particle emissions from airplanes improves and progresses, those laboratory studies will need to be extended to assess advances in the understanding of the composition and surface properties of the resulting particles.

Contrail Models: The basic conditions for contrail formation and initial understanding of what aircraft parameters are important to contrails have now been established. The subsequent evolution of contrails into cirrus clouds and the radiative properties of the ice crystals throughout that process must be understood more fully. In addition, the ability to calculate the frequency and extent of contrail coverage is evolving rapidly, and discrepancies in current analyses need to be resolved. To support these efforts, global gridded inventories of soot and sulfate aerosols are required, based on emissions characterization measurements. Also detailed understanding of background aerosol loading and water vapor distributions will be necessary. The longer-term evolution of contrails into cirrus clouds must account for small-scale atmospheric dynamics, radiative processes involving the contrail particles, and the microphysical evolution of the growing ice particles themselves. Finally, there is also a need to understand how aircraft particle emissions impact cirrus formation and the resulting clouds even when no contrail forms behind the emitting airplane.

Cloud Models: Building on the microphysical modeling of contrails, the cloud properties of the resulting cirrus clouds need to be explored. Connections between the near term microphysics of a persistent contrail (numerous small, nearly spherical ice particles) need to be made with a cirrus cloud that has properties that begin to approach those of a "natural" cirrus (ice crystal habit and number density). In what ways do the aircraft emissions continue to exercise control over the cirrus properties, via differences in radiative properties such as absorption due to black carbon? As in the contrail modeling studies, cirrus cloud models need reliable background aerosol distributions, water vapor concentration fields and small-scale atmospheric dynamics, which can drive vertical motions. Field measurements that provide these inputs and measure evolving nuclei and cloud particle properties to validate model calculations are needed both in and outside of air traffic corridors, and in and out of cirrus clouds.

GCMs and Climate Models: The first calculations using GCMs to assess the impact of aircraft particle emissions have been accomplished in the past few years. Continued interaction between contrail and cloud modeling activities are essential to explore proper and scientifically sound means to parameterize contrails and related plume/wake sub-grid processes accurately in global models. Until such causal relationships between aviation emissions and sub-grid processes can be established and data are available for sub-grid phenomena, inclusions of these contrail and cloud effects as sub-grid processes will necessarily be parametric and statistical, and will be left with significant uncertainties. In addition to contrail effects, discrepancies regarding the effects of plume processing of gaseous species on global impact need to be resolved. Contrail identification algorithms based on satellite image analysis need to be rigorously tested and applied to global impact assessment to resolve differences in interpretation of the radiative impacts currently being reported. In concert with satellite analysis, the water vapor distribution at cruise altitudes near the tropopause, including sub grid statistics, must be better understood if reliable predictions of contrail frequency, duration, and optical properties are to be achieved. Causal relationships between near field airplane parameters and the resulting cloud property inputs to global models need to be established to quantify aviation impacts due to contrails and clouds.

The uncertainties remaining in interpreting NO_x emissions effects on ozone and methane also motivate further research. Improved understanding is required for the non-aviation NO_x budget (transported ground sources, lightning), stratosphere/troposphere exchange across the tropopause, and possible cloud processing of emissions. Global modeling of the troposphere, in combination with improved understanding of HO_x and NO_x chemistry and their interactions with atmospheric radical and reservoir species, will help to reduce the uncertainties in NO_x impact on ozone and methane and the resulting radiative forcing changes. Interpreting these radiative forcings in terms of absolute global warming potentials will inform both the determination of the relative long-term impacts of all engine emissions and the evaluation of tradeoffs in mitigation strategies that may be considered. In addition to calculations using global models, laboratory chemical kinetics studies and field measurements in the atmosphere should be pursued by the atmospheric science community.

1.2.1.1. Research Issue	**a. Relative** **b. Uncertainty**	**c. Time Prior ity**
Particle Emission Characterization		
Non-volatile particle data	Moderate	Immediate
Role of condensables (sulfate, organics)	High	Immediate
Particle contrail/cloud properties	High	2-5 years
Contrail Models	High	Immediate
Cloud Models	High	2-5 years
GCM and Climate Models	Moderate or High for different impacts	2-5 years

Table: Research issues, uncertainties, and time priorities. The four areas of suggested future work are ranked for current levels of uncertainty and prioritized in time for the sequence in which the uncertainty reductions can be propagated through the assessment process.

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