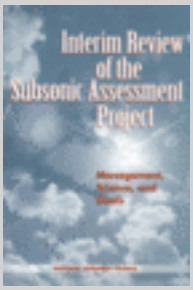

Interim Review of the Subsonic Assessment Project: Management, Science, and Goals

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Interim Review of the Subsonic Assessment Project

MANAGEMENT, SCIENCE, AND GOALS

Panel on Atmospheric Effects of Aviation

Board on Atmospheric Sciences and Climate

Commission on Geosciences, Environment, and Resources

National Research Council

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Preface

The Subsonic Assessment (SASS) project is the half of NASA's Atmospheric Effects of Aviation Project (AEAP) that is oriented toward the current and future fleets of subsonic aircraft flying in the upper troposphere and lower stratosphere. A component of the Advanced Subsonic Technology Program, SASS has the overall objective of developing an assessment that can answer the questions of how aircraft emissions and their subsequent products affect ozone, radiative forcing, and, ultimately, climate. Begun in late 1993, SASS collected data and developed models in 1994 and 1995, and undertook its first field campaign in 1996. A first project report was also issued in 1996; this panel has drawn heavily on that report in evaluating the progress of SASS. NASA's first assessment report on SASS is due to be published in mid-1997.

The present review of SASS is the product of the NRC Panel on the Atmospheric Effects of Aviation (PAEAN). PAEAN consists of sixteen people selected to provide expertise in relevant fields that include field observations, laboratory chemistry, atmospheric dynamics and modeling, aircraft engines, climate, and public policy. The charge from its NASA sponsor, AEAP, is to provide assessment of and guidance to AEAP by evaluating the appropriateness of AEAP's research plan, appraising the project-sponsored results relative to the current state of scientific knowledge, identifying key scientific uncertainties, and suggesting research activities likely to reduce those uncertainties. The effects of the current subsonic fleet are of particular concern at the moment, and in this report (one of three in process) PAEAN has focused on how AEAP can most effectively increase understanding of the processes involved. Only issues relating to impacts on the upper troposphere have been addressed, however; possible

impacts of the current fleet on the lower stratosphere will be discussed in a future review. This panel's report on SASS evaluates progress on each of the relevant project topics and makes specific recommendations for the next steps. It also presents two recommendations for more effective project management.

PAEAN has met four times as a panel, and each of its working groups—supersonic/stratospheric, subsonic/tropospheric, and emissions—has met on its own. The tropospheric group put together the initial draft of this document, and we thank them for their efforts. We appreciate the skill and perseverance of our staff officer and editor, Ellen Rice, and the administrative support of Doris Bouadjemi. Last, we are grateful to the many people, both those involved with AEAP and those outside it, who through briefings and reports have kept us apprised of the progress of SASS and the science.

Albert J. Kaehn, Jr.
PAEAN Chair

Contents

Executive Summary

Exhaust products emitted by the current subsonic-transport fleet may influence tropospheric ozone and clouds, and thus Earth's climate. Such emissions in the upper troposphere may affect climate at the surface of the Earth by means of many chemical and meteorological processes. Some of these processes are poorly understood, and thus cannot be quantified with much certainty. NASA's Atmospheric Effects of Aviation Project (AEAP) has as its objective the development of a scientific basis for assessment of the atmospheric impacts of the exhaust components of subsonic and supersonic fleets of civil aircraft. The NRC's Panel on Atmospheric Effects of Aviation (PAEAN) has been requested to evaluate the appropriateness of AEAP's research plan, appraise the project's results, and suggest how best to reduce the remaining uncertainties.

It is essential that AEAP apply its research funds where they are most likely to reduce the major uncertainties. This report evaluates the scientific questions being addressed in AEAP's Subsonic Assessment (SASS) project that are related to the perturbation of the ozone and aerosol concentrations in the upper troposphere, and discusses setting priorities for this research support. It provides preliminary recommendations related to work in each of the four main atmospheric-science foci of SASS: laboratory studies; two groups of observations designed to increase our knowledge of relevant processes in the troposphere (chemical and radiative); and the Global Modeling Initiative. The main thrust of these recommendations is the need to (1) study the sensitivity of key species in the upper troposphere and lower stratosphere to various chemical and dynamic processes, and (2) endeavor to characterize the same region as regards aerosols.

These steps will make it possible to quantify uncertainties (or at least bound them), focus fieldwork most profitably, and optimize model design.

In addition to making these scientific recommendations, the panel recommends two important program-management steps. To achieve the desired results from the SASS project, and to employ the available funds most effectively, it is essential that AEAP first draw up and execute an adequately detailed, prioritized, unambiguous research working strategy and plan. Some of the elements needed exist in various documents, but nowhere is there a single strategy that sets out the important topics, evaluates them in terms of costs and benefits, and assigns them priorities that also reflect the associated uncertainties and sensitivities. Second, AEAP needs to give SASS strong scientific leadership. To ensure that the many tasks involved contribute measurably to the goals of this single research strategy, the science must be managed by a person with recognized experience and authority, who is in a position to manage the implementation of the strategy through the end of the project.

Introduction

Like all fossil-fueled power plants, aircraft engines emit a variety of gases (among them carbon monoxide and dioxide; water vapor; methane and other hydrocarbons; and oxides of nitrogen, hydrogen, and sulfur), as well as particles such as soot. Each of these can affect Earth's climate, either directly or indirectly —for instance, by adding to the "greenhouse gases", by reducing or increasing ozone concentrations, or by providing nuclei that influence cloud formation. Subsonic-aircraft exhaust components are of concern because they are emitted primarily in the upper troposphere and the lowermost stratosphere, a region where additions are thought to have a relatively large effect on global climate.

Not all atmospheric processes at these altitudes are well understood, particularly those involving cloud physics and upper-tropospheric chemistry. Nor is there a large number of observations to provide "background levels" with which levels measured in high-traffic areas could be compared, or by means of which natural variability could be defined. Recent work has suggested that climatic impacts of upper-tropospheric ozone changes caused by the current subsonic aircraft fleet should be relatively minor, but impacts of aircraft-related particles on climate and lower-stratospheric ozone are largely unknown. Furthermore, with air traffic a rapidly growing part of the transport sector, especially in developing countries, this particular type of fossil-fuel pollution is likely to increase more rapidly than others.

NASA's Atmospheric Effects of Aviation Project (AEAP) has as its goal the development of a scientific basis for assessment of the atmospheric impact of the exhaust constituents discharged during cruise operations by fleets of subsonic and supersonic civil aircraft. AEAP has two subprojects. The Atmospheric

Effects of Stratospheric Aircraft project (AESA, a subelement of NASA's High-Speed Research Program) is designed to develop the body of scientific knowledge necessary for evaluating the impact of stratospheric aircraft on the atmosphere, whereas the Subsonic Assessment project (SASS, an element of the Advanced Subsonic Technology Program) is designed to develop an assessment that can say how aircraft emissions affect radiative forcing and climate, as well as how they affect ozone. The October 1996 colloquium organized by ONERA (the French Office National d'Etudes et de Recherches Aérospatiales) and the Comité Avion-Ozone showcased an impressive amount of research into aviation emissions and their behavior, and it was clear that investigators sponsored by AEAP were making major contributions. The NRC's Panel on Atmospheric Effects of Aviation (PAEAN) judges that AEAP has made significant progress, but that some shift in priorities could help reduce uncertainties more rapidly and, in a time of increased budget pressures, increase return on the taxpayers' investment.

The SASS component of AEAP (a relatively new undertaking) is designed to assess the effects of emissions from both the current world fleet of subsonic aircraft and a likely larger future fleet. The next chapter of this PAEAN report discusses two of the major issues related to the current subsonic air fleet's emissions: the emittants' potential effect on ozone, principally through NO_x, and the possible radiative forcing of climate resulting from aerosol scattering and increased cloudiness. The following chapter looks at each of the atmospheric-science topics of the SASS project as they appear in Table 1-2 of the first SASS report (Thompson et al., 1996), notes some questions and comments, and makes specific recommendations. Last, two overarching recommendations are presented for the project as a whole, which PAEAN considers to be of the utmost importance: the development of a complete, coherent, detailed strategic research plan, and the designation of a strong, experienced scientist to be charged with its implementation.

This PAEAN report discusses only tropospheric issues; emittant deposition in, or exchanges and/or interactions with, the lower stratosphere will be reviewed in a later report. Also, the project elements that deal with emissions characterization and interactions in the near field (the region in which the emissions are still influenced by aircraft-related effects) are reviewed in a separate report now in press, *An Interim Assessment of AEAP's Emissions Characterization and Near-Field Interactions Elements* (NRC, 1997). A report on the AESA project is in preparation.

Atmospheric Effects

Much of the SASS-sponsored research to date has focused on aviation emissions' chemical effect on upper-tropospheric ozone (O_3), and on how much such emissions add to the number of atmospheric aerosol particles. One of the most important potential consequences of aircraft emissions' effects on the troposphere is the possible alteration of climate through perturbations of ozone and aerosol concentrations. Ozone is highly reactive chemically, and is also a strong specific greenhouse gas that absorbs atmospheric radiation in the troposhere. Aerosols not only absorb radiation, but also can change the direction of light propagation (usually in anisotropic ways), commonly referred to as scattering. They have indirect effects as well, since they can serve as nuclei promoting cloud formation and as surfaces for heterogeneous reactions. Both ozone and aerosols are discussed in greater detail below.

OZONE

In 1990 commercial aircraft consumed roughly 170 million tons of fuel per year (about 3 percent of the total fossil fuel burned), and that consumption is expected to increase at a rate of 2 to 3 percent per year (WMO, 1995). Moreover, about 60 percent of the aircraft exhaust is emitted into the upper troposphere, a region that otherwise receives only weak, attenuated input from anthropogenic or natural emissions at the Earth's surface.

Aircraft emissions already contribute significantly to the NO_x budget of the upper troposphere, up to 50 percent in the most heavily traveled corridors—a major perturbation. Because NO_x catalyzes the formation of O_3 by the slow

photochemical oxidation of CH_4, CO, and possibly other volatile organic compounds (VOCs), the possibility of an increase of O_3 in the upper troposphere has become an immediate concern. Various groups have presented model calculations of the expected O_3 increase, but at present the magnitudes of the numbers resulting from such calculations should be considered highly uncertain.

The concentration of ozone in the upper troposphere is the result of transport of ozone from the stratosphere plus net production in the troposphere (Roelofs and Lelieveld, 1995). The chemical ozone-formation rate depends on the local NO_x concentration in a highly nonlinear fashion. The contribution of NO_x from aircraft could thus lead to an increase or decrease in the local rate of O_3 formation, depending on the NO_x concentration already present. When averaged zonally, O_3 production prevails, and because of ozone's long lifetime in the upper troposphere, current models predict an increase in O_3 as a result of aircraft emissions everywhere in the upper troposphere (Ehhalt and Rohrer, 1995; Brasseur et al., 1996).

The unperturbed NO_x concentration field, however, is poorly known and poorly understood: Available measurements are insufficient to characterize well the background distribution of NO_x, and other source processes that introduce NO_x into the upper troposphere (namely, lightning, convective transport from the boundary layer, and input from the stratosphere) are insufficiently quantified to permit reliance on model calculations of background NO_x. The resulting uncertainties propagate to the averaged O_3 production rate.

Local formation of O_3 also depends on temperature and on O_3, H_2O, CO, and VOC concentrations. The latter dependence arises because the local formation of ozone in the upper troposphere and lower stratosphere is also catalyzed by oxides of hydrogen, or HO_x (OH and HO_2). HO_x is produced primarily from ozone, ultraviolet radiation (which varies with the stratospheric total-ozone column), and water, and is maintained by reactions with CO and VOCs. Removing current uncertainties in predicting impacts of aircraft exhaust on upper-tropospheric O_3 will require substantial research that quantifies the processes governing upper-tropospheric catalysts (NO_x and HO_x) and reactive trace gases (globally, mainly CO, and regionally, VOCs as well).

Furthermore, in view of the longitudinal variations of background and aircraft-emitted NO_x, and of the non-linear response of local ozone production to NO_x, PAEAN believes that realistic assessments of O_3 changes can be made only with three-dimensional chemical-transport models of both the troposphere and stratosphere that effectively represent the salient features of horizontal and vertical transport as well as the pertinent chemical reactions. Defining actvities to test and evaluate such a model must be a primary, although difficult, task of SASS.

PAEAN's preliminary recommendations in this area are to:

- Study the sensitivity of the NO_x, HO_x, H_2O, CO, VOC, and O_3 budgets in the upper troposphere and lowermost stratosphere to the transport and chemical processes thought to be most important to them.
- Provide a quantitative analysis of the current uncertainties in the NO_x, HO_x, H_2O, CO, VOC, and O_3 budgets in the upper troposphere and lowermost stratosphere resulting from these processes.
- Set targets for the uncertainty levels that SASS research should be able to achieve, and use them as guides for prioritizing research in future field studies and AEAP's Global Modeling Initiative (GMI).

AEROSOLS

"Aerosols", properly called "aerosol particles", are liquid or solid particles suspended in air. Ubiquitous throughout the atmosphere, aerosols arise from a variety of natural and anthropogenic processes. Particles larger than about 1 mm diameter are generally dominated by mechanically derived sea salt, dusts, and fly ash, whereas smaller particles (e.g., sulfates and soot) typically arise and grow via gas-to-particle conversion in gas plumes (from, e.g., volcanoes and combustion), in cloud-free air, and through processes occurring within clouds and cloud droplets. The size distributions, compositions, and concentrations of aerosol particles reflect a dynamic balance among source, transport, evolution, and removal mechanisms that vary in both space and time. (For instance, some particles and gases are injected from the atmospheric boundary layer into the upper troposphere and lower stratosphere by deep convection. Because of concurrent removal through precipitation, however, this injection process is not so efficient for particles as for gases with only slight solubility in water, such as NO and NO_2.) These and other processes result in a "background aerosol" present in the free troposphere, and it is the nature and significance of perturbations of this background aerosol by aircraft emissions that must be evaluated in the SASS project.

The background aerosol can be highly variable, with large excursions in effective particle size and with mass concentrations ranging over three orders of magnitude (Clarke, 1993). The surfaces of these particles may act as sites for preferred chemical reactions ("heterogeneous" chemical reactions), which can further influence the evolution of the size distribution and its chemistry. In turn, these physical and chemical properties directly affect the interactions of the particles with light and the abilities of the particles to nucleate cloud droplets and ice crystals. Therefore, any "signal" caused by aircraft exhaust must be identified and assessed within the context of this variable background.

Determining the possible climate perturbation becomes very complex when both the links with ozone concentration and the role of aerosols are included.

Assessments of aircraft perturbations of aerosols must evaluate influences on atmospheric chemistry, clear-air radiative transfer, cloud-droplet and ice-crystal nucleation, and the associated optical properties of clouds. Aerosols alter the forward- and backscattering of radiation, as well as lead to absorption in some situations. Particles that scatter light effectively at relative humidities below saturation, yielding direct radiative effects, are usually about 0.1 to 10 μm in diameter; normally they dominate the aerosol mass concentration in the upper troposphere. One subset of the total aerosol population, which can grow into cloud droplets through the condensation of water vapor at typical cloud supersaturations, is called cloud condensation nuclei (CCN). Another subset of particles (not necessarily disjoint), which are most effective as sites for water-vapor deposition leading to ice-crystal formation and growth in cold clouds, is identified as ice nuclei (IN). The roles of IN versus CCN for the formation of ice clouds appear to be temperature dependent. IN are important above –38°C; below –40°C homogeneous nucleation seems to dominate the ice-forming process, depending on the size of the CCN (Sassen and Dodd, 1989; Heymsfield and Sabin, 1989). An increase in these CCN and IN could have important indirect climate consequences (Twomey, 1977; Coakley et al., 1983; NRC, 1996). (Early calculations with aerosols in a radiative-convective model (e.g., Reck, 1975) showed that effects on Earth's surface temperature varied with altitude of the aerosol, but were also dependent on surface albedo and seasonal effects. More recent estimates (Charlson et al., 1990) show that a 1 percent change in average daily cloudiness could lead to a change in surface radiation forcing of about 1 watt per square meter.)

The physical and chemical properties of the particles dictate their effectiveness as CCN and IN. The radiative effects of clouds depend on cloud phase (liquid water, ice, or mixed phase), liquid (and/or ice) path, cloud morphology (three-dimensional effects), and optical properties. The latter in turn depend on microphysical properties, including particle size and shape (ice crystals). The size increase of CCN and IN during growth under cloud conditions dramatically enhances the light scattered and absorbed by these cloud nuclei. Hence, the radiative properties of clouds, for both solar and terrestrial radiation, are closely linked to the concentration and composition of the CCN on which water condenses and the IN on which ice forms (Twomey, 1980; Reck and Hummel, 1981; Twomey et al., 1984; Sassen, 1992; Liou, 1992). It has been suggested (Twomey, 1991; Stamnes et al., 1995) that a consequence of increasing aerosol burden might be a tendency for cloud drops to become more numerous and smaller. This would suppress drizzle (Albrecht, 1989), and lead to more persistent stratus coverage with higher liquid-water content (Feingold et al., 1994, 1996; P. Olsson, personal communication). Cloud-radiation interactions and feedbacks constitute the main focus of the Atmospheric Radiation Measurement (ARM) program, supported by the Department of Energy (Stokes and Schwartz, 1994). The indirect radiative effect (i.e., that associated with contrails and with influences of

aircraft aerosols on natural clouds) is the most uncertain, and potentially the most significant, impact of aircraft-generated aerosols. Both this indirect effect and the direct effect of radiative forcing, as well as their links to potential climate change, have been recognized in a recent National Research Council report (NRC, 1996) that outlines a plan for a research program aimed at this topic.

The indirect effect of aerosol can be illustrated by its potential impact on low-level marine stratocumulus clouds. This type of cloud covers large areas of the global ocean, and contributes a significant measure of shortwave cloud forcing (Atkinson and Zhang, 1996). (This forcing is only slightly offset by longwave forcing, because the albedo difference between the cloud and the ocean is high, whereas the temperature difference is low.) Such clouds could be markedly influenced by an increase in cloud-seeding nuclei from aircraft-engine exhaust. If subsidence causes particles produced aloft to constitute a substantial component of boundary-layer aerosol, it will be important to understand the source and evolution of those particles, including their eventual incorporation into marine stratus.

There are two basic types of aircraft-generated aerosols. Aircraft generate both primary particles (e.g., soot) and secondary particles that are formed though gas-to-particle conversion in aircraft wakes (e.g., sulfates). Freshly formed soot is believed to be hydrophobic (does not take up water easily), making it a poor CCN but possibly a better IN. However, interactions with sulfuric acid and soot already present in aircraft plumes may modify this hydrophobic behavior markedly (Schumann et al., 1996). If small sulfuric acid particles form in the wake, they will take up water vapor easily, but at first may be far too small to be effective either as CCN or IN. Hence, the evolution of particles in the wake (including coagulation, heterogeneous growth, and deposition of hydrophilic sulfates on soot) can result in changes that affect both direct and indirect radiative properties of aircraft-generated particles. The nature of this evolution, both physically and chemically, is likely to depend on the surface area of the aerosol mix in the wake region. Because these aerosol-production processes depend so strongly (in many cases, exponentially) on such ambient conditions as temperature, humidity, and concentrations of various other species, it is clear that aerosol-production data must be obtained from series of "complete" measurements taken behind aircraft flying at normal flight altitudes. Such measurements were recently attempted in a specific location in the SASS project's Subsonic Aircraft: Contrail and Cloud Effects Special Study (SUCCESS) program, as well as under the German Advanced Technologies Testing Aircraft Systems (ATTAS) program (Schumann et al., 1996).

One of the stated targets of the SUCCESS program was contrails, which are clouds that form in the wake of aircraft under certain favorable conditions. The origin, persistence, growth, and decay of contrails are not all well understood, but are expected to depend on the interplay of environmental, meteorological, and wake conditions. Contrails are the most visible wake effects. They can cover an

appreciable fraction of the sky in areas of heavy air traffic, obviously perturbing local cloudiness and its impact on radiation. These readily observable effects, however, may be of less significance globally than emissions that do not result in contrails but contribute to the CCN available for later cloud nucleation. Consequently, we view the study of contrails as important for SASS, but nonetheless only a part of the larger subject of aircraft emissions and their effects on clouds.

The panel's preliminary recommendations in this area are to:

- Designate a team of researchers to review extant data sets (U.S. and other) for the mid-troposphere (e.g., NASA-PEM, NASA GLOBE, NSF ACE-1), to assess the extent to which they provide a consistent picture of the aerosol and gas-phase characteristics of the free troposphere, and its regional variability. Such an assessment is needed to provide a framework into which the results of brief, intensive measurements can be placed.
- Use these data sets and other information to bound current uncertainties and sensitivities of the relationships among clouds, aerosol, and radiative effects.
- Evaluate and prioritize research strategies on the basis of these existing data sets and uncertainties, balancing research needs against realistic appraisals of cost and achievability.
- Expand the current support for miniaturization of gas-phase instrumentation to include aerosol-measurement instrumentation.
- Increase efforts to characterize the size and properties of soot particles emitted under ambient operating conditions.
- Pursue direct interactions with aircraft manufacturers and air carriers to identify a workable joint strategy for using the commercial air fleet as platforms for measurements of both aerosol and gas-phase species.

Review of the SASS Questions and Responses

As a preliminary review of the SASS project's research topics and strategy, the NRC's Panel on Atmospheric Effects of Aviation has chosen to evaluate the scientific questions and program responses that appear in Table 1-2 on page 10 of NASA Reference Publication 1385, *Atmospheric Effects of Aviation: First Report of the Subsonic Assessment Project* (Thompson et al., 1996). Two of the "Aviation-Unique Topics" listed there will be the subject of a separate PAEAN report, *An Interim Assessment of AEAP's Emissions Characterization and Near-Field Interactions Elements*. The third, Operational Scenarios, PAEAN considers to be beyond its charge. In this report we confine our detailed evaluation to the "Atmospheric Science Topics". Nonetheless, we do have a few comments relative to the near-field interactions, which are included directly below. In each case the Table 1-2 entry is reproduced verbatim in italics before the discussion of that topic.

NEAR-FIELD INTERACTIONS

Question:

- *Can fluid dynamics and/or chemical processes in aircraft wakes alter properties of engine exhaust products or their deposition altitude to significantly influence the background atmosphere?*

Program Response:

- *Develop efficient and accurate algorithms for thermodynamic, physical, and chemical properties of wake and exhaust products between the engine exhaust plume and the location where interaction is influenced only by background atmosphere.*

- *Couple models with in situ and/or remote exhaust plume measurements using current aircraft platforms.*

In general, the panel agrees with both the importance of this question and the programmatic responses as written. We add the caution, however, that any new study of a complex environment may yield unexpected results. For instance, no one anticipated the surprisingly high concentration of particles in the Concorde plume that was found in the October 1994 measurements (Fahey et al., 1995), so their size distribution was not measured and their radiative significance cannot be assessed. PAEAN also agrees that the number of new particles that form, evolve, and survive in the wake will be influenced by the ambient aerosol population, particularly the existing surface area. Both measurements (Clarke, 1993) and models (Shaw, 1989; Hegg et al., 1992) indicate that a higher pre-existing surface area suppresses new-particle nucleation, because of preferential condensation of precursors onto existing surfaces. Hence, measured particle concentrations in wakes (as observed by the Airborne Southern Hemisphere Ozone Experiment and Measurements for Assessing the Effects of Stratospheric Aircraft (ASHOE/MAESA) programs, for instance) can depend on engine-combustion characteristics, emission products, the dynamic/thermodynamic environment, and the pre-existing aerosol (which can vary in space and time). Aerosol nucleation and growth in aircraft wakes also appears to be sensitive to the concentration of ions emitted by the combustors into the nucleation zone (R. Turco, personal communication).

The implications of these effects may be subtle. For example, if a given mass of sulfuric acid produces large number concentrations of particles, they can be expected to be smaller and less effective as CCN or IN than if only a small concentration of larger particles were produced. It is thus important to characterize adequately aerosol particle size and composition as well as concentrations, both for the emitted species and for aerosols in the surrounding environment. This will be true not only for in situ measurements but also for interpretation and extrapolation of ground-level engine testing to operational high-altitude environments. Given the nonlinearities of many critical properties, careful characterization will be critical to the interpretation of observations and the modeling of effects.

Recently, some of the needed measurements were accomplished in SASS's SUCCESS Project (NASA, 1996). In discussions at a 1997 meeting, PAEAN members conveyed to AEAP their concerns about the diffuse nature of that project's measurement plans and the lack of adequate commitment to development of instrumentation critical to the project's goals. The panel would have more confidence that the proposals NASA solicited in NRA-96-OA-01 (3 June 1996) would indeed achieve the goals of the SUCCESS project if a tighter link were apparent between the key issues identified for near-field interactions, the

strategy proposed for addressing them, and the determination of the merit and appropriateness of proposed new instuments.

LABORATORY STUDIES

Question:
- *What chemical and physical processes in the atmosphere could be perturbed by aircraft emissions?*

Program Response:
- *Use model sensitivity studies to identify chemical and radiative processes most likely to be perturbed or, in collaboration with models, place upper limits on minor processes.*
- *Identify chemical processes for gas, liquid, and solid phases that are affected by aircraft emissions.*
- *Determine rates of physical and chemical processes to guide observations and modeling.*

The Atmospheric Effects of Stratospheric Aircraft (AESA) and Subsonic Assessment projects have supported several laboratory studies that have provided key kinetic information required for computer simulation of the effects of aircraft emissions on tropospheric and stratospheric ozone. The question quoted immediately above is indeed the crucial one, and the project responses will be important steps in the forthcoming SASS assessment.

For a number of years, NASA's Jet Propulsion Laboratory (JPL) and the International Union of Pure and Applied Chemistry (IUPAC) have made careful evaluations and reviews of kinetic data related to gas-phase reactions important in stratospheric chemistry. The latest of NASA's reviews appeared in 1994 (DeMore et al., 1994), and a new evaluation is being prepared at this time. These reviews provide valuable starting points for the suggested studies, but the greater complexity of the composition of the troposphere requires the evaluation of many more chemical reactions to account properly for the presence of additional nonmethane hydrocarbons (NMHCs) and the reactive oxidation products that they form (volatile organic compounds, or VOCs).

The research plan suggested in Chapter 5 of the first SASS report (Thompson et al., 1996) is to extend the existing rate-coefficient evaluation to include the specific reactions of the C_3 hydrocarbons and their oxidation products (propane, propene, acetone, etc.) and to use a lumped-parameter approach for the higher-molecular-weight species (C_4 to C_{4+n}). The need for additional evaluation of rate coefficients for hydrocarbons > C_3 should be based upon a study of upper-tropospheric air analyses that are available in the literature (e.g., Blake et al., 1996), the range of concentrations of each species encountered, and the sensitivities of the ozone-generation steps to the concentration of each. The composition of the upper troposphere is far simpler than that of the polluted lower troposphere, and

evaluation and inclusion of the reactive hydrocarbons (RHs) > C_3 may or may not be high-priority tasks.

The SASS report notes that heterogeneous chemistry and solution-phase chemistry are to be emphasized in the suggested research because they are less well understood than the gas-phase chemistry. This is reasonable in the long term, but achieving useful results within AEAP's time frame will be very challenging. Attention should probably be focused first on heterogeneous chemistry associated with types of particles expected to be of significance to cloud-nuclei formation and radiative effects, such as black carbon and sulfuric acid (see Stolarski and Wesoky, 1993). An activity in the area of aqueous chemical kinetics, as suggested in the SASS report, would also be of interest. Perturbations of ozone by aircraft emissions are most likely to arise from increases in tropospheric NO_x, SO_2, SO_3, and both H_2SO_4 and carbon-rich aerosols. The extent to which H_2SO_4 and other aerosols enhance contrail and cloud formation ultimately will determine the impact of aircraft emissions via heterogeneous reactions. If the results of current and future observations suggest that the amount of aqueous aerosol in the troposphere is significantly increased by aircraft emissions, then several potentially important reactions should be included in the evaluation studies, among them N_2O_5 + H_2SO_4 aerosol (Fried et al., 1994) and HO_2 + aqueous aerosols containing transition metal ions (Mozurkewich et al., 1987; Cooper and Abbatt, 1996). (See also the discussion of Johnston (1994) on the importance of including heterogeneous chemistry in modeling of the upper atmosphere.)

The reaction of N_2O_5 on sulfuric-acid aerosols is now reasonably well characterized for a variety of surfaces, and its significant participation in ozone loss in the aerosol-enhanced stratosphere has been reasonably well established in modeling studies (Solomon et al., 1996). In addition, the nitrate/sulfate ion ratios in precipitation suggest that the reaction of N_2O_5 to form HNO_3 is important in the troposphere (Calvert et al., 1985). The HO_2 radical removal at aerosol surfaces (Mozurkevich et al., 1987) has been confirmed recently to have an accommodation coefficient > 0.2 on H_2SO_4 surfaces (Cooper and Abbatt, 1996), and this could be an important loss process for HO_2 in aerosol-rich regions of the troposphere. To our knowledge, this reaction is not now included in any tropospheric models of the atmosphere.

The evaluation of the kinetics of potentially important aqueous-phase chemistry is suggested as part of the SASS research plan. The possible importance of solution-phase reactions within the troposphere has been given extensive consideration through the years (see, e.g., the discussion of Pruppacher et al., 1983; Hoffmann and Jacob, 1984; Schwartz, 1984; and Jaeschke, 1986). In November of 1993, AEAP held a workshop devoted to the discussion of heterogeneous and solution-phase chemistry that could be important to the SASS project. It is not clear which aspects of the recommendations made there have been implemented to date, but NASA's program for evaluation of these types of chemistry has continued to evolve. Recent modeling efforts have suggested a number of reac-

tions that may be of significance in the chemistry of the troposphere (see, e.g., Jacob, 1986; Lelieveld and Crutzen, 1990; Faust and Allen, 1992; Möller and Mauersberger, 1992; and Warneck, 1992). On the other hand, using different assumptions from Lelieveld and Crutzen about the water content of clouds, solubility of CH_3O_2, and the $HO_2 + HO_2(H_2O) \rightarrow H_2O_2(H_2O)$ rate coefficient, Liang and Jacob (1997) have concluded that the effects of aqueous chemistry on summer tropospheric ozone in the tropics and middle latitudes are less than 3 percent. Together, this newer work and the significant wealth of older literature should provide the basis for deciding which reactions require further study. Among the reactions that should be considered is OH-radical generation through sunlight irradiation of aqueous aerosols containing iron salts in solution, which are ubiquitous throughout the troposphere (Graedel et al., 1985, 1986; Weschler et al., 1986).

At present, models considerably overpredict HNO_3 (by a factor of up to 5). It has been difficult to make reliable measurements of HNO_3 and NO_y, and large uncertainties are associated with previous data. Recently developed techniques can provide rapid response and seemingly accurate measurements of HNO_3 in the upper troposphere (R.L. Mauldin III, personal communication), and more reliable HNO_3 data will be forthcoming. NASA field programs should lead in the development and application of these improved methods. It is important to resolve the problem of this overprediction, since the failure of models to predict the observed NO_y components correctly will greatly affect the validity of assessments made with the GMI or other models.

An important element missing from the kinetic evaluation outlined in the SASS report is the program to reevaluate *j*-values (the apparent first-order decay coefficients related to photochemical processes) for the important light-absorbing species over the vertical extent of the troposphere, e.g., reactions of O_3 to form $O(^1D)$, of CH_2O (formaldehyde) to form H, HCO (ultimately giving HO_2), CO, and H_2, and of CH_3COCH_3 (acetone) to form CH_3, CH_3CO (ultimately forming CH_3COO_2 and CH_3O_2). The latest NASA evaluation of the *j*-value components (absorption cross-sections and quantum yields) (DeMore et al., 1994) does not include significant dissociation through light absorption of ozone within the long-wavelength tail, although current results of both theory and field studies (Michelsen et al., 1994; Shetter et al., 1996) suggest that this is significant. The ozone *j*-values recommended by DeMore et al. are thus probably incorrect. It must be remembered that the recent agreement seen between the *j*-values employed in the AEAP model intercomparisons (Stolarski et al., 1995) is proof only of the consistency of the model assumptions, not of the accuracy of the common choices of *j*-values now employed.

A major problem remains in lowering the uncertainties associated with *j*-value calculations in the presence of clouds and aerosols, conditions normally present in the real troposphere. Considerable progress has been made in delineating the expected effects in theoretical calculations (Lantz et al., 1996). Upward-

and downward-looking receivers that permit measurement of spectrally resolved solar radiation have been mounted on aircraft involved in NASA's tropospheric-observation programs. As expected, total irradiance varies greatly from clear-sky values when the aircraft fly above, within, and below clouds. The continuation of such measurements will be an important element in testing current theories and in arriving at reasonable algorithms to account for the effects of clouds and aerosols on *j*-values in tropospheric-chemistry models.

Recommendations for the Laboratory Studies topic:

- Update not only the NASA and IUPAC evaluations of gas-phase rate coefficients, but those of *j*-value components for the photochemically active trace gases as well.
- Using existing representative chemical analyses of trace gases in the upper troposphere, together with measured (or extrapolated) rate coefficients, estimate the magnitude of ozone change that results when the chemistry of NMHCs $> C_3$ is included in the chemical model.
- If the estimated ozone change above is greater than a few percent, develop a lumped mechanism to simulate the chemistry of this group of "heavy" hydrocarbons.
- Estimate the average magnitude of the increases in NO_x, aerosols (surface area), and cloudwater (volume) expected as a result of aircraft emissions. If these estimated increases are relatively insignificant (less than a few percent), the models need to include only the currently recognized heterogeneous and solution-phase chemistry. If the expected effect is greater than a few percent, a significant effort should be expended to identify all possible heterogeneous reactions that could affect ozone levels in the troposphere. This study may involve largely modeling studies constrained by a combination of existing data and plausible uncertainty limits to bound the issues. The rate parameters for the reactions that appear to be potentially important in the modeling studies should be examined and tested carefully with well-planned, pertinent laboratory measurements.

ATMOSPHERIC OBSERVATIONS — CHEMISTRY

Questions:
- *What is NO_x conversion time and odd nitrogen partitioning in lower stratosphere and upper troposphere?*
- *What is aircraft contribution to upper troposphere NO_x budget compared to strat/trop exchange, lightning, and convective input of pollution?*
- *How reliably can NO_x and NO_y (gas and bulk phase) be measured in the upper troposphere and how does it affect the reliability of a NO_x budget assessment?*

Program Response:
- *Perform in situ measurements of tracers (e.g., CO_2, N_2O, CH_4).*
- *Plan NO_x and HO_x budget experiment(s).*
- *Support development work on NO_x and NO_y sensors.*
- *Assemble existing NO_x and NO_y database and study budget information from past UT/LS measurement campaigns.*

This SASS table entry identifies the key questions correctly, if rather generally. The program response given in general terms is also adequate, except that the definition of the tracers to be measured in situ should be sharpened to read "... of the tracers that help to identify the origin of upper tropospheric NO_x." For example, high O_3 but low CO and H_2O would point to stratospheric air, high radon to continental surface air, and high H_2O to air processed in moist convection and possible influence of lightning. It should be noted, however, that an attempt should be made to search for an unequivocal tracer for air processed through jet engines (e.g., soot). The panel does agree with SASS's philosophy of conducting process-oriented field campaigns, rather than continuous monitoring; the former promises immediately useful results within the existing budget.

Assembly of a data base should include not only the species currently being followed, but also the molecules O_3, H_2O, CO, CH_3COCH_3, and other VOCs. It should also incorporate data for the upper troposphere from the space shuttle and satellites, as well as from MOZAIC, the European program for measuring O_3 and H_2O from commercial aircraft. Some details of that research—but not enough for evaluation of progress—were given in the description of SONEX handed out at the January 1996 PAEAN meeting. In principle, aircraft campaigns with the duration, spatial coverage, and instrument mix outlined for the SONEX experiment could go far toward characterizing the relative contribution of NO_x from aircraft to the upper-tropospheric budget. But the main objectives of SONEX are not made clear in that writeup, and the sub-objectives are not prioritized. Some, but not all, of the sub-objectives can be achieved within one type of mission.

To allow proper evaluation of an experiment such as SONEX, and of progress toward SASS's goals, the main mission objectives need to be clearly stated. For example:

- **Study upper-tropospheric NO_x and HO_x chemistry:** Do observations confirm or deny present conceptions and model results? With what uncertainties?
- **Study upper-tropospheric NO_x distribution and budget:** Can contributions from different sources be quantified? What geographical locations and seasons have to be selected to demonstrate the efficiency of the various source processes, in particular lightning? What tracers correlate or anticorrelate with which sources?

A list of desirable sub-objectives should be provided, and the selected sub-objectives noted with a rationale for their selection. The priorities of each partial mission should be clearly stated, and the objective(s) it fulfills should be noted, so that all participants understand the reasons for the field director's decisions.

Other relevant questions are:

- What can the SONEX program learn from measurements made by SUCCESS and other AEAP-related experiments?
- How can the SONEX results be used for evaluation of the Global Modeling Initiative and other models?
- What information will SONEX provide on the lightning source?

Although SASS has a limited lifetime, in it NASA has an opportunity to leave a valuable legacy. Future research on changes in the chemistry and composition of the atmosphere would benefit greatly from a strategy for atmospheric monitoring to detect changes of significant magnitude or character in tropospheric chemistry. Public concerns over climate and environmental change can best be allayed by trustworthy data. SASS, with its involvement in both modeling and observations, is in a position to propose an appropriate strategy.

Recommendations for the Atmospheric Observations — Chemistry topic:

- Ensure that HO_x, and all HO_x precursors and sinks currently thought to be of importance in the upper troposphere, are included in proposed measurement programs. Examples of additions needed are CH_3COCH_3 (see Singh et al., 1995) and CH_3OOH, methylhydroperoxide.
- Use model sensitivity analyses to identify the transport and chemical processes most important for the NO_x, HO_x, and O_3 budgets in the upper troposphere. What can SONEX do to study these and reduce their current uncertainties?
- Seek model guidance as well for the placement, timing, and instrumentation of the missions. What kinds of model would be needed for that purpose? Are they available within SASS?
- Clarify the management structure, planning process, and operational implementation of SONEX. These steps should ensure better responsiveness to SASS's needs than is currently apparent.
- Consider looking beyond SONEX to participation in a coordinated program for long-term monitoring of tropospheric chemistry.

ATMOSPHERIC OBSERVATIONS — RADIATIVE PROCESSES

Questions:
- *What are effects of contrails on Earth's radiation budget?*
- *Does aircraft exhaust affect ambient cirrus properties?*
- *Do aircraft emit enough soot or sulfate to be radiatively significant?*

Program Response:
- *Satellites and ground based observations, supplemented by aircraft overflights.*
- *Focused aircraft expedition to sample ambient clouds, including chemical composition.*
- *Retrospective analyses of aerosol data, use of estimated emissions from aircraft, and future measurements.*

The PAEAN panel agrees that climate forcing through direct and indirect radiative effects of aircraft effluents could be one of the most important potential consequences of aviation emissions. SASS's three questions listed above are relevant, but it would be well to reevaluate them in the light of the current concern with aerosols (NRC, 1996). The number, mass, and composition of emitted aerosols are expected to evolve over time as they go from the point of emission to a location at which they may influence the properties and microphysics of clouds. It will therefore be important to incorporate the evolution of aerosol emissions into assessments of possible cloud perturbations, both at aircraft operating altitudes and elsewhere in the troposphere.

The program responses shown above appear to be reasonable. Because PAEAN has heard most about the aircraft (SUCCESS) campaign, it seems appropriate to review it as an example of how SASS is executing its program responses. Chapter 7 in the first SASS report (Thompson et al., 1996) identifies radiative forcing as a "major area", and emphasizes that "experimental strategies will be developed so that process models are an integral part of the design, with each model selected to answer a key question defined in the mission plan." It notes further that this type of assessment will require prioritization of two types: the use of models and previous studies (including sensitivity studies) to focus measurement strategies on the highest-priority species, and determination of the conditions responsible for variability of selected trace gases, so that sampling aircraft will be flown in regions where the variability will be appropriately characterized. The chapter also notes that a 1994 workshop stated bluntly that "the sensor technology for making the most important measurements is either inadequate or nonexistent at this time."

The panel supports this deliberate approach to identifying high-priority objectives and placing statistical bounds on the variability observed, as well as the recognition that the "radiative forcing" questions being addressed involve com-

plex issues in heterogeneous chemistry and subtle interactions with meteorological and dynamic environments, including water-vapor concentrations as well as detailed aerosol microphysical and optical properties. While direct injection of exhaust aerosol may at times have measurable radiative effects, the marked amplification of particle-light interactions when these particles act as CCN or IN in contrails and/or clouds make this a particularly important and difficult area of study. PAEAN suggests that because of the relevance of its aerosol observations to possible climatic effects, SASS consider formulating objectives and missions that are consonant with the approach and recommendations outlined in *A Plan for a Research Program on Aerosol Radiative Forcing and Climate Change* (NRC, 1996).

The inconsistency between the careful approach outlined in the SASS report and the approach of the SUCCESS campaign as described in its mission plan (NASA, 1996) is therefore surprising. The mission document provides an extensive listing of potential questions that might be addressed, but no effort is made to prioritize these questions or to establish key mission objectives. Indeed, the only prioritizing mentioned is identification of which SUCCESS mission type should be flown first. There is no mention of acceptable uncertainty limits for the measurements, or for that matter the mission objectives, let alone how they might relate to model requirements. Furthermore, there is no evidence that model results were used to either identify or "focus strategies on highest-priority species," nor does any assessment appear of the readiness, appropriateness, or adequacy of the selected instruments.

We caution that these considerations need to be reflected in the analysis or interpretation of SUCCESS data, and strongly recommend that future aircraft missions explicitly address these issues in establishing their science plans. For example, before even beginning to outline plans for exploring the aerosol topics mentioned above, the sequence below should be followed:

- Ask what needs to be known about the aerosols resulting from aircraft exhaust to (i) establish their direct radiative effects within a prescribed uncertainty, (ii) establish their indirect radiative effects through possible perturbations of CCN spectra, and (iii) establish their effects on actinic flux.
- Determine what kinds of coordinated measurements need to be made by ground-based, airborne, and spaceborne sensors to elucidate the questions posed above. On the modeling side, decide what kind of modeling should be done to determine the sensitivities of radiative effects to the changes in cloud optical properties caused by changing aerosol properties, and what kind of modeling is needed to help design effective field experiments.

Once these steps have been taken—and they should hold for all measurement campaigns, not just aerosols—the mission plan of any field experiment should state clearly how the results of the experiment will fulfill one of the needs identified.

Recommendations for the Atmospheric Observations — Radiative Processes topic:

- As part of the "retrospective analyses" mentioned above, use existing data sets (U.S. and other) to endeavor to establish background levels of aerosols and species of interest, and a history of the changes in both as far as they can be documented.
- As part of a more coordinated research strategy, require all principal investigators to demonstrate explicitly how, and how well, proposed work will meet the identified SASS needs and priorities, both in this area and for the project as a whole.
- As part of a more focused modeling strategy, determine what kind of physical parameters (e.g., refractive index, size distribution, shape) and theoretical developments are required to model the optical properties of the particles.
- As part of a more coordinated measurement strategy, determine what kind of measurements are required to establish the direct and indirect effects of aerosols from aircraft exhaust on radiative forcing and actinic flux.

GLOBAL MODELING

Questions:
- *What are predicted ozone changes and climatic impact associated with aviation?*
- *Can models explain observations?*
- *What are uncertainties in these predictions?*

Program Response:
- *Develop 3-D global chemical transport assessment model.*
- *Use global climate models and their embedded radiative models to evaluate the potential climate forcing from aircraft.*
- *Test models against atmospheric measurements.*
- *Model intercomparisons and error analysis, including subgrid processes and parameterizations.*

The first question above is really a composite of two questions, and should be broken into (1) what are the predicted changes in ozone associated with present and future aviation? and (2) what is the impact of these changes and other aviation-related changes upon climate? They might be better stated as "What changes in concentrations of chemically and radiatively active constituents are predicted to result from various possible levels of aviation in the future?" and "What would be the climatic impact of these changes?" The constituents here would have to include all active species in or resulting from aircraft exhaust, from CO_2 to soot. The next closely related question would be how each of these constituents relates to potential changes in ozone, aerosols, cloudiness, and so on that affect climate. All these would need to be determined by the models as a

function of space and time, because the consequences of changes might be highly time- or region-specific. Modifications of stratospheric/tropospheric exchanges and the shifts in the tropopause level could also affect tropospheric (and stratospheric) climate. This first question is therefore extremely complex, even if SASS must currently restrict its investigation to determining the parameters needed to calculate the radiative forcing resulting from aircraft emissions.

The AEAP has begun to respond to this question by designing the Global Modeling Initiative (GMI), which has undertaken the development of a general-circulation-type chemical-transport model—composed of a core structure and various modules that simulate atmospheric processes such as transport and chemistry—that will reveal the effects of aircraft emissions on the chemistry of the troposphere and lower stratosphere. These modules, including input data, are submitted by contributing scientific groups. Such an approach looks promising, and the panel supports AEAP's decision to apply its resources to a single "community" model, rather than several separate ones. It is essential, however, that the GMI model and any others that are used as the basis for AEAP assessments be rigorously compared with available observations (concentrations as well as ratios of quantities). The meteorological data sets used to drive the transport of species, which come from either assimilation of observations (for example, those of the European Centre for Medium-Range Weather Forecasting or the NASA Data Assimilation Office) or from archives of general-circulation model data, should be carefully evaluated. Evaluation of results, with regard to both the transport of long-lived species and the distribution of chemical compounds, should be a high priority; in particular, the different advection, convection, diffusion, and chemical schemes used for the GMI should be intercompared in detail. For optimal comparisons, SASS needs to define which data sets at which time scales should be compared with model results.

Laboratory as well as modeling studies have shown during the past few years that heterogeneous-chemistry processes occurring at the surface of particles could be important for modeling the distribution of chemical species such as ozone. Although such processes are not well understood, their possible impact on global-scale species distributions should be evaluated. To this end, it would be desirable to establish an archive of observational aerosol data that would represent the troposphere. Important characteristics to include would be type, size, composition, and regional characteristics (e.g., regions of the troposphere where Asian or Saharan dust is commonly found, or products of biomass burning). Such a data base could be used in conjunction with known aircraft emission characteristics to guide laboratory studies of heterogeneous chemistry on aerosols, or provide realistic aerosol scenarios for modeling studies.

Currently existing three-dimensional (3-D) chemistry–transport models (including those funded through other programs) should be used to identify and evaluate key issues such as NO_x budget, tropospheric heterogeneous chemical processes, deep convection, and stratospheric/tropospheric exchange. Perform-

ing sensitivity studies with models that have lower temporal and spatial resolution will help evaluate the main processes that determine the impact of aircraft, and define the uncertainties associated with these processes. Such evaluations should be regarded as essential, and should also be used in designing new observation campaigns and assessment strategies that will help reduce the uncertainties.

The GMI effort is mostly concerned with evaluation of impacts of aircraft emissions on the distribution of gaseous chemical species (and ultimately aerosols) and calculation of radiative forcing resulting from these changes. As was discussed in the first SASS report (Thompson et al., 1996), however, the GMI is not intended to evaluate possible climate perturbations resulting from changes in forcing caused by the effects of aircraft. Possible feedbacks between temperature and chemical-species distributions (which are nonlinear) will not be taken into account, and perturbations of the climate system resulting from indirect impact of particle emission or formation will not be evaluated on the global scale. While changes in temperature could further alter O_3 concentration, the resulting effects are expected to be small, so neglect of the second-order effects can be justified at this stage. Considerably more resources would be required for SASS to evaluate climate impact; SASS researchers can instead take advantage of ongoing related efforts in the United States and abroad. For example, extensive work in the area is performed under the aegis of the World Climate Research Programme (WCRP).

The Global Modeling Initiative is unique to NASA, and has the potential to be a valuable vehicle for modeling other global environmental processes in the future. Because the GMI model will not be fully coupled to any general-circulation model for the next few years, the impact of changes in the radiative balance caused by aircraft emission of either gas-phase species or particles will have to be evaluated non-interactively by using existing climate models. Perturbations of ozone concentration or of particle distribution calculated by the GMI model could be used as the input to such climate models. These first evaluations could be performed through collaboration between AEAP or SASS research groups and climate modeling groups at institutions such as NOAA's Geophysical Fluid Dynamics Laboratory, NASA's Goddard Institute for Space Studies, and NSF's National Center for Atmospheric Research.

The GMI model is expected to be an important contributor to the next SASS assessment. The development of this model represents a large amount of work, and it implies collaboration of many scientific groups. For successful completion of this initiative, it is important to define a detailed plan for the GMI components' development and integration, as well as for the model's evaluation and integration, and to estimate the computational and support resources required and available. The timeliness of the modeling results is a concern, and when funding cuts are a possibility, some strategic planning may be needed to ensure that efforts are applied in the most cost-effective areas.

Recommendations for the Global Modeling topic:

- First, define a detailed time scale for GMI model development, testing and evaluation (including the aircraft-specific components), use for assessments, and coupling with other models.
- Put a high priority on GMI model evaluation, through comparisons of its results with those of separate modules, with available observations, and with results of other existing 3-D models.
- Perform chemistry and transport sensitivity tests with existing 3-D chemical-transport models. Where forcing terms appear to be small, as that for ozone does at present, perform sensitivity computations to test the model results.
- Use emissions scenarios, recent measurements, and the results of 2-D models that treat aerosols to assess what ranges of aerosol properties are important to models (both 2-D and 3-D), and set boundaries that can be incorporated into the GMI.
- Use the results of model sensitivity studies in designing new experiments—for example, the necessary spatial frequency of sampling—and define what is needed for the results to be most useful to the model.
- Develop stronger interactions with the U.S. and international climate communities to obtain estimates of the effects of the projected emissions on climate; determine how computations of changes in greenhouse gases and in aerosols could be used as input for climate models.

Strategies, Priorities, and Principal Recommendations

The SASS project is confronted with issues that involve a large number of questions, a variety of possibilities, a relatively data-poor research area, and the need to establish a strategy that can bound a complex problem in a cost-effective way. Without documentation of hypotheses and preliminary assessments, and of the analyses used to determine priorities, PAEAN cannot properly evaluate what is driving the current SASS project and how its current funding of research operations has evolved. We strongly urge NASA to correct this weakness. The problem might be considered as though it were a third category in Table 1-2 of the first SASS report (Thompson et al., 1996), entitled "Project Management Topics." A first entry could be the following:

"Question:
- *What topics do preliminary assessments suggest are most important, given their hypothesized effects, the consequences thereof, and their probabilities of occurrence?*

"Program Response:
- *Perform initial cost/benefit analyses to determine the broad division of effort among the project's major elements.*
- *Perform uncertainty and sensitivity analyses to discover how, within those elements, uncertainties can best be reduced to a common level.*
- *Draw up an initial research strategy for SASS, with provisions for modifying it as new information is received."*

In the absence of large-scale-model results that could help formulate a strategy, this process would yield a defensible project plan for SASS. Such an approach might involve some risk, but on the whole the panel considers identifying (and investing in addressing) a few critical issues well to be more useful than trying to cover many issues sketchily.

The discussion so far has focused on the objectives of the program, the scientific questions that dominate programmatic issues, and project management from the standpoint of integrated planning, priority-setting, and resource allocation. PAEAN believes that one other important measure must be taken to implement all of these: Continuous, strong scientific leadership must be provided. The panel understands that organizational shifts at NASA (which have continued during the writing of this report) have affected the administration and management of AEAP. The recent assignment of a dedicated on-site AEAP manager is a positive step, but for optimum scientific progress PAEAN recommends that the responsibility and authority for relating and integrating all scientific and technological aspects of SASS be vested in a permanently assigned, experienced person, who can ensure that the disposition of research resources properly reflects program priorities. The panel has suggested that some of the field operations have not been thoroughly planned or properly focused, although closer control and oversight during the last couple of years have alleviated that problem to some degree. A SASS-dedicated (rather than rotating) scientist with broad experience would be in a better position to make hard decisions (and perhaps suggest new approaches) in a time of potential reductions in research funding, and would be more apt to see and effect appropriate links to other national and international programs (such as the WCRP) where collaboration could cost-effectively accomplish SASS's objectives. We therefore urge NASA to consider redefining the current management structure to include such a senior scientist who will stay with the project not for a year or two, but until its anticipated end.

The following, then, are the two recommendations that PAEAN concludes should receive the highest possible priority from NASA/AEAP management.

RECOMMENDATION NO. 1:
Draw up and execute an adequately detailed, prioritized, unambiguous research strategy and plan

Some of the elements of a SASS research strategy and plan are contained in the various documents and briefing materials provided by NASA, but they are scattered, hard to compare, and far from complete. A detailed and unambiguous research plan is needed. The current over-general strategy handicaps SASS in several ways. Among them are:

- **Unclear priorities.** It is extremely difficult to compare either current or optimum priorities, let alone determine the important gaps, if specific goals are

not outlined and a strategy laid out. In case of significant changes in funding levels, or unexpected research successes or failures, how will priorities be altered? All program components are treated as though they were relatively equal in importance, and their interdependencies are not clearly described.

- **Reduced leveraging.** When the strategy and priorities are not clear, the potential is diminished for leveraging of other agencies' activities, the interests of researchers outside the SASS community, and international programs. Given the current funding situation, it behooves AEAP to draw on information available from other parts of NASA, from other nations, or from international groups such as the WCRP or the International Geosphere-Biosphere Programme (IGBP). Without an explanation of exactly how the project aim of understanding the impacts of aircraft operations on climate is to be achieved, the applicability of others' work may be overlooked.
- **Evaluation problems.** When quantifiable links between project components are not clearly laid out, real progress toward the overall goal is difficult to judge. Review of the parts will not yield a consensus on the success of the whole.

The panel understands that efforts are being made to remedy the situation. PAEAN therefore recommends that concerted attention be given to constructing a research strategy and a program plan of such clarity that no researcher or agency program manager need wait for a call for proposals to know what SASS needs and where their own skills or resources may contribute. Such a plan is likely to need modification as research progresses, but is essential for wise reassessment of goals, priorities, and schedules.

RECOMMENDATION NO. 2:
Give SASS strong scientific leadership

Determining the atmospheric effects of aviation is extremely difficult and controversial, from the standpoint of both the science involved and the finite resources available to address a scientific and technological problem that is virtually unbounded. Demands on AEAP are great, since its scientific results will provide a foundation for the formulation of a U.S. policy position regarding the international operation of current and future subsonic aircraft fleets: Such international protocols could be formulated as early as 1998 under the auspices of the International Civil Aviation Organization (ICAO).

Because the stakes are high, the time is short, and budget trends suggest reductions, the subsonic-aircraft portion of AEAP must have focused, uninterrupted scientific leadership and management in the future. The experiments and investigators must be selected via a methodology that ensures a balanced, integrated, cohesive approach to the overall task. Accountability for the planning and execution of all phases of the program must be specific, clearly understood, and not fragmented, so as to permit effective program evaluation.

AEAP is a scientific project with technological and economic implications. It needs leadership by a person who (i) has a technical reputation that is recognized in the scientific community at large, (ii) has the broad perspective needed for setting appropriate priorities, (iii) is experienced in the management of large scientific or technological programs, and (iv) is assigned for the duration of SASS/AEAP. Like the Project Manager, he or she should be in the direct chain of command. A long-term assignment would enable that person to have a lasting impact on project effectiveness and productivity, while personally experiencing the effects of project success or failure. Although AEAP has been very fortunate in its Project Scientists, the current arrangement of a two-year tour for a relatively young scientist gives the job the appearance of a senior internship. Someone with the qualifications outlined above could dramatically affect the project through sharing with the Project Manager significant authority, responsibility, and accountability in program planning, resource allocation, overall execution, and measurable results. The position would of necessity distance its holder somewhat from active research, but successful management of other large, complex, critically important programs has been a significant stepping stone in a career path to positions of even greater scientific and programmatic responsibility.

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Acronyms and Other Abbreviations

2-D	Two-dimensional
3-D	Three-dimensional
AEAP	Atmospheric Effects of Aviation Project
AESA	Atmospheric Effects of Stratospheric Aircraft
ACE	Aerosol Characterization Experiments (of the International Global Chemistry Programme)
ASHOE/MAESA	Airborne Southern Hemisphere Ozone Experiment and Measurements for Assessing the Effects of Stratospheric Aircraft programs
ATTAS	Advanced Technologies Testing Aircraft and Systems
CCN	Cloud condensation nuclei
GLOBE	Global Backscatter Experiment
GMI	Global Modeling Initiative
ICAO	International Civil Aviation Organization
IGBP	International Geosphere-Biosphere Programme
IN	Ice nuclei
IUPAC	International Union of Pure and Applied Chemistry
JPL	NASA's Jet Propulsion Laboratory

MOZAIC	Measurements of Ozone by Airbus In-service Aircraft
NASA	National Aeronautics and Space Administration
NMHC	Non-methane hydrocarbon
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
ONERA	Office National d'Etudes et de Recherches Aérospatiales
PAEAN	NRC Panel on Atmospheric Effects of Aviation
PEM	Particle environment monitor
PI	Principal investigator
RH	Reactive hydrocarbon
SASS	Subsonic Assessment project
SONEX	SASS Ozone and NO_x Experiment
SUCCESS	Subsonic Aircraft: Contrail and Cloud Effects Special Study
VOC	Volatile organic compound
WCRP	World Climate Research Programme