

Climate Change

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CRITICAL ISSUES

Policy makers on the international, national, regional and local levels are paying increasing attention to the effects of anthropogenic activities on the earth's climate. Human activities have increased atmospheric concentrations of so-called greenhouse gasses, which are thought by most atmospheric scientists to increase global temperatures. This critical issues paper does not seek to address or resolve the degree to which human activities in their totality affect climate or the effects of any such climate changes. It instead attempts to provide a summary of the state of knowledge regarding how aviation activities may affect climate mechanisms and identifies critical areas of uncertainty that may affect possible policy approaches to reduce impacts.

Aviation activities are among many anthropogenic activities that affect the atmosphere through the combustion of fuel and are currently thought to contribute around three percent of the total radiative forcing from anthropogenic activities. However, aviation is unique in a number of ways that may explain its increasing importance to policymakers, including (1) the fact that many of the emissions from aviation activities take place in the upper troposphere/lower stratosphere (UT/LS); (2) the challenges associated with addressing climate-related impacts through changes in aircraft technology due to the physical and technical requirements of flight; and (3) the potential tradeoffs between reduction in greenhouse gasses and the control of noise and local air quality emissions. While not unique to aviation, factors such as the anticipated continued growth in air transportation and the current reliance of aircraft on conventional fossil fuels have also increased interest in aviation's potential contribution to greenhouse gasses.

The effects of aviation-related impacts on climate are exceptionally complex and subject to considerable uncertainty. Regardless of these uncertainties, entities such as the European Union (EU) are considering regulatory approaches to address aviation's impacts through emissions trading and other mechanisms. At the same time, the International Civil Aviation Organization (ICAO) is increasingly considering fuel efficiency and potential climate implications as factors in the assessment of noise and local air quality stringency measures. Policymakers must confront and weigh the uncertainties in both scientific and economic understanding of climate change. This critical issues paper identifies elements of the scientific and technical research that are needed to help inform policymaking in this area.

This critical issues paper focuses on those mechanisms unique to aviation (such as the emission of pollutants during flight), and does not attempt to cover better-understood aviation-related activities such as aircraft manufacturing, ground vehicle emissions, airport energy use and airport facility development that are identical or similar to other non-aviation activities. A full assessment of the policy implications of any proposed regulatory or other action would require consideration of the climate-related impacts of these other aviation-related activities as well as other modes of transportation and potential tradeoffs among modes. This critical issues paper also does not attempt to address the potential consequences of climate change on U.S. transportation, including how planning, construction, maintenance and operation of airport infrastructure might need to adapt, which is the subject of an ongoing study by the Committee on Climate Change and U.S. Transportation, a joint committee of TRB and the Division of Earth and Life Studies (DELS). The Committee on the Effects of Aviation on the Environment may develop future critical

issues papers to address (1) how climate change and adaptation to it affects transportation planning and environmental reviews; and (2) potential means for reduction and mitigation of greenhouse gas emissions from aviation, including tradeoffs that may occur with such measures.

CURRENT STATE

Although substantial uncertainties remain, the research community has made significant progress in identifying the potential mechanisms by which aircraft operations may affect climate change. Understanding how these mechanisms may affect climate is important to inform policy decisions, regardless of the form that such policymaking may take.

Primary Mechanisms for Climate Impacts

The following are the primary physical mechanisms through which aviation may affect climate.¹ Other than contrails, these are not unique to aviation; however, aviation is unique in that many of its emissions occur in the upper troposphere and lower stratosphere.

- **Carbon dioxide (CO₂):** CO₂ is the best understood greenhouse gas and can reduce the radiation of heat from the earth into space. Aviation contributes to CO₂ inventories through the combustion of fuel.
- **Ozone (O₃):** Ozone is another greenhouse gas that can reduce the radiation of heat from the atmosphere. Aviation-related emissions of oxides of nitrogen (“NO_x”) can cause increases in ozone in the troposphere in complex chemical reactions in the presence of volatile organic compounds and sunlight.
- **Methane (CH₄):** Methane is a potent greenhouse gas that, ton-for-ton, will trap approximately 25-times more heat in the atmosphere than CO₂. Aviation-related emissions of NO_x can indirectly destroy methane on a global scale through photochemical processes.
- **Water (H₂O):** Water vapor (as opposed to condensed or frozen water in contrails or cirrus clouds) directly released by aircraft can act as a greenhouse gas. Current emissions of H₂O vapor by subsonic aircraft are not believed to have a significant direct effect on climate forcing, but large fleets of high-altitude supersonic aircraft could have a more significant effect.
- **Sulfate:** Sulfate, a byproduct of the combustion of sulfur-containing fuels, can reflect incoming radiation and have a net cooling effect.
- **Soot:** Soot or carbonaceous particles can absorb heat from incoming radiation and, thus, have a warming effect on the atmosphere. Aircraft engines create soot and other particulates on the ground or in flight, as discussed above in the “Air Quality” section. In addition, soot and other particulates may affect the process for creating contrails or cirrus clouds by providing additional nuclei for condensation.
- **Contrails:** The contrails formed by aircraft under appropriate atmospheric conditions can trap heat and increase radiative forcing.
- **Cirrus Clouds:** Aircraft emissions and contrails can also spur the production of more cirrus clouds. Like contrails, cirrus clouds can trap heat and contribute to increased radiative forcing.

It is important to note that these mechanisms have different potential effects on climate in terms of the magnitude, duration and spatial distribution of the effect. As discussed below, CO₂ and cirrus clouds may have a significant effect on the balance of heat retained in, versus radiated from, the atmosphere shortly after an aircraft flight. However, CO₂ can reside in the atmosphere for hundreds of years, while clouds may have a residence time of minutes or days. In addition, while CO₂ related impacts may be spread spatially throughout the globe, impacts from

¹ There are a number of other substances that affect climate, but for which aviation is not considered a significant source, such as nitrous oxide (N₂O).

other mechanisms, such as contrails, are likely to be more regional or local.

Metrics for Assessing Impact

Identifying appropriate metrics for evaluating the effects of aviation on climate is a fundamental issue. A range of options exist, from aircraft mass emissions to monetized impacts from climate change. As described below, the choice of metrics will be an important subject of near-term research and debate.

Mass emissions of a particular species provide little information about their ultimate impacts and provide no ability to understand tradeoffs relating to climate change or other environmental impacts (e.g., noise or local air quality). As a result, much of the past and ongoing research has relied on intermediate metrics connecting aviation-related emissions with measures of climate change. One traditional metric is radiative forcing (or “RF”), a measure of the direction and degree to which a process affects the atmosphere’s energy balance in watts per square meter (W/m^2). There is ongoing debate over whether the use of this metric by itself is appropriate for policy purposes, because it does not account for differences between mechanisms in the efficiency by which a given change in RF translates into changes in surface temperature regionally or globally. In addition, the RF metric addresses instantaneous climate-forcing effects, but not the different temporal scales of the pollutants. For example, carbon dioxide can remain in the atmosphere for hundreds of years, while contrails are measured in minutes or hours. The radiative forcing metric does not account for the longer residence time of the carbon dioxide.

As a result, some have advocated use of different metrics such as change in global mean surface temperature, rise in global mean sea level or ultimate economic impact of climate change impacts (e.g., the total of changes to storm-related damage, crop productivity, disease and other potential impacts). Monetization of the effects of climate change is a complex subject beyond the scope of this paper. While theoretically an attractive way to address the temporal question identified above, the ability to estimate costs associated with climate change has progressed slowly. Even the physically-based metrics, such as change in surface temperature or sea level, involve many additional levels of uncertainty. They also can be less transparent and less simple to understand.

Another metric that has received use in other contexts and some attention in the aviation context is the Global Warming Potential (“GWP”), which is a time-integrated RF following the pulse emission of a gas. This has the benefit of accounting for the temporal impacts of the different mechanisms, and it could be adjusted to reflect the different efficacies of the mechanisms. However, the GWP does not work as well for short-lived gases as for longer-lived gases like CO_2 . In addition, how this metric might account for contrail and cirrus effects is unclear.

As noted earlier, aviation-induced atmospheric perturbations span a range of spatial scales. Therefore, there is a need for metric(s) to measure the regional and global climate impacts and their associated variabilities based on the life cycle of each contributing factor.

History and State of Current Research

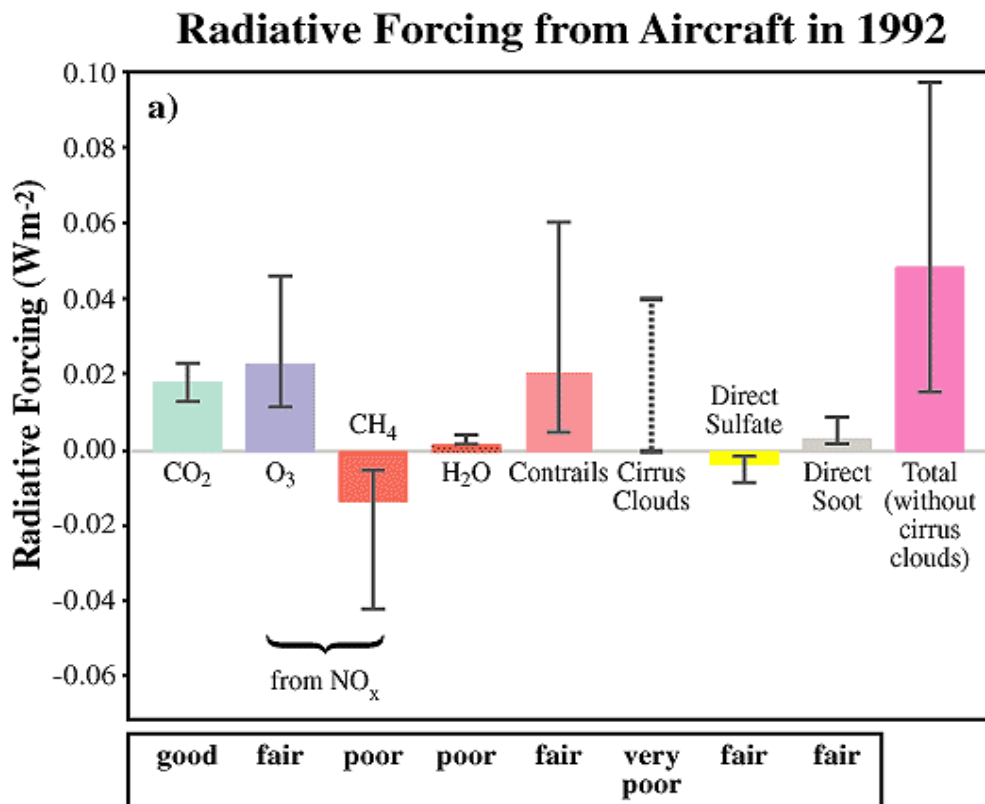
Much of the research relating to the atmospheric effects of aircraft emissions arose out of efforts that began in the 1970s by the Department of Transportation, National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), European agencies and industry to understand the impacts of proposed supersonic aircraft. Much of this original research aimed to comprehend the potential for supersonic aircraft to affect the ozone layer as a result of emissions in the stratosphere. As part of this process, researchers learned a great deal about the range of emissions by aircraft in the troposphere and stratosphere.

In 1996, as global attention to the issue of climate change was increasing, ICAO requested that the Intergovernmental Panel on Climate Change (IPCC) (which operates under the umbrella of the World Meteorological Organization and the United Nations Environment Programme) assess this research to provide the best characterization of the effects of aviation on climate. This effort included dozens of scientists and other experts representing the majority of experts actively interested in the subject. In 1999, the IPCC released a pivotal report, *Aviation and the Global Atmosphere*, which attempted to synthesize the state of research and estimate the effects of aviation on climate for the year 1992. This report has provided a foundation for subsequent research and policy discussions regarding the climate-related effects of aviation.

Using the RF metric, the IPCC report identified and evaluated the different mechanisms identified above by which

aviation can affect climate. Figure 1, from the IPCC report, reflects the IPCC's best estimates in 1999 of the magnitude and direction of these impacts, as well as its qualitative assessment of the level of uncertainty. In total, IPCC estimated that these effects caused RF increases of 0.0485 W/m^2 , not including the potential impacts of cirrus clouds. IPCC found the largest impacts to come from CO_2 (increasing RF), Ozone (increasing RF), Methane (aviation reducing RF), and contrails (increasing RF). Direct emissions of water vapor (increasing RF), sulfate (reducing RF) and soot (increasing RF) were found to have more modest impacts. A crucial uncertainty in the IPCC report resulted from its determination that the poor state of knowledge associated with cirrus clouds prevented the inclusion of these effects in the best estimate of total RF impacts.

Overall, aviation's relative contribution to total global RF was estimated to be approximately three percent of total RF. However, the report projected that this share would increase in the future – by about four times by 2050 to around 0.2 W/m^2 – as a result of increased operations and a relatively slow rate of incorporating technological improvement in the fleet. Again, this relative contribution is based on the use of the RF metric, which does not capture the different temporal effects of the various pollutants or potential differences in the efficiency of causing actual on-the-ground temperature changes.



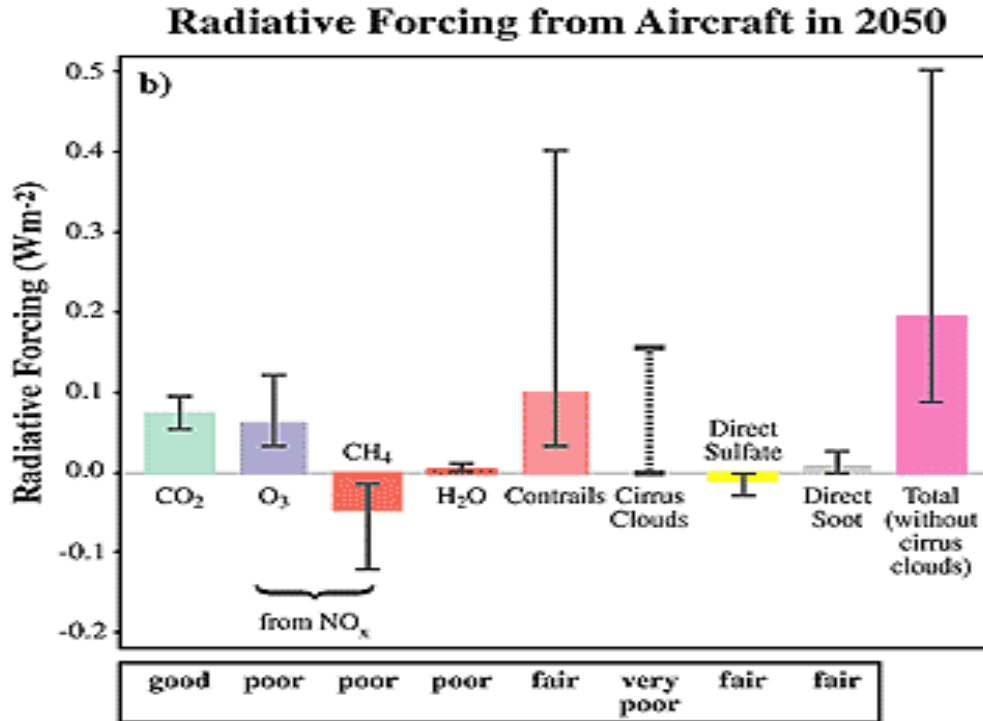


Figure 1: 1999 IPCC Estimates of Aviation Contributions to Radiative Forcing in 1992 and 2050

Since the release of the 1999 IPCC report, there has been additional, incremental improvement of the state of knowledge regarding aviation-related effects on climate. However, none of the research efforts since 1999 have brought together the breadth and depth of expertise as went into the IPCC report or the extent of peer review. Much of the research has attempted to reduce the uncertainties associated with cirrus cloud formation, contrails and particulate matter issues relevant to soot, cloud and contrail processes.

For example, NASA's Aircraft Particle Emissions Experiment (APEX), Experiment to Characterize Aircraft Volatile Aerosol and Trace Species Emissions (EXCAVATE), EC Partemis and other projects have been producing better data regarding the characterization of aircraft engine emissions from in-use engines. These data are helping improve the ability to understand the chemical and physical processes associated with the emissions of species from aircraft that may affect climate. Many of these programs are discussed in greater detail in the "Air Quality" section of *Critical Issues in Aviation and the Environment*.

Researchers have also used satellite data, modeling and other tools to reduce the range of uncertainty associated with contrail and cirrus cloud formation and aviation's role in this process. *E.g.*, Minnis (2004), K. Shine (2005), Ponater (2005).

The European Union has been conducting a research project called TRADEOFF to develop better estimates of radiative forcing from aviation. A recent paper by R. Sausen, *et al.* (August 2005), attempts to consolidate some of this post-IPCC research and develop new estimates of aviation-related climate change for the year 2000. In that analysis, the authors concluded that the largest difference between the IPCC analysis and their current assessment was a downward revision, by a factor of about three, in the assumed impact of contrails on RF. The authors based this downward revision on their assessment of additional observation of contrails, contrail physical properties and the temporal and spatial variation of contrail coverage, and other factors. As a result, the researchers estimated that total RF effects of aviation in 2000, not including cirrus cloud effects, were approximately .0048 W/m².

Sausen, *et al.*, also discussed the continued uncertainties regarding aviation-related effects on cirrus cloud formation and the consequent impacts on RF. These include: (1) contrails that can grow into larger cirrus clouds, known as

“contrail cirrus”; (2) emissions of particulate matter that may form additional nuclei for cloud condensation; and (3) effects that aircraft-related aerosols may have on the micro-physical properties of cirrus clouds (such as the number, size and form of cloud particles) that may affect radiative properties of clouds, cloud lifetime and other factors. The paper concluded that total RF for aviation may be twice as large as the estimate identified above if cirrus-related impacts could be more reliably quantified. Again, however, this conclusion may not capture the different temporal, spatial or efficacy differences associated with the various climate forcing mechanisms.

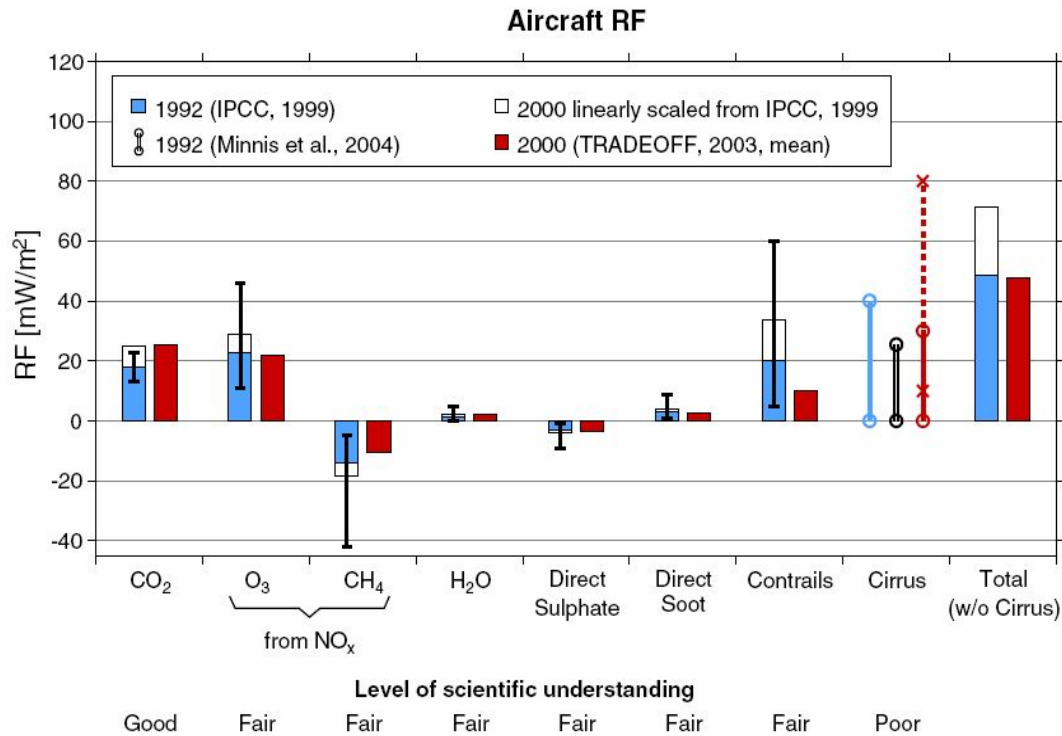


Figure 2: Sausen, et al., 2005 Estimates of Aviation Impacts on Radiative Forcing

In 2006, Stuber, *et. al.*, published a study concluding that the seasonal and diurnal incidence of flights significantly affects radiative forcing associated with contrails.

In June 2006, the U.S. Joint Planning and Development Office (“JPDO”) Environmental Integrated Product Team and the PARTNER (the FAA/NASA and Transport Canada sponsored Center of Excellence - Partnership for AiR Transportation Noise and Emissions Reduction) convened a workshop on the climate impacts of aviation. This workshop was attended by 30 international science experts and was the first such gathering on this issue since the IPCC 1999 report on the Aviation and the Global Atmosphere. The main objectives of this workshop were to assess and document the present state of knowledge of climate impacts of aviation, identify the key uncertainties and gaps in scientific knowledge, identify ongoing and further research needed and to make prioritized recommendations. The workshop focused on three key areas: (1) emissions in the UT/LS and resulting chemistry effects, (2) contrails and cirrus and (3) climate impacts and climate metrics. This workshop acknowledged the need for focused research efforts in the United States to address the uncertainties and gaps in our understanding of current and projected impacts of aviation on climate and to develop metrics to characterize these impacts. The workshop recommended that this specific research need can be addressed through co-ordination and/or expansion of existing and planned climate research programs or through new activities.

Following the workshop recommendation, the FAA (Office of Environment and Energy) and NASA (Earth Science Research Division and Applied Sciences Program) have jointly developed an Aviation-Climate Change Research Initiative (ACCRI) with the objective to improve the state of scientific knowledge and address key knowledge gaps while making best practical use of available science and modeling capability to quantify the climate impacts of aviation. The overall structure of ACCRI is based on a sequential multi-step process in which outcomes of the prior

steps will guide the direction and expectations of the next steps. The timelines to implement various steps of this effort and expected outcomes are designed in such a way that they will provide timely intermediate input towards scoping and implementation of following steps as well as scientifically informing policy-making decisions for NextGen and the International Civil Aviation Organization's Committee on Aviation Environmental Protection.

Airport-Level and Local Climate Change Issues

Under international treaties, greenhouse gasses are addressed at a national level. However, responding to local political pressure and lack of action on the federal level, cities and counties across the United States are beginning to quantify the contribution of sources within their boundaries to local greenhouse gas (GHG) emissions using methods that differ from IPCC protocols. These local aviation GHG inventories show a wide variation in results primarily due to the methodologies used to quantify emissions rather than actual level or variance in the type of activity.

The Airport Cooperative Research Program entered into a contract in October 2007 to develop a "Guidebook on Preparing Airport Greenhouse Gas (GHG) Emissions Inventories." The project is designed to provide guidance for developing accurate and consistent emissions inventories. Some of the questions the Guidebook is expected to address are (a) which pollutants to model, (b) what emission rates and metrics to use, (c) how to geographically allocate emissions, and (d) how to avoid double-counting. This project should be completed during Fall 2008.

FUTURE VISION

Building off of the current state of knowledge and research, the research community will significantly reduce uncertainties associated with the contribution of aviation to climate forcing mechanisms to inform and support decision making on international, national, state and local levels. This research will foster a better understanding of the potential tradeoffs of any economic, design, fuel or operation control strategies both (1) among different potential mechanisms for climate forcing (*e.g.*, between contrail formation and CO₂ emissions associated with fuel burn) and (2) among environmental impacts (*e.g.*, between climate-related impacts and ground-level air pollution or noise). In addition, the research community will continue to assess and report to policymakers the degree of uncertainty associated with aviation's impacts on climate.

RESEARCH NEEDS

Considerable research is needed to better understand the effects of aviation on climate and the potential effects of different possible policy options. The following are examples of some of the critical areas of research need. Much of the research is required from the atmospheric science community as it attempts to better understand climate processes on a global level. Other research must come on an individual aircraft or engine basis, as well as on the range of physical processes between an individual aircraft and the global atmosphere.

- The appropriate metric or metrics for assessing climate impacts, including metrics to allow a "common currency" among (1) climate forcing mechanisms with different temporal scales and (2) other modes of transportation and economic activity. Note that this is an issue that is not limited to aviation or even transportation generally, and the metrics should be assessed in the context of other sources of climate-related emissions.
- The effects of aviation activity on contrails and cirrus clouds and their consequent effects on climate. This issue continues to be identified as the one with the greatest combination of uncertainty and potential significance. Some specific uncertainties include:
 - An understanding on a general basis about the formation of cirrus clouds and effects of anthropogenic emissions (such as biomass burning, stationary sources, and surface transportation).
 - The effects of aviation-related emissions of particulate matter, water and other substances on cirrus clouds (including when no contrails are created) and the effects of these cirrus clouds on climate.
 - The effects of changed background climate (temperature, humidity and chemical composition) on

the environmental conditions for the formation of cirrus clouds.

- Spatial and temporal variation in aviation-related cirrus cloud or contrail formation.
 - The climate impacts associated with contrails and the best means of estimating such effects.
 - The effects of different aircraft operating conditions (e.g., altitude and routing) on cirrus cloud and contrail formation.
 - The effects of different particulates, especially soot and sulfates, on ice nucleation.
 - The relative contributions of aviation and other sources of particulate matter in the UT/LS, as well as the physical properties of such particulate matter.
 - Emissions plume, cirrus and contrail formation and evolution on scales smaller than the large scale grids used in global models.
 - The effects that aircraft engine or other technologies have on contrail production, such as the temperature at which contrails form.
- The effects of aviation-related emissions of oxides of nitrogen on ozone and methane levels and subsequent climate impacts. The following are examples of this type of research:
 - Atmospheric chemistry that occurs on scales smaller than the large scale grids used for global modeling, including aircraft emissions plume evolution.
 - Ozone and methane-related effects using the most current atmospheric models.
 - Transport and exchange of NO_x and other species within the UT/LS region..
 - Chemistry and transport relating HO_x and NO_x in the upper troposphere
 - Future atmospheric conditions resulting from climate change and other factors.
 - Potential differences among climate-related mechanisms in their efficacy of driving surface temperature change.
 - Consistent means of creating and allocating aviation-related emissions inventories on local, regional, and national scales.
 - Regional distribution of aircraft-induced climate change
 - Tradeoffs among climate effects associated with fuel burn and different aircraft operating conditions.
 - Uncertainties in future trends in traffic, technology and emissions, including projections of future air traffic control, fuel prices, infrastructure constraints, technology change and penetration, fleet turnover and other factors relevant to future emissions.
 - The monetary value of aviation-related climate effects for assessing trade-offs and/or market-based measures.
 - The economic effects of potential policy options.
 - Economic and technical issues associated with inclusion of aviation in any emissions fee, cap-and-trade or other market-based measure.

- Development of standardized aviation-related greenhouse gas (GHG) and climate change assessment methodologies on a sub-national level;

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