Aviation and the changing climate

To improve its technology and reduce its aircraft emissions, the aviation industry will need a better understanding of the effects of these effluents on the atmosphere

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Commercial aviation's dramatic growth over the past four decades has occurred amid increasing concern for the health of the atmosphere. International attention has focused on the integrity of the ozone layer, increasing emissions of greenhouse gases, and the influence of aerosols on climatic change.

Emissions from jet engines are deposited throughout the atmosphere, including remote regions of the upper troposphere and lower stratosphere, where long-distance aircraft cruise. At those altitudes, aviation emissions have greater potential to change ozone abundances and affect climate.

Recent scientific assessments of the problem have been performed in both Europe and the U.S., culminating in the "Special Report on Aviation and the Global Atmosphere," prepared under the auspices of the Intergovernmental Panel on Climate Change. The IPCC report is the first focused assessment of a transportation sector or related industry. It describes the current and projected states of commercial aviation technology and the present and predicted atmospheric changes from aviation based on computer models and observational data.

In a separate effort, the International Civil Aviation Organization (ICAO) is studying the policy implications of this issue. In late 1998, the 185 ICAO Assembly nations approved a resolution requesting the governing council "to study policy options to limit or reduce the greenhouse gas emissions from civil aviation, taking into account the findings of the IPCC special report and the requirements of the Kyoto Protocol [to the U.N. Framework Convention on Climate Change], and to report to the next ordinary session of the Assembly" in 2001.

The Kyoto Protocol states that the industrialized nations "shall pursue limitation or reduction of emissions of greenhouse gases not controlled by the Montreal Protocol from aviation and marine bunker fuels, working through ICAO and the International Maritime Organization, respectively."

Radiative forcing

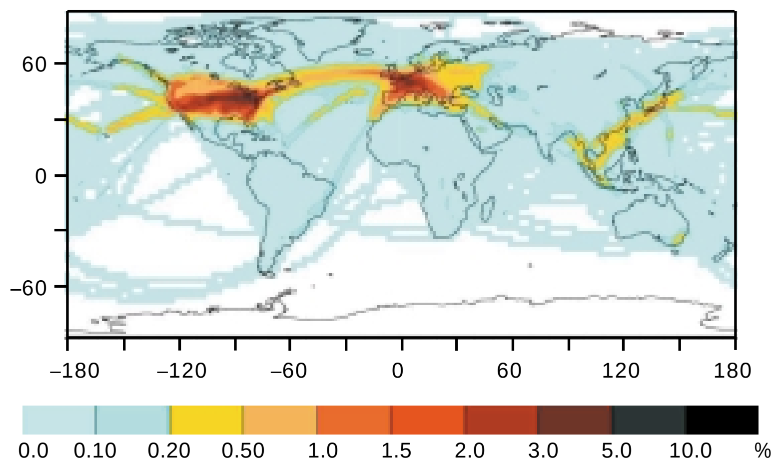
Aircraft emissions have greater potential to change climate than do those from hydrocarbon fuel combustion occurring at ground level. In general, emissions can cause climate change by affecting how much solar energy reaches the Earth and how much (mostly thermal) radiation escapes from Earth to space. The incoming and outgoing energies are balanced at about 340 W/m^2.

A useful measure of the potential for atmospheric changes to influence climate is the shift in Earth's radiative balance, or the radiative forcing, associated with such atmospheric changes. The estimated radiative forcing due to human activities has grown to about 1.4 W/m^2, indicating a net warming tendency relative to preindustrial times.

Aviation's radiative forcing per unit of fuel consumed is larger than that from surface fuel consumption, because of both the accumulation of emissions at altitude and the changes they induce in atmospheric chemical composition and cloudiness. A

This material is based upon *Aviation and the Global Atmosphere,* A Special Report of the Intergovernmental Panel on Climate Change Working Groups I and II. The report's Summary for Policymakers can be found at http://www.ipcc.ch/.

PERSISTENT CONTRAIL COVERAGE, 1992



Estimated persistent contrail coverage for the 1992 fleet [For this calculation, the global mean cover is 0.1%].

key finding of the IPCC report is that the radiative forcing due to aviation fuel use is two to four times that from carbon dioxide emissions alone. In comparison, the value averaged over all of human activities is at most 1.5 times that of CO_2 emissions alone. In addition to this evaluation of the radiative forcing on a per-unit-of-fuel basis, the total radiative forcing from aviation's emissions is estimated to be about 3.5% of the total radiative forcing from all human activities.

Many aircraft emissions contribute to total radiative forcing due to aviation. Some contribute directly (CO_2, H_2O, soot, sulfate aerosol), while others are indirect—NO_x affects atmospheric levels of ozone and methane; particle emissions in concert with water vapor can induce contrails and perhaps additional cirrus clouds.

The total radiative forcing for aircraft is due to several contributors and is larger than radiative forcing due to CO_2. This indicates the larger influence aviation use of fossil fuel may have on the atmosphere relative to other human activities. This forcing that would result from midrange growth in aviation is projected to be roughly four times larger in 2050 than the 1992 estimate.

The impact of NO_x illustrates the complexity of the atmospheric effects of aviation emissions. NO_x emissions create ozone and remove methane at cruise altitudes. Hence, the radiative forcing due to changes in ozone and methane are opposite in sign and of similar magnitude. Yet the changes do not cancel one another, because methane's impact is global, while the effect of tropospheric ozone is regional and primarily concentrated in the northern hemisphere. It is worth emphasizing that NO_x emissions at the cruise altitudes of subsonic aircraft primarily increase ozone and do not exacerbate the stratospheric ozone loss caused by other human activity.

There are significant unknowns associated with many individual radiative forcings, contributing to the uncertainty in the total. These unknowns arise primarily from two factors. The first is an incomplete understanding of how aircraft emissions, with their unique deposition patterns, disperse in the atmosphere and perturb processes such as atmospheric chemistry and the formation of contrails and clouds. The second is an incomplete knowledge of the composition and evolution of the exhaust emissions, particularly regarding reactive trace species, particles, and their gaseous precursors.

CO_2 and H_2O emissions from aircraft result from burning hydrocarbon fuel and are very accurately known. NO_x emissions for existing engines are also well known, because they are measured during engine certification for near-airport air pollution requirements. Significant efforts have been directed at developing engine technology to reduce NO_x emissions. But experts do not fully understand the evolution of the major reactive emission families (NO_x, SO_x, HO_x) from the flame zone in the combustor, through the engine hot sections, and on through the still-concentrated regions of the engine plume and aircraft wake.

Measurements of some primary emission species, such as NO and NO_2, are available from ground tests and in-flight measurement campaigns. However, similar data are mostly unavailable for other important species, such as SO_2, SO_3, HNO_2, HNO_3, O, and OH, as well as for particle sizes and number densities for soot emissions. These species are present in small concentrations, often several parts per million by volume or less, and require sophisticated measurement techniques. Furthermore, the role of engine operating parameters in affecting the post-combustor evolution of emissions has yet to be determined, and such factors are not currently considered in engine design.

Contrails and clouds

One factor still not completely understood is contrail formation. A condensation trail, or contrail, forms in the wake of an airplane as a result of water vapor and aerosol emissions perturbing the local atmosphere when it is at conditions very close to forming a natural cloud. Although it is apparent that aircraft-emitted particles provide sites for water vapor condensation, and that these particles may well participate in initial condensation processes, field measurements demonstrate that contrail ice particles growing on entrained ambient particles begin to dominate in the contrail relatively soon.

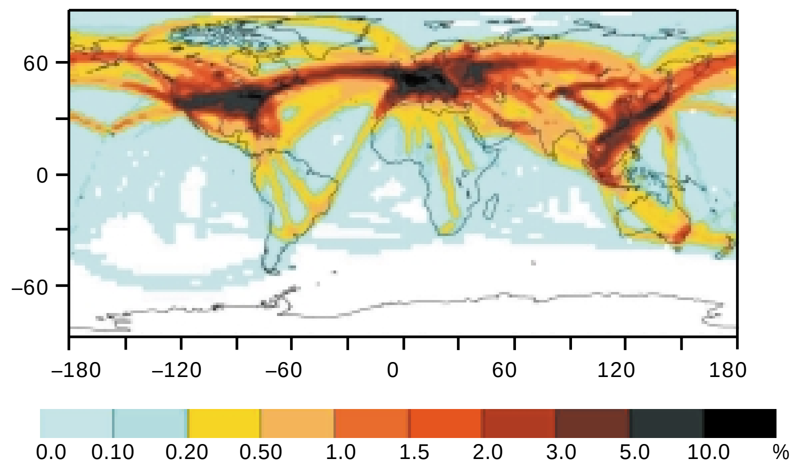
Currently, global contrail coverage is a few tenths of a percent of the global surface or less, and is highly regional. The radiative impact is unclear because of uncertainties in this coverage and in the radiative effects of the contrails. According to estimates, however, their contribution to the total radiative forcing due to aircraft is comparable to that due to CO_2, and thus can be considered to have a critical potential impact. Contrails, like high cirrus clouds, have a positive radiative forcing (warming effect), because they trap thermal radiation emitted from the Earth's surface more than they block incoming solar energy.

Equally important is the evolution of persistent contrails into high cirrus clouds that last for significant periods and have a positive radiative impact. Although individual instances of this phenomenon have been observed, the extent to which aviation increases cirrus cloud cover by this process remains highly uncertain. The effect is potentially one of the largest contributors to aviation radiative forcing. The impact on cloudiness from the accumulation of aviation aerosols at flight levels, whether or not a contrail formed initially, is another potential contributor. At present, the connection between airplane emissions and cirrus clouds is not well understood.

The longevity of a contrail is determined primarily by local atmospheric conditions, including the relative humidity of the air in which the exhaust is deposited. Thus, contrails will be less frequent for flights in warmer, less humid air. Exhaust aerosols composed of soot and sulfuric acid also play a role in contrail formation, albeit an uncertain one, and may affect the optical properties of contrail particles. Changes in the combustion process can influence the amount and size of the soot particles that are generated. Reductions in the sulfur content of the fuel may also reduce the generation of sulfate aerosol outside the engine.

Engines with higher overall efficiency produce less CO_2 and H_2O, but tend to enhance the potential for contrail formation. Improvements in engine efficiency increase the relative humidity of the exhaust plume, because reductions in plume temperature are greater than the corresponding reductions in water concentration as efficiency increases. The estimated growth in contrail coverage due to increased flights and more efficient engines will add significantly to the impact of contrails.

PERSISTENT CONTRAIL COVERAGE, 2050



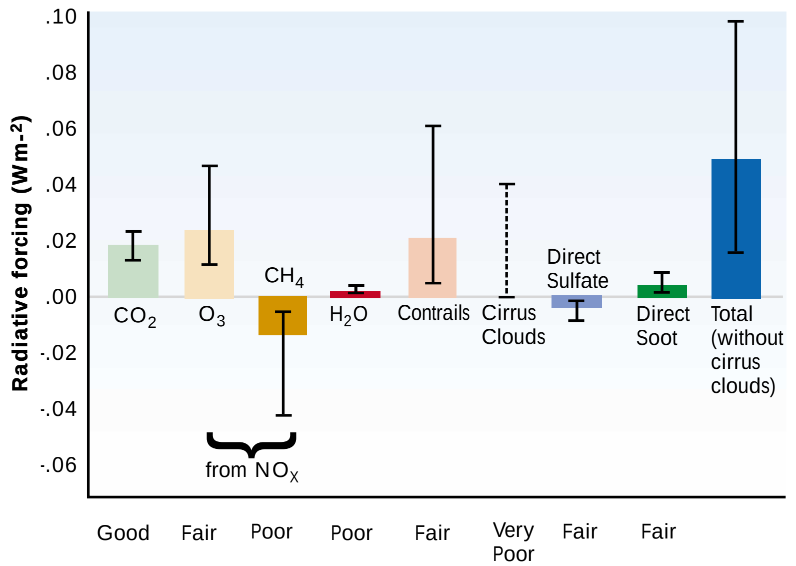
Estimated persistent contrail cover for the 2050 fleet, assuming a midrange fleet growth scenario and an aggressive improvement in overall propulsion efficiency from 0.3 to 0.5

Sulfur emissions

Sulfur species emissions result from the oxidation of fuel-bound sulfur and its subsequent release as gaseous species, SO_X. Thus the fuel sulfur content determines the total amount of emitted sulfur. Although most of the sulfur is emitted from the engine as SO_2, a significant fraction may be further oxidized within the engine and exhaust to form sulfuric acid (H_2SO_4). Sulfuric acid rapidly condenses and forms numerous small sulfate particles, especially in the cold of the upper troposphere or lower stratosphere where commercial airplanes cruise. These particles can play a role in forming contrails and are expected to accumulate in the atmosphere, increasing the number of particles at cruise altitudes by 10-100% of the background number densities. Upper atmospheric particles cause concern because of their role in determining cloud cover. They may also catalyze chemical reactions on their surfaces, changing the chemical balance in the remote atmosphere.

To predict the impact of sulfate aerosol on the atmosphere, scientists need a better

RADIATIVE FORCING FROM AIRCRAFT IN 1992



Estimates of the contributions to the radiative forcing due to aircraft emissions and their uncertainty ranges

understanding of the processes in the engine and exhaust plume that further oxidize SO_2, and of particle formation and growth in the airplane's wake. Important unknowns include the fraction of SO_x emissions that become sulfuric acid in the exhaust, and to what extent engine technology can influence this fraction. Changes in the fuel sulfur content will affect the total sulfur emissions.

In addition, other requirements to reduce sulfur in petroleum refineries will likely influence the total sulfur in aviation fuel. Further atmospheric research and engine emission studies are needed to determine environmentally acceptable levels of condensable emissions.

The future

Future emissions will depend on both fleet sizes and aircraft technology. The latter includes engine emissions performance, a factor that, along with airframe performance, will affect the overall fuel consumed. Local air quality concerns already motivate regulations for NO_x, CO, unburned hydrocarbons, and visible smoke emissions, and technology has been developed to satisfy current requirements. If the impact of global aviation emissions increases sufficiently, and if local NO_x air quality issues remain, mitigation options will be considered. Ideally, technical feasibility, degree of mitigation, and associated costs of the various options will be used to develop a balanced response to both the local and global impacts of aviation.

Technology advances could bring about improved fuel efficiency, lowering the amount of fuel burned and the total emissions released. Such advances could also reduce one emission in relation to others. However, there are tradeoffs to be considered, such as that between contrail formation and fuel burn, as overall engine efficiency is increased.

The IPCC report reviews the current state of airframe and engine technology, making projections for how advances may affect individual emissions in the coming decades. Emissions can decrease with improved aircraft operations, especially communications, navigation, and surveillance/ air traffic management. The document also notes that regulatory and market-based mitigation measures may be considered in the future, particularly with the possibility of international agreements such as the Kyoto Protocol under consideration.

Meeting stringent technical and airworthiness requirements poses significant challenges in considering further improvements to the efficiency or emissions performance of aircraft. Compared to other transportation modes, aircraft are more constrained by weight and volume considerations and by flight safety factors. All of these limit technology and operational choices. Moreover, aircraft systems are typically more complex and more expensive to develop, purchase, and operate than other transportation.

With respect to technical improvements in emissions performance, several points need emphasizing Any improvements require significant development time, and the resulting equipment will likely be in service for several decades. Consequently, the fleet operating during that period will be using technology developed to meet either current requirements or those identified in the next several years.

Also the limited improvements in fuel consumption and NO_x reduction attainable in the near future will counteract only a modest amount of growth in aviation. At the same time, significantly increased demand is anticipated—the IPCC studies assumed a 5% annual rise in revenue passenger kilometers through 2015, and a midrange growth scenario of 3% a year from 1990 through 2050.

Advanced engine technology

Higher fuel efficiency, whether achieved through airframe weight and drag reductions or improved overall engine efficiency, cuts the total amount of fuel used and thus directly reduces many emissions. Specifically, CO_2 and H_2O emissions decrease in direct proportion to reductions in fuel burn, and most other emissions also are reduced. Total SO_x emissions depend on fuel sulfur and also are affected in proportion to reduced fuel burn. Other emissions such as NO_x may be reduced to varying degrees.

However, if the higher fuel efficiency is achieved through advances in engine thermodynamic design, the proportion of NO_x emitted per unit of fuel burned (NO_x emission index) may increase. The net change in NO_x emission performance, then, is a tradeoff between decreasing the fuel burn and increasing the NO_x emission index.

The tradeoff between engine efficiency and NO_x emissions performance is centered in the engine combustor. Engine overall efficiency has been increasing, from less than 20% in early turbojets to 30% in current high-bypass turbofans. Improvements in both propulsive and thermal efficiencies have contributed to these increases, and further improvements in both factors can be expected in the future. Gains in thermal efficiency are achieved through increases in the engine pressure ratio, higher operating temperatures, and improved component efficiencies. Higher pressures and temperatures in the combustor translate into higher NO_x production, assuming similar combustor technology is retained.

To counter the trend of higher NO_x emissions from higher thermal efficiency, low-NO_x combustors have been developed, and new designs are being pursued to further reduce NO_x emissions. The weight increases associated with some of these advanced designs will affect the overall fuel efficiency of the aircraft, so the tradeoffs between CO_2 and NO_x emissions can be complex. But application of low-NO_x combustors will likely be based on a need to reduce emissions affecting local air quality. Thus, some increase in CO_2 emissions may result from mitigating associated health and environmental problems.

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Aviation will be emitting CO_2 and H_2O for the foreseeable future. Advances in aviation technology can reduce the amount of fuel used in transporting passengers and thus reduce both the primary emissions of CO_2 and H_2O and pollutant species that are emitted in proportion to the total fuel burn. Beyond reducing the amount of fuel used, combustor technology improvements may lower the amount of NO_x emission relative to CO_2 emission, although NO_x/CO_2 tradeoffs must be considered in optimizing the overall emissions reductions. Sulfur emissions can be reduced by reducing sulfur in the fuel.

Technology exists to reduce aviation's major emissions to varying degrees. Although reductions in emissions can compensate for some growth in air traffic, the actual growth expected over the next several decades may significantly exceed that which realizable reductions can counteract.

Aviation emissions have a greater impact than the same amount of ground-level emissions because of the induced changes in the abundances of radiatively active gases such as ozone and methane, and because of persistent contrail formation and contrail-induced cloudiness. There are still significant uncertainties in the predicted impacts, due to an incomplete understanding of how the unique location and nature of aviation emissions affect ambient air chemistry and contribute to atmospheric aerosols. Particle and gaseous emissions that are involved in contrail formation, and may affect cirrus cloud cover, are estimated to have a role comparable to that of CO_2 emissions and must be better understood to reduce uncertainties in aviation's climatic impact. It has been recognized only recently, for instance, that engines with higher overall efficiency tend to increase the potential for contrail formation.

Given these significant uncertainties along with the rapidly evolving regulatory environment and the relatively long timescales for technological change, a continued investment in understanding the potential impacts of aviation and various mitigation options is warranted.

The IPCC report raises important questions regarding how increases in commercial aviation may affect global climate. The aviation industry can inform the debate on any future regulations by helping to identify the technological, policy, and economic options that could serve to mitigate aviation's effects, and by determining the feasibility and costs of these options.

The industry's present operations result in only a few percent of the total radiative forcing of all human activities. To remain a small part of the total human-induced global climate change while serving an ever-increasing global market is a challenging goal for aviation in the next century.