Aviation and the Global Atmosphere
A Special Report of IPCC Working Groups I and III

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## Introduction

In May of this year, the IPCC published a special report on Aviation and the Global Atmosphere. The report was prepared at the request of the International Civil Aviation Organization and the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer. It assesses what is known about the effects of aviation on the earth's climate and on atmospheric ozone, both in the past and in the future. In addition, the report examines scientific, technological, social and economic issues associated with various options to mitigate adverse effects of aviation on climate and stratospheric ozone.

As is the case for all reports of the IPCC, the special report on aviation was subjected to extensive review by scientific and technical experts, and by the governments of countries that participate in the IPCC. More than 200 experts from universities, research institutions, industry groups, government agencies, and other groups from 30 countries participated in the review of the report. These reviews contributed to a strengthened, more balanced assessment of the state of knowledge about aviation and the global atmosphere. Such review is critical to the IPCC for assuring that our reports provide comprehensive, scientifically valid assessments that are balanced in their presentation of differing yet scientifically supportable points of view.

## Overview of effects

Aircraft emit gases and particles directly into the upper troposphere and lower stratosphere where they modify atmospheric composition, radiative forcing, and climate. Radiative forcing, expressed in watts per square meter, is a measure of the strength of the effect of a change in the composition of the earth's atmosphere

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on climate. A positive radiative forcing leads to warming of the climate, while a negative radiative forcing leads to cooling.

Aircraft emissions include greenhouse gases that directly add to radiative forcing and warming, e.g. carbon dioxide and water vapor. Other emissions from aircraft, e.g. nitrogen oxides, indirectly affect climate by producing or destroying the greenhouse gases ozone and methane, with corresponding effects on radiative forcing and climate. Sulfur and soot particles emitted by aircraft, along with water vapor, trigger the formation of line-shaped white clouds called condensation trails, or contrails. Contrails have a positive radiative forcing and add to warming. These emissions may also induce greater cirrus cloud cover, which would increase warming as well. But this process is poorly understood and it is not yet clear how much, if at all, aircraft emissions increase cirrus cloudiness.

Ozone, in addition to being a greenhouse gas, absorbs ultraviolet radiation and shields the Earth's surface from this biologically damaging form of radiation. Most of the absorption occurs at stratospheric altitudes, but tropospheric ozone is also important in this process. A variety of human created compounds (e.g. chloroflorocarbons and halons) have caused depletion of ozone in the atmosphere. Ozone depletion increases the amount of ultraviolet radiation that reaches the Earth's surface.

Increases in ultraviolet radiation at the surface have a number of harmful effects. These include an increase in the incidence of skin cancer, accelerated formation of cataracts (the leading cause of blindness in many developing countries), possible suppression of the human immune system, and reduced productivity of terrestrial and aquatic ecosystems, including agriculture.

Aircraft emissions play a role in ozone formation and depletion. Depending upon the altitude at which gases are emitted, and other factrs, aircraft emissions can either produce and destroy ozone. Nitrogen oxides emitted by subsonic aircraft in the upper troposphere and lower stratosphere, 9 to 13 km above the surface, are expected to *increase* ozone and thereby *decrease* the amount of ultraviolet radiation reaching the surface. Emissions at this altitude are more effective at producing ozone in the upper troposphere than an equivalent amount of emissions at the surface.

In contrast, supersonic aircraft cruise at higher altitudes of 17 to 20 km in the stratosphere. Emissions of nitrogen oxides at these altitudes are expected to *deplete* the stratospheric ozone layer. The result would be an *increase* in ultraviolet radiation at the surface.

## Present effects of aviation on climate and UV radiation

In 1992, the total radiative forcing from all human activities is estimated to have been 1.4 watts per square meter. This includes positive forcing of 2.7 $Wm^{-2}$ from greenhouse gases and negative forcing of –1.3 $Wm^{-2}$ from aerosols. In the report, the effects of the various emissions from aircraft on atmospheric composition are estimated. The best estimate of the total contribution to radiative forcing from aircraft in 1992 is 0.05 $Wm^{-2}$. This estimate excludes possible effects on cirrus cloud formation, which are considered to be too uncertain to include. This is about 3.5% of the total from all human activities.

The precise contribution cannot be known with certainty. It is estimated that there is a 67% probability, or 2 out of 3 odds, that the radiative forcing from aviation is between 0.01 to 0.10 $Wm^{-2}$. Conversely, there is a 1 in 3 chance that the contribution from aviation is greater or smaller than the upper and lower bounds of this range, respectively.

If we look at the individual components, carbon dioxide from aircraft contributed 0.018 $Wm^{-2}$ in 1992.

Nitrogen oxide emissions from aircraft influence the concentration of two greenhouse gases. NOx emissions of subsonic aircraft are estimated to have increased ozone concentrations at cruise altitudes of 9 to 13 km. In northern mid-latitudes, the increase is roughly 6% relative to the concentrations that would have occurred in 1992 without aircraft. Total column ozone in these latitudes increase 0.4%. Lesser increases occurred in the Southern hemisphere. The ozone increase is estimated to increase radiative forcing by 0.023 $Wm^{-2}$. NOx emissions also lower the concentration of methane by roughly 2% in 1992, which resulted in negative forcing of – 0.014 $Wm^{-2}$.

The magnitudes of these two opposing effects of NOx are roughly the same. However, the effects on ozone are concentrated in northern mid-latitudes while the effects on methane are global in extent. Consequently, the two effects on regional radiative forcing do not cancel.

Contrails are estimated to have contributed 0.02 $Wm^{-2}$. The effect is similar in magnitude to carbon dioxide and ozone effects of aircraft, but is subject to greater uncertainty.

The direct effects of water vapor, sulfate, and soot are estimated to have been small in 1992. Aircraft emissions may also induce increased cirrus cloud cover, which would increase warming. But this process is poorly understood and estimates of radiative forcing from cirrus clouds are not included in the estimate of total forcing from aircraft.

**Present effects on ozone and UV-B**

The ozone increase caused by aircraft NOx emissions also reduced the amount of ultraviolet radiation reaching the Earth's surface. The change in ozone concentration will vary by latitude and season. As already noted, aircraft NOx emissions are estimated to have increased ozone concentration by 6% in 1992 at 45$^{o}$ N in July. As a consequence, the erythemal dose rate, which is a measure of UV irradience weighted according to how effectively it causes sunburn, is estimated to have been decreased by 0.5%. For comparison, ozone depletion caused by human created chlorine and bromine compounds from the period 1970 to 1992 is estimated to have increased the erythemal dose rate by about 4%.

**Emissions are expected to grow**

Aviation has experienced rapid expansion as the world economy has grown. Since 1960, passenger traffic has grown at an average annual rate of nearly 9%, or more than twice the rate of growth in gross domestic product of the world. The growth rate has slowed in recent years, but continues to outpace income growth and is expected to continue to do so in the future. Consequently, the contribution of aviation to radiative forcing is expected to increase relative to other sources in the future.

Scenarios of future aircraft emissions for the period 1990 to 2050 were developed for the special report. Future emissions from aircraft will vary with the growth in air traffic, technological improvements that reduce fuel consumption and emissions per passenger mile, and the efficiency with which air traffic is managed. The scenarios developed for the report incorporate technological changes that would increase fuel efficiency 40 to 50% by 2050 relative to aircraft produced today. The scenarios also assume that improvements in air traffic management will reduce aviation fuel burn by 8 to 18% within 20 years.

Despite these technological and management improvements, future emissions from aircraft are projected to increase. For example, by 2050, carbon dioxide emissions are projected to grow 1.6 to 10 times the 1992 level of 0.14 Gt C/year.

One of the seven scenarios was selected as the reference scenario for evaluation and comparison of climate and ozone effects. For the reference scenario, emissions of carbon dioxide grow 3 fold to 0.40 Gt C/year by 2050. This represents 3% of the total carbon dioxide emissions projected for all human activities for that year. In 1992, carbon dioxide emissions from aircraft was 2% of the total emissions from all activities.

**Future effects of subsonic aviation on climate**

For the reference scenario of future emissions, the best estimate of the total contribution of aviation to radiative forcing in 2050 is 0.19 $Wm^{-2}$. This is a 3.8 fold increase from the 1992 contribution from aviation. The share of total forcing attributable to aviation increases from 3.5% in 1992 to 5% by 2050.

Because of uncertainties about the processes by which aviation alters the Earth’s atmosphere and the effect, the precise contribution from aviation is uncertain. It is estimated in the report that there is a 67% probability that aircraft emissions, as projected in the reference scenario, would increase radiative forcing in 2050 by 0.1 to 0.5 $Wm^{-2}$.

If uncertainty about future emissions is also taken into consideration, the range of plausible changes in radiative forcing due to aircraft expands. The best estimates of radiative forcing derived from each of the seven emission scenarios range from 0.13 to 0.56 $Wm^{-2}$.

The individual gases and particles contribute to the total radiative forcing in much the same proportion in 2050 as was the case in 1992. Carbon dioxide, ozone and contrails again contribute most of the positive forcing from aircraft, while methane reduction contributes a significant negative forcing.

**Future effects of subsonic aviation on ozone and UV-B**

NOx emissions from subsonic aircraft are estimated to increase ozone 13% by 2050 in Northern mid-latitudes, more than doubling the 1992 effect of aircraft on ozone. The increase in total column ozone is 1.2%. The projected increase in ozone concentration would further decrease the amount of ultraviolet radiation reaching the Earth’s surface. The erythemal dose rate is estimated to decrease by 1.3 percent.

**Future effects of supersonic transport**

A source of considerable uncertainty for the future effects of aviation on the atmosphere is the role of supersonic aircraft. At present there are only 13 supersonic aircraft in a civil aviation fleet of roughly 12,000 aircraft. The report investigates a case in which it is assumed that the fleet of supersonic aircraft begins to grow in 2015 and reaches 1000 aircraft by 2040. These aircraft replace a portion of the subsonic fleet.

Supersonic aircraft would fly at an altitude of about 19 km, 8 km higher than subsonic aircraft. This difference in altitude leads to very different effects on the atmosphere. The radiative forcing of civil supersonic aircraft is estimated to be about a factor of 5 larger than that of the displaced subsonic aircraft in the reference scenario.

The effect of a fleet of 1000 supersonic aircraft is to increase the total radiative forcing from all aircraft in 2050 from a best estimate of 0.19 $Wm^{-2}$ to 0.27 $Wm^{-2}$. Most of this increase is due to accumulation of stratospheric water vapor. The increase in forcing is more than 40%. Clearly, the climatic effect of aviation is highly sensitive to inclusion of supersonic aircraft in the civil aviation fleet.

The effect of introducing a civil supersonic fleet is also to *reduce* stratospheric ozone and increase the amount of ultraviolet radiation that would reach the Earth's surface. The supersonic fleet would reduce column ozone by 1.3% at $45^{o}$N in July, while the subsonic fleet would increase ozone 0.9%. The net effect for the entire fleet would be a 0.4% reduction in ozone and a 0.3% increase in the erythemal dose rate of ultraviolet radiation. In contrast, a fleet composed solely of subsonic aircraft is estimated to result in a net increase in ozone.

**Options to reduce emissions**

A range of options for reducing emissions from aviation are examined in the report. The examined options include changes in aircraft and engine technology, reductions in sulfur content of fuel, improved operational practices, and regulatory and economic measures.

As noted previously, the emission scenarios already include significant technological advances and improvements in air traffic management that would reduce the emissions per passenger mile traveled. And yet, growth in passenger demand is anticipated to dominate these changes such that most aircraft emissions are projected to increase in the future.

Policy options to reduce emissions further include more stringent aircraft engine emissions regulations, removal of subsidies and incentives that have negative environmental consequences, environmental levies, emissions trading, voluntary agreements, research programs, and substitution of rail and coach for aviation. Further investigation of the costs and effectiveness of these options is needed to help inform decisions to mitigate the effects of aviation on the global atmosphere.

### ***Ordering a copy of the report***

The IPCC special report Aviation and the Global Atmosphere can be ordered from the publisher, Cambridge University Press, 40 West 20th Street, New York, NY 10011-4211. Their toll free service phone number is 1-800-872-7423.