Aircraft Emissions

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Aircraft Emissions

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Aircraft emit gases and particles directly into the upper troposphere and lower stratosphere, mainly in Northern Hemisphere mid-latitudes, where they have an impact on atmospheric composition. These gases and particles alter the concentration of atmospheric greenhouse gases, including carbon dioxide (CO_2), water vapor (H_2O), ozone (O_3), and methane (CH_4). They may trigger the formation of condensation trails (contrails), increase cirrus cover and change other cloud properties, all of which affect the energy and water budgets of the atmosphere and hence may contribute to climate change at the regional and global scale.

The disturbances induced by global aviation cause an additional radiative forcing (heating) of the Earth–atmosphere system by aircraft of about 0.05 $W m^{-2}$ or about 3.5% of the total radiative forcing by all anthropogenic activities in 1992. The values are presently increasing both in absolute and relative terms. Nitrogen oxides (NO_x) emissions from current aircraft are calculated to have increased O_3 by about 6% in the region 30–60 °N latitude and 9–13 km altitude. Calculated changes in the total column of O_3 in this latitude range are approximately 0.4%. Calculated effects are substantially smaller outside this region. Emissions of NO_x into the stratosphere above about 20 km might cause a reduction of O_3. An order 1% reduction of O_3 in the stratosphere and a corresponding increase of ultraviolet (UV)-B radiation at the surface may occur if a large (1000 aircraft) fleet of supersonic aircraft were to become operational.

Aircraft emissions near airports contribute to local air pollution. The emitted nitrogen oxides (NO_x) reduce the ozone (O_3) concentration in the immediate neighbourhood of the airport and, together with the emitted hydrocarbons, may induce additional O_3 several 10 km downstream from the airport by photochemical smog reactions. Outside the immediate neighbourhood of airports, in regions with high ground traffic and high population density, the emissions and the resultant smog are dominated by other forms of traffic such as motor vehicles, or by industry and domestic emissions. Noise induced by aircraft engines and aircraft structures during take-off and landing is often considered as a significant environmental problem.

TRAFFIC

Aviation is an integral part of the infrastructure of today's society. It plays a vital role for global commerce and private travel. Air traffic has grown strongly in recent decades, see Figure 1, faster than the economy as a whole. In 1997, 13 489 jet, 3213 turbo-prop, and 291 piston-engine commercial aircraft carried 1457×10^6 revenue passengers worldwide, on average over 1766 km distance per flight. The number of jet aircraft increased by 4.8% $year^{-1}$ from 1981 to 1997, turbo-props by 2.2% $year^{-1}$, while the number of aircraft with piston-engines is decreasing. The number of revenue passengers increased by 4.2% $year^{-1}$ from 1981 to 1997. Passenger traffic increased by 5.3% $year^{-1}$ to 2573×10^9 $year^{-1}$ revenue passenger-kilometres, and freight traffic by 7.8% $year^{-1}$ to 103×10^9 freight tonne-kilometres per year in the same period. For comparison, the world economic output (gross national product, GNP, in market prices of 1995) grew by 2.4% annually on average in the years 1991 to 1998 (World Bank, Washington, DC, March 2000).

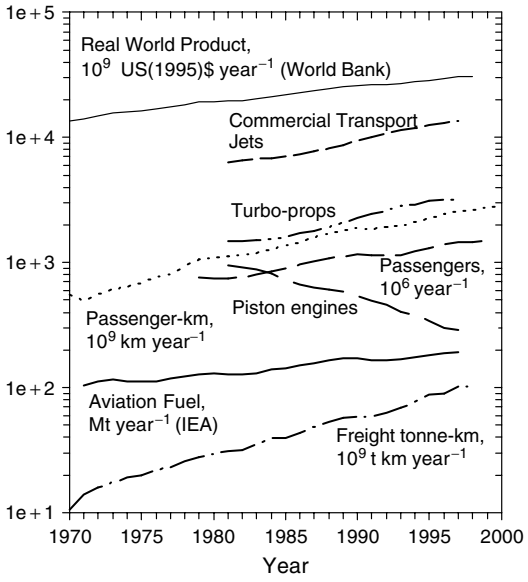

Figure 1 World aviation in the years 1970–1999: civil commercial transport aircraft (three types) registered in International Civil Aviation Organization, ICAO states, and traffic of commercial air carriers as reported by the ICAO (Montreal), aviation fuel production as reported by the International Energy Agency (IEA, Paris), together with the real world economic product (Worldbank, Washington, DC)

FUEL CONSUMPTION

Global air traffic consumed aviation fuels at a rate of 130 to 170 Mt $year^{-1}$ during the year 1992 (i.e., about 5–6% of all petrol products), including a military fraction of about 18% (Intergovernmental Panel on Climate Change (IPCC), 1999). The upper bound fuel consumption value is the

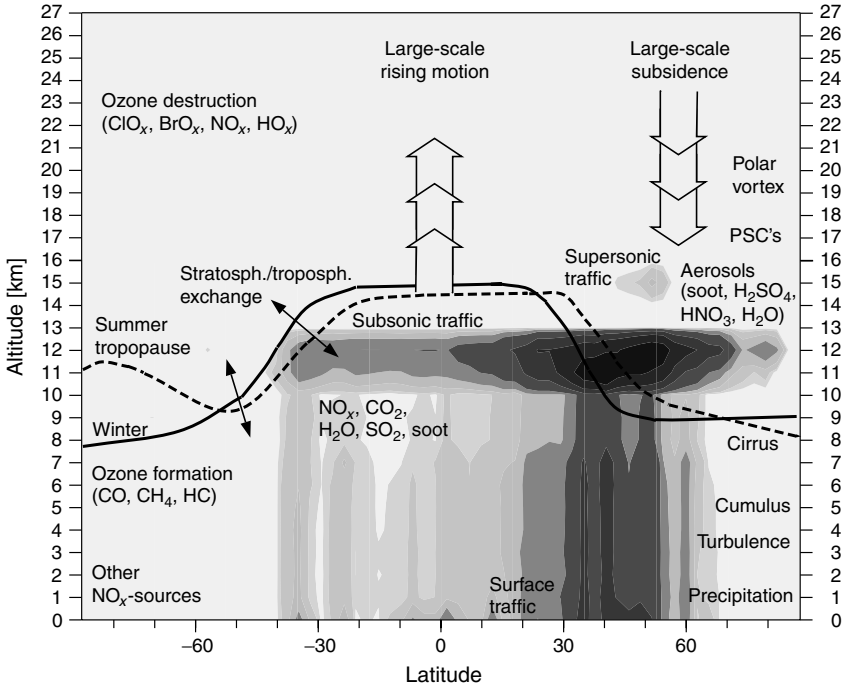

Figure 2 Mean altitude of the tropopause in June and December, and distribution of NO_x emission source rates from aircraft versus altitude and latitude (the emission rate is the larger the darker the shaded area), and indications of mean circulation and some relevant processes

Table 1 Consumed or emitted species, mean emission indices, i.e., mass of emissions per unit mass of burned fuel, for the fleet of aircraft in 1992, total emission rates due to aviation, and comparable emission rates. (Reproduced by permission of Intergovernmental Panel on Climate Change (IPCC), 1999)

Species	Emission index, g kg^{-1} (ranges)	Emission rate (1992) in Mt year^{-1}	Comparable emission rate, Mt year^{-1}	Comparable emission source
Kerosene		140 (139–170)	3140	Total petrol production
CO_2	3160	440 (430–540)	26 000–30 000	Total anthropogenic CO_2 emissions
H_2O	1230	176	45	Methane oxidation in the stratosphere
			525 000	Evaporation of H_2O from Earth's surface
NO_x	14 (12–16)	2	2.9 ± 1.4	Stratospheric sources
			90 ± 35	Total anthropogenic source
Soot	0.04 (0.01–0.1)	0.006	12	Combustion of fossil fuels and biomass
SO_2	0.8 (0.6–1)	0.12	130	Total source from burning fossil fuels
			20–100	Natural sources
			5.4, 8.0	Non-eruptive, eruptive volcanoes
CO	4 (2–6)	0.56	1500	Total anthropogenic sources
H_xC_y	0.6 (0.2–3.0)	0.2	90	Total anthropogenic sources

aviation fuel production reported by the IEA (International Energy Agency), the lower bound results from analysis of air traffic, and aircraft/engine specific fuel consumption estimates. About 65% of the fuel is consumed at cruise altitudes between 10 and 13 km, see Figure 2. The largest fraction is consumed by wide-body aircraft on long-distance flights. Most of the emissions occur between 30° and 55 °N over the USA, Europe, and the North Atlantic. Globally the fraction of fuel burnt above the tropopause has been estimated to be about 30%. Over the North Atlantic the stratospheric fraction of fuel consumption is about 50% of the annual mean, with larger values during winter. The noon/midnight ratio of air traffic (in terms of fuel consumption) amounts to about 3 globally. Aviation fuel production grew by about 2.6% annually from 1981 to 1997, and was estimated to be about 200 Mt year^{-1} in the year 2000. The fuel consumption has grown at a slower rate than the traffic because of improved aircraft (engine and frame) technology, increased load factors of the aircraft, and a reduced fraction of fuel consumption for military purposes.

For the future, global passenger air travel, as measured in revenue passenger-km, is projected to grow by about 5–6% year^{-1} between 1990 and 2015, whereas total aviation fuel use, including passenger, freight, and military, is projected to increase by 3–4% year^{-1}, over the same period. The military fraction is expected to decrease to 7% in 2015.

EMISSIONS

In burning kerosene (a hydrocarbon mixture with about 13.8% hydrogen mass fraction) with air, engines emit mainly the greenhouse gases carbon dioxide (CO_2) and water vapor (H_2O) (Table 1). Minor emissions formed during combustion in the engine include nitric oxide (NO) and nitrogen dioxide (NO_2) (which together are termed NO_x, the emissions being measured in terms of mass units of NO_2), hydrocarbons (H_xC_y), carbon monoxide (CO), and soot. Soot includes around 10^{15} particles kg^{-1} of burnt fuel with typical diameters of 10–30 nm (Kärcher, 1999). Kerosene contains about 0.8 (0.001–3) g sulphur kg^{-1} of fuel. During the combustion in the engines, this sulphur is converted to sulphur oxides (SO_x), mainly sulphur dioxide (SO_2), but partly into sulphur-trioxide (SO_3) and after some cooling and with H_2O, into sulphuric acid (H_2SO_4). The conversion fraction of fuel sulphur to H_2SO_4 in the young plume is in the range of 0.4% to about 10%.

Aviation contributes about 1.6 to 2.2% to the global anthropogenic CO_2 emissions of about 7000 Mt C year^{-1}, 10 to 13% of traffic-originating CO_2, and 2% of all NO_x sources. Other NO_x sources (in units of Mt NO_2 year^{-1}) include biomass burning (17.5), industry and surface traffic (72), microbial activities in soil (11.7), lightning (16.4), and stratospheric sources (2.1; Lee *et al.*, 1997). Aircraft emission amounts of CO and hydrocarbons are much smaller than other anthropogenic emissions and of little importance for air chemistry outside airports. The methane (CH_4) concentration at engine exit may be smaller than in the ambient air. Total aviation NO_x emissions increased faster than fuel consumption over recent decades because of higher combustion temperature and pressure in more fuel-efficient modern engines. Other types of emissions decreased per unit of fuel consumption.

CHANGES IN AIR COMPOSITION

The gases and particles emitted by aircraft accumulate in the atmosphere near the flight routes, mainly in the northern mid-latitudes, depending on their residence time. Emissions into the lowermost stratosphere (see Figure 2), just above the tropopause get mixed mainly poleward and downward by the mean circulation, and leave the stratosphere by stratosphere-troposphere exchange processes (see Figure 2). Lower-stratospheric inert emissions reside there for an order of weeks to months. Some of the emissions have shorter residence times because of chemical conversions. For example, NO_x near the tropopause gets converted to nitric acid (HNO_3) within a few days or weeks. The NO_x concentration in the upper troposphere is about 1000 times lower than in urban regions, and the residence time for NO_x emissions near the ground is about ten times smaller than near the tropopause. Therefore, the relatively small amounts of aircraft emissions have notable effects on the NO_x concentration near the tropopause. Accumulations of aircraft emissions of NO_x are measurable regionally near main traffic corridors at least under low wind conditions (Schumann *et al.*, 2000). Increases of the concentration of small particles emitted from aircraft with similar residence times have also been measured near dense flight routes. CO_2 on the other hand, has a lifetime of the order of 100 years and gets distributed essentially over the whole atmosphere. Therefore, the effects of CO_2 emissions from aircraft are indistinguishable from the same quantity of CO_2 emitted at the same time by any other source.

The gases and particles emitted or formed as a result of aviation have an impact on climate both directly and indirectly. The direct effect is due to absorption and scattering of radiation. Indirect effects are many. They result from chemical or physical effects of the aircraft emissions on the gases and clouds, which act as greenhouse gases or radiative scatterers or influence clouds and precipitation, and influence the energy budget and the hydrological cycle on Earth.

CO_2

Concentrations of and radiative forcing from CO_2 today are those resulting from all anthropogenic emissions during the last 150 years. The atmospheric CO_2 concentration increased by about 80 $\mu mol\,mol^{-1}$ since 1850, and is responsible for a radiative forcing of 1.6 $W\,m^{-2}$. For an order of magnitude estimate, one assumes that 1 $W\,m^{-2}$ radiative forcing causes a global change in surface temperature of the order 0.3–1.0 K.

Aviation caused less than 1.4 $\mu mol\,mol^{-1}$, i.e., 1.2–1.7% of the total increase (Sausen and Schumann, 2000). This percentage is lower than the percentage for emissions (<2.4%) because aviation emissions have occurred mainly in only the last 40 years. The related CO_2 radiative forcing due to aviation fuel consumption in the past is 0.02 $W\,m^{-2}$. The corresponding increase in surface temperature is too small to be observable but is computed to be about 0.004 K. For a scenario used in Intergovernmental Panel on Climate Change (IPCC) (1999) with 3.2-fold increase in aviation fuel consumption from 1992 to 2050, one computes a CO_2-concentration increase of about 6 $\mu mol\,mol^{-1}$, causing a temperature and sea level increase of 0.025 K and 3 mm (Sausen and Schumann, 2000). Note that these are scenario calculations covering CO_2 effects only.

O_3

O_3 is a greenhouse gas, which is particularly effective within the tropopause region because of low temperature in this region and low thermal radiation emission at low temperatures. O_3 also shields the surface of the Earth from harmful UV radiation. This shielding increases to first approximation with the column of O_3 (most O_3 resides in the stratosphere). O_3 also acts as a biologically effective air pollutant at the Earth's surface.

O_3 in the stratosphere might get reduced when NO_x concentrations increase there. The photocatalytic cycles for NO_x in the stratosphere are similar to those by which halogen compounds (ClO_x and BrO_x) and hydroxyls (HO_x) cause catalytic O_3 destruction. However, NO_x also binds other O_3-destroying radicals and hence, additional NO_x reduces O_3 only above altitudes of about 20 km. In the troposphere and lower stratosphere, other photocatalytic cycles dominate, which cause oxidation of CO and CH_4 and other hydrocarbons, and cause O_3 formation at a rate which increases with the NO_x concentration at least up to a certain maximum of NO_x concentration (Brasseur *et al.*, 1998). The O_3 formation in the upper troposphere is controlled by the concentration of NO_x, but depends also on the availability of CO, hydrocarbons, and gases that provide sources for HO_x radicals such as O_3, H_2O and acetone. Hence, NO_x emissions from the present fleet of subsonic aircraft, flying essentially below 13 km altitude, cause O_3 increases, while the same emissions from a potential future fleet of supersonic aircraft, flying above 16 km, could cause O_3 destruction. Because of the much larger time scales of photochemistry of O_3 (on the order of weeks), the O_3 concentration change is spread more smoothly over the zonal belt downwind of and adjacent to the main flight corridors. The O_3 change is also notable at far distances from the corridors. Aircraft emissions of NO_x are more effective in producing O_3 in the upper troposphere than an equivalent amount of emission at the surface. Also increases in O_3 in the upper troposphere are more effective in increasing radiative forcing than increases at lower altitudes.

The NO_x emissions from subsonic aircraft in 1992 are estimated to have increased O_3 concentrations at cruise altitudes in northern mid-latitudes by up to 6%, compared to an atmosphere without aircraft emissions (Intergovernmental Panel on Climate Change (IPCC), 1999). This change in O_3 concentration is of similar magnitude as the natural year-to-year variability. The impact on O_3 concentrations in other regions of the world is substantially less. These increases, on average, tend to warm the surface of the Earth. Computational studies with a global climate model show that aircraft-induced O_3 changes cause temperature changes, which are large enough regionally (order 0.2 K at some latitudes) to be distinguishable from climatic noise at the time scale of a few decades. It seems that aviation induced O_3 is particularly effective in heating the troposphere (Ponater *et al.*, 1999).

CH_4

CH_4 is also a greenhouse gas. Direct contributions from aircraft emissions to methane are unimportant, but NO_x increases in the upper troposphere lead indirectly to reductions of CH_4. The additional NO_x from aircraft enhances the oxidation cycle of CO, which causes local increases in OH radicals (*see* **OH–Radical: is the Cleansing Capacity of the Atmosphere Changing?**, Volume 2). Such radicals are short-lived and react with CO both in warm and cold air masses; they react also with CH_4 but essentially only in warm air. The induced OH radicals in the cold upper troposphere reduce the concentration of CO at flight levels. CO has a lifetime of about two months, longer than typical vertical transport times in the atmosphere. Therefore, the CO reduction is felt also near the surface. Reduced CO abundance near the surface leaves more OH radicals from other sources to react there, in warm air masses, with CH_4. Hence, aircraft NO_x emissions indirectly cause a reduction of CH_4. The CH_4 concentration in 1992 is estimated to be about 2% less than that in an atmosphere without aircraft (Intergovernmental Panel on Climate Change (IPCC), 1999). This aircraft-induced reduction of CH_4 concentration is much smaller than the observed overall 2.5-fold increase

since pre-industrial times. The reductions in CH_4 tend to cool the surface of the Earth.

H_2O

Water vapor is a greenhouse gas and of chemical importance. The amount of H_2O emitted by aviation is much smaller than the amount of water evaporating at the Earth's surface but comparable in magnitude to the amount of water resulting from CH_4 oxidation in the stratosphere (Table 1). Most subsonic aircraft H_2O emissions are released in the troposphere where they are removed by precipitation within 1–2 weeks. Some fraction of H_2O emissions is released in the lower stratosphere where it can build up to larger concentrations. Because H_2O is a greenhouse gas, these increases tend to warm the Earth's surface. Additional H_2O in the stratosphere may also induce hydroxyl radicals and reduce O_3 either directly or indirectly by forming polar stratospheric clouds, which cause halogen activation. However, for subsonic aircraft, these effects are small compared to the other climatic or chemical effects of aircraft emissions (Intergovernmental Panel on Climate Change (IPCC), 1999).

SULPHATE AND SOOT AEROSOLS

Besides soot, large numbers (about $2 \times 10^{17}\,kg^{-1}$ fuel) of small (radius 1–5 nm) liquid particles are formed in the exhaust plumes of cruising aircraft. These new particles initially form from H_2SO_4, chemi-ions, condensable hydrocarbons, and H_2O; they grow in size by coagulation with other particles and by uptake of H_2O and other condensable gases. Chemi-ions are charged molecule clusters formed during combustion. Charged particles enhance the coagulation efficiency (Kärcher, 1999). The fuel sulphur content has little influence on the conditions for contrail formation but has strong impact on the size of newly formed particles. The particles from aviation add to the atmospheric aerosol and impact cloud formation. The number of ice particles formed in the young contrail varies by a factor of about 3 for a factor 500 change in fuel sulphur content.

Subsonic aircraft emissions near the tropopause at northern mid-latitudes are a significant source of soot and sulphate aerosol concentrations, at least by number. Aircraft generate far less aerosol mass than that emitted and produced at the Earth's surface or by strong volcanic eruptions (Table 1). Aircraft emissions injected directly at 9–12 km altitudes are more important than similar surface emissions because of longer atmospheric residence times and lower background concentrations of pollutants in the upper troposphere. The direct radiative forcing by the accumulated aerosol is small compared to those of aircraft induced gases. The chemical effects of soot and other particles from aviation on O_3 by means of heterogeneous chemistry, and the physical effects of aerosol on cloud properties are not well known, but may be important.

CONTRAILS

Contrails are visible line clouds, see Figure 3, which form from H_2O emitted by aircraft flying in sufficiently cold air. Contrail formation, according to the Schmidt-Appleman criterion (Schumann, 1996), is due to the increase in relative humidity that occurs in the engine plume during mixing of the warm and moist exhaust gases with the colder ambient air, see Figure 4. When the humidity reaches liquid saturation in the young plume behind the aircraft,

Figure 3 Contrails of various ages at high ambient humidity. (Photo: U. Schumann)

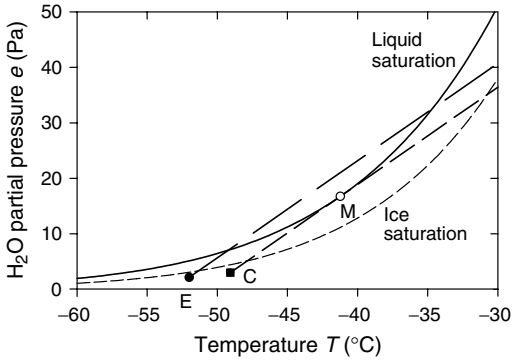

Figure 4 Mixing lines (dashed lines) and saturation curve over liquid water (full) and ice (dashed) in a diagram of partial water vapor pressure e versus temperature T. The mixing lines are plotted for environmental conditions with temperature T in the environment below (point E) and at (point C) the threshold temperature. At point M liquid saturation is reached during mixing under threshold conditions. Contrails remain short if E is below the ice-saturation curve and contrails may grow and persist if E is above ice saturation

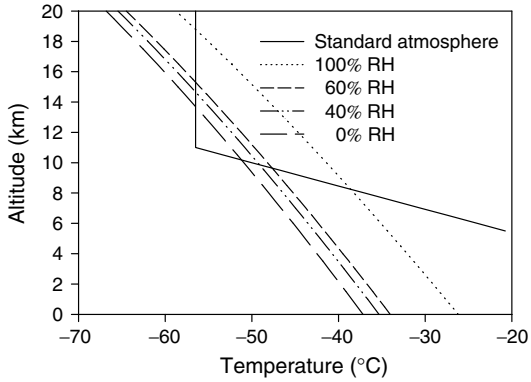

Figure 5 Threshold temperature for 0, 40, 60, and 100% relative humidity over liquid saturation (RH) for overall propulsion efficiency $\eta = 0.3$, kerosene fuel with water vapor emission index $EI_{H_2O} = 1.223$, and combustion heat $Q = 43.2\,\mathrm{MJ\,kg^{-1}}$, and temperature profile of the mid-latitude standard atmosphere versus altitude, z

liquid droplets form, mainly by condensation of H_2O on exhaust particles, which then soon freeze to form ice particles. In the absence of aircraft-induced particles, water in the moist aircraft plume would condense on ambient aerosol entrained into the plume, causing less but larger ice particles, with smaller optical thickness and less radiative impact. Contrails typically form at temperatures below about -35 to $-60\,^{\circ}\mathrm{C}$, see Figure 5, but the actual value increases with ambient relative humidity and with the parameter:

$$G = \frac{EI_{H_2O} p c_p}{[\varepsilon Q(1-\eta)]}$$

which is the slope of the mixing line in the diagram of water vapor partial pressure versus temperature, Figure 4. Hence the threshold temperature for contrail formation depends also on fuel and combustion properties in terms of the emission index EI_{H_2O} of water vapor and the combustion heat Q, on ambient pressure p at flight level, on the specific heat capacity of air c_p, the ratio $\varepsilon = 0.622$ of molar masses of water vapor and air, and on the overall efficiency η of the aircraft/engine system at cruise.

Contrails evaporate quickly when forming in dry ambient air. The fractional global coverage by these contrails is less than 0.001% and hence of no importance to the climate. Contrails persist, sometimes for hours, and grow when the ambient air is very humid with humidity above ice saturation. Ice particles in such persistent contrails grow by uptake of H_2O from the surrounding air. About 10–20% of all jet aircraft flights occur in air masses that are humid enough to cause persistent contrails. Ice-supersaturation in these regions is often too small to allow cirrus to form naturally, so aircraft act as a trigger to form cirrus clouds.

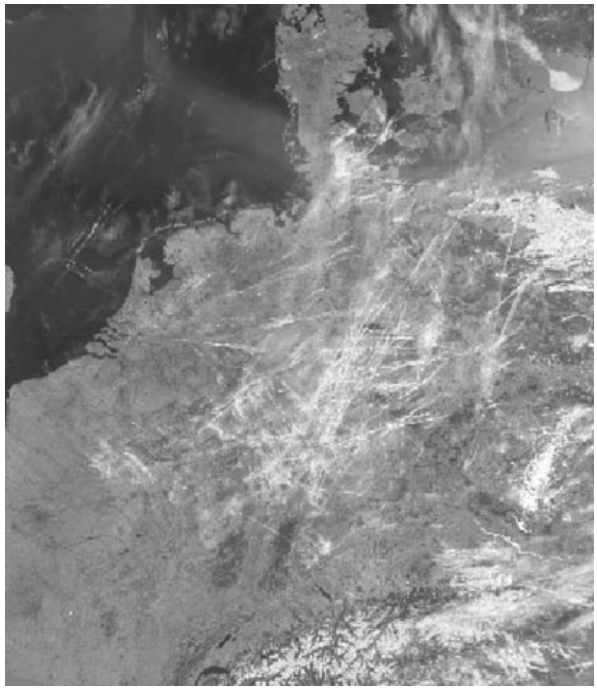

Figure 6 Contrails over mid-Europe on May 5, 1995, 7 : 43 UT, processed from NOAA-12 AVHRR data (as explained in Mannstein *et al.*, 1999). Photo: DLR/DFD

Contrail clouds can be identified and discriminated from natural cirrus clouds in satellite data based on their linear shape, see Figure 6, at least up to some age depending on the ambient conditions (Mannstein *et al.*, 1999). In 1996 and 1997, satellite data reveal that linear persistent contrails cover about 0.5–0.7% of the sky at noon over Europe in the annual average. This represents a lower bound for the actual contrail cover. The fraction of cirrus clouds with non-linear shape which originated from old contrails or from aircraft induced particles is unknown. The satellite data indicate a night-time contrail cover which is about 1/3 of that during daytime.

The mean global cover by linear contrails has been estimated to be 0.1% (possibly 0.02–0.2%) for 1992. The contrail cover grows faster with traffic than aviation fuel consumption because air traffic increases mainly in the upper troposphere where contrails form preferentially. Future improvements in the overall propulsion efficiency η will increase the threshold temperature of contrail formation and, hence, the contrail cover.

Contrails cause a positive mean radiative forcing at the top of the atmosphere, in particular during night and over warm and bright surfaces. They reduce both the solar radiation reaching the surface and the amount of longwave

radiation leaving the Earth to space. Contrails reduce the daily temperature range at the surface and cause heating of the troposphere. The radiative effects of contrails depend mainly on their coverage and optical depth, both of which are still not well known.

For 0.5% additional cirrus cloud cover regionally, a regional surface temperature increase of the order 0.05 K is expected. Such an increase can hardly be discriminated from natural variability. However, an increase of mean cirrus cloudiness in regions with heavy air traffic from typically 20% to 25% (i.e., by 5% cloud cover) has been found in models to cause a significant regional temperature change of order 1 K. The daily temperature range at the ground decreases with increasing cirrus cover but only little because of stronger sensitivity to lower atmospheric humidity.

CIRRUS CLOUDS

Some correlation between soot and ice particle concentrations have been measured in cirrus clouds which indicates an aviation impact on ice particle formation. Contrails trigger cirrus clouds in air masses which are sufficiently humid to let contrails spread but not humid enough to let cirrus form naturally. On average an increase in cirrus cloud cover tends to warm the surface of the Earth. More than 20% of the Earth is covered with cirrus clouds. Long-term observations of cloud frequencies at some meteorological stations and some satellite data indicate strong increases of the frequency or cover of cirrus clouds (Boucher, 1999; Intergovernmental Panel on Climate Change (IPCC), 1999), for unknown reasons. The increases are particularly large in regions with high air traffic density. The global trends suggest a cirrus cover increase of up to 0.2% since the beginning of jet aviation, in addition to the 0.1% cover by line-shaped contrails. The cirrus cover changes cannot be conclusively attributed to aircraft emissions or any other causes.

CLIMATE EFFECTS

The radiative effects of the emitted greenhouse gases and particles, of changes in O_3, and of changes in cloudiness, can be compared to each other and to climate effects from other causes by using the concept of radiative forcing. *Radiative forcing* is defined as the net radiative flux change at the top of the atmosphere calculated in response to a perturbation, such as a change in gas concentration or cloud cover (with the stratosphere thermally adjusted to the change in radiative fluxes) (*see* **Radiative Forcing**, Volume 1). A positive net flux change represents an energy gain and, hence, a net heating of the Earth System. The global mean climate change of surface temperature at sea level is approximately proportional to the global average radiative forcing. However, the strong concentration of air traffic at the northern mid-latitudes may cause larger regional climate changes. Up to now, such regional changes are not detected.

The radiative effects resulting from aircraft engine emissions are summarised in Figure 7 (Intergovernmental Panel on Climate Change (IPCC), 1999). The uncertainty associated with several of these effects is large. The best estimate of the radiative forcing in 1992 by aircraft is $0.05\,W\,m^{-2}$ or about 3.5% of the total radiative forcing by all anthropogenic activities. The overall radiative forcing by aircraft (excluding that from changes in cirrus clouds) is a factor of 2–4 larger than the forcing by aircraft CO_2 alone.

In the future, for a reference scenario with a 6.7-fold increase in traffic and about a 3-fold increase in fuel consumption from 1992 to 2050, the Intergovernmental Panel on Climate Change (IPCC) (1999) reported a computed radiative forcing by aircraft in 2050 of $0.19\,W\,m^{-2}$ (3.8 times the value in 1992). For the range of scenarios considered in that assessment, the forcing is projected to grow to 0.13 to $0.56\,W\,m^{-2}$ in 2050, i.e. 2.6 to 11 times the value in 1992. These estimates of forcing combine the effects from changes in concentrations of CO_2, O_3, CH_4, H_2O, line-shaped contrails, and aerosols, but do not include possible changes in cirrus clouds.

The emissions of NO_x cause changes in CH_4 and O_3, and their influences on the radiative forcing are of similar magnitude, but of opposite sign. Changes in tropospheric O_3 are mainly in the Northern Hemisphere, while those of CH_4 are global in extent so that, even though the global average radiative forcings are of similar magnitude and opposite in sign, the latitudinal structure of the forcing is different so that the net regional radiative effects do not cancel.

The climatic effects of aircraft are superimposed on those caused by anthropogenic emissions of other greenhouse gases and particles, and on the background natural variability. It has not yet been possible to separate the aviation effects in observed climate parameters, such as surface temperature, from those of other natural or anthropogenic disturbances.

ULTRA-VIOLET RADIATION EFFECTS

Besides being a greenhouse gas, O_3 provides a shield against solar UV radiation. The calculated total O_3 column in northern mid-latitudes due to aviation is computed to be about 0.4% in 1992 (Intergovernmental Panel on Climate Change (IPCC), 1999). The increase in O_3 induced by subsonic aircraft decreases the UV radiation. The *erythemal* dose rate, defined as UV irradiance weighted according to how effectively it causes sunburn, is a maximum at northern

mid-latitudes and is estimated to have been decreased by aircraft in 1992 by about 0.5% at 45 °N in July. The aircraft effect on UV is small compared to that caused by other O_3 changes.

RADIATIVE FORCING AND UV RADIATION EFFECTS OF SUPERSONIC AVIATION

About 13 supersonic aircraft of type Concorde were in operation until the accident in Paris on July 25, 2000. Their effect on the global atmosphere can be neglected compared to the effects of the far larger fleet of subsonic aircraft. Plans for a new fleet of supersonic aircraft have been discussed but no definite decision has been made to develop such a fleet (Intergovernmental Panel on Climate Change (IPCC), 1999). Supersonic aircraft would cruise at an altitude of about 16–24 km, would emit CO_2, H_2O, NO_x, SO_x, and soot directly into the stratosphere, and contribute to changes in stratospheric O_3, other trace gases and aerosols. Supersonic aircraft consume more than twice the fuel per passenger-km compared to subsonic aircraft. The radiative forcing of civil supersonic aircraft is estimated to be about a factor of 5 larger than that of an equivalent fleet of subsonic aircraft. The calculated radiative forcing of supersonic aircraft depends on the treatment of H_2O and O_3 in models which are difficult to simulate accurately. The effect of introducing a fleet of 500 civil supersonic (Mach 2.4, $EI_{NO_x} = 5\,g\,kg^{-1}$) aircraft is to reduce the stratospheric O_3 column in the Northern hemisphere by −0.4% (range −2.5 to +0.5%, Kawa *et al.*, 1999), and to increase erythemal dose rate by a similar amount.

UNCERTAINTIES

Considerable progress has been made in recent years in quantifying the impact of aircraft emissions on the atmosphere. However, the scientific uncertainties are generally large. The state of scientific understanding of the radiative forcing of the various emissions has been evaluated by the Intergovernmental Panel on Climate Change (IPCC) (1999) as indicated in Figure 7. The evaluation is based on the evidence available, the degree of consensus in the scientific literature, and the scope of the analysis. The error bars and the scientific uncertainty are largest for the complex impact of NO_x on CH_4 reduction, for contrail cover and contrail optical depth, and, in particular, for the indirect effects of aviation on cirrus cloud cover and changes in cirrus properties. The figure accounts for global effects

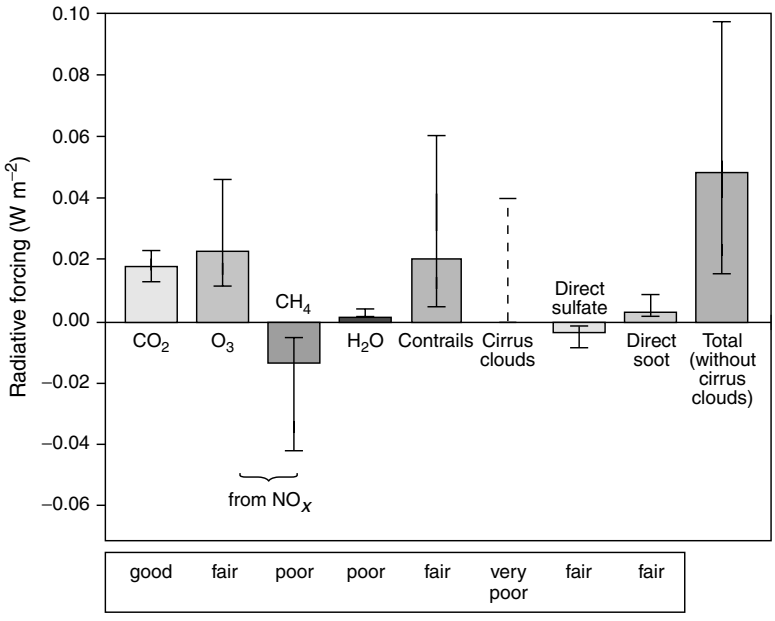

Figure 7 Radiative forcing (W m^{-2}) due to aircraft emissions in 1992 (Intergovernmental Panel on Climate Change (IPCC), 1999). The columns indicate the best estimate of forcing. The error bars denote the range within which the best-estimate value is expected with a 2/3 probability. The available information on cirrus clouds is insufficient to determine either a best estimate or an uncertainty range; the dashed line indicates a range of possible best estimates. The estimate for total forcing does not include the effect of changes in cirrus cloudiness. The evaluations below the graph (good, fair, poor, very poor) are a relative appraisal associated with each component and indicates the level of scientific understanding. (Reproduced by permission of Intergovernmental Panel on Climate Change (IPCC), 1999)

only. More work needs to be done to assess the impact of aviation on the climate in the northern mid-latitudes, where most of the air traffic takes place.

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