3 The environmental impacts of aircraft in flight

Introduction

3.1 The main environmental concerns associated with aircraft are:

- climate change
- stratospheric ozone reduction, leading to increased surface UV radiation
- regional pollution - changes in tropospheric chemistry for tens to hundreds of kilometres downwind of the airport. In particular, emissions of oxides of nitrogen in air increase ozone
- local pollution - both noise and decreased air quality caused by aircraft and also by the associated ground transportation.

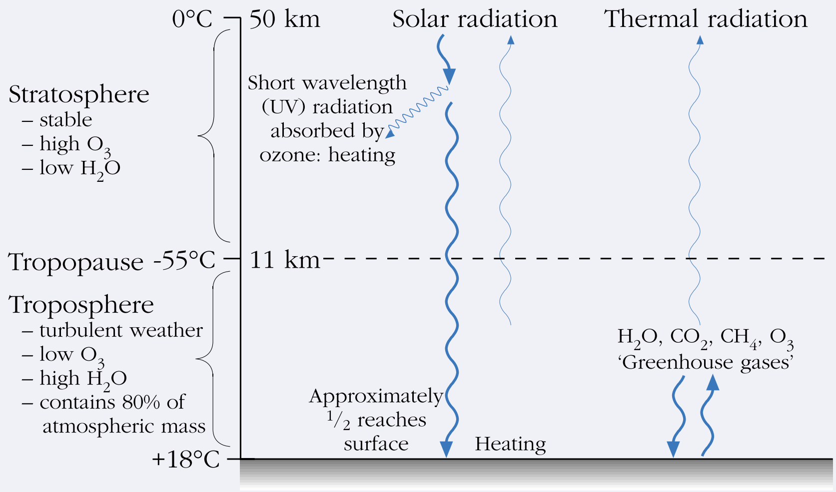
3.2 There is no doubt that both local pollution and regional pollution are very serious issues. It is thought that European Directives on permitted levels of oxides of nitrogen may limit the expansion of some airports.[22] Concern has been expressed to us that the techniques for assessment of the impact of aircraft emissions on both local and regional air quality are poorly developed and that the available modelling tools are in general inadequate.[23] This issue needs addressing urgently, especially in the light of the recent consultation documents on regional airport development. However, the focus here is on the possible larger-scale impacts of aviation, on surface UV radiation through changes in atmospheric ozone and on climate.

Aircraft emissions

3.3 During flight, aircraft engines emit carbon dioxide, oxides of nitrogen, oxides of sulphur, water vapour, hydrocarbons and particles - the particles consist mainly of sulphate from sulphur oxides, and soot. These emissions alter the chemical composition of the atmosphere in a variety of ways, both directly and indirectly. On the larger-scale, sulphur oxides in aircraft emissions are important only as a source of particles.

3.4 The unique feature of these emissions is that the majority of them occur far above the Earth's surface. Subsonic aircraft generally cruise in an altitude range of 9 - 13 km, close to the tropopause, the sharp transition between the troposphere and the stratosphere (see box 3A). The troposphere is the region in which the turbulent motions and precipitation related to weather occur. In contrast the stratosphere is relatively stable and the vertical motions in it are generally sufficiently small compared with the horizontal motions that the air travels almost horizontally.

Box 3A The structure of the atmosphere below 50 km



Ultra-violet (UV) solar radiation is absorbed by ozone (O_3) as it passes through the atmosphere, heating the upper portion of this region and causing a temperature maximum near 50 km. Below this, some of the solar radiation is reflected, mainly by clouds, and some is absorbed but about half gets through to the surface. This heats the near surface region and results in a second temperature maximum, this time at the surface. The tropopause marks the sharp boundary between the troposphere, in which the temperature drops markedly with height, and the stratosphere, where it generally increases with height.

Various atmospheric constituents allow most of the short-wave solar radiation through but absorb and then re-emit the long-wave thermal radiation. This warms the near surface region, the so-called greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4) and ozone (O_3) are examples of important 'greenhouse gases'. A convenient measure of the greenhouse effect of a change in a constituent is provided by the imbalance between solar and thermal radiation at the tropopause when the change in the constituent is suddenly imposed. This is known as radiative forcing.

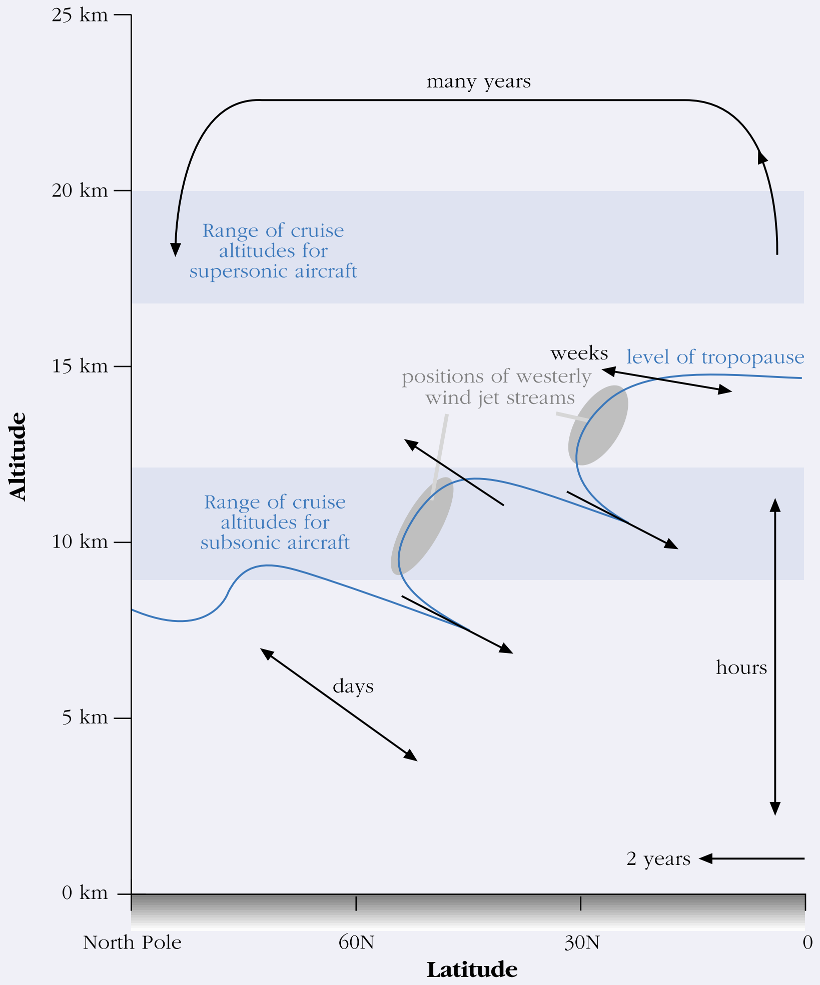
3.5 At the top of the atmosphere, the solar energy absorbed by the Earth/atmosphere is balanced by the emission of longer wavelength thermal radiation (heat). However, the thermal radiation emitted from the near surface region is absorbed by greenhouse gases (see box 3A), which then re-emit back towards the surface, keeping it warm. The heat lost to space is from levels typically near 5 km where the air is colder than at the surface.

3.6 The impact of aircraft emissions can be very different depending whether they are in the upper troposphere or the lower stratosphere. Both the abundance of trace gases and the dominant chemical composition and associated chemical reaction are very different in the two regions. In particular water vapour content is relatively high in the troposphere and low in the stratosphere whereas ozone levels are much higher in the stratosphere. Stratospheric ozone absorbs radiation from the sun. This leads to a heating profile in the stratosphere that determines its character, and also protects life at the surface from the harmful effects of the UV radiation.

3.7 The height of the troposphere varies with latitude. In the tropics the tropopause is higher than the normal range of subsonic cruise altitudes but in polar regions it is usually at the lower end of this range. Whether an aircraft cruises in the upper troposphere or the lowermost stratosphere depends on its location, the weather and the time of year (see box 3B). Supersonic aircraft typically cruise at levels in the range 17 - 20 km, which is always in the stratosphere.

3.8 Jet streams are typically located at the tropopause in regions where there are abrupt transitions in the horizontal between the troposphere and the stratosphere. Since eastward-flying aircraft are often routed in the strong westerly winds in jet stream regions to save fuel and time, they often fly close to this almost vertical tropopause.

Box 3B Transport times in the Northern Hemisphere



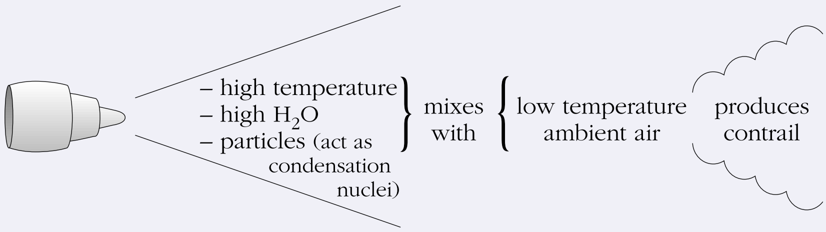
A schematic showing a latitudinal profile of the tropopause in the Northern Hemisphere and giving transport time-scales. The tropopause is typically near 9 km in altitude in polar latitudes and 16 km in equatorial regions. On any particular day at any particular longitude its position could be as shown, with a structure determined by the weather systems. The likely position of 'jet streams', westerly wind maxima, is indicated. The range of cruise heights for subsonic and supersonic aircraft are shown. Arrows indicate typical directions for transport of gases and time-scales for these transports are given.

3.9 The dominant physical and chemical processes differ between the troposphere and stratosphere, as do the time-scales for transporting air between regions. Water vapour added by any human activity in the troposphere is soon lost through mixing and precipitation processes, whereas at 20 km it persists and moves slowly towards the pole.

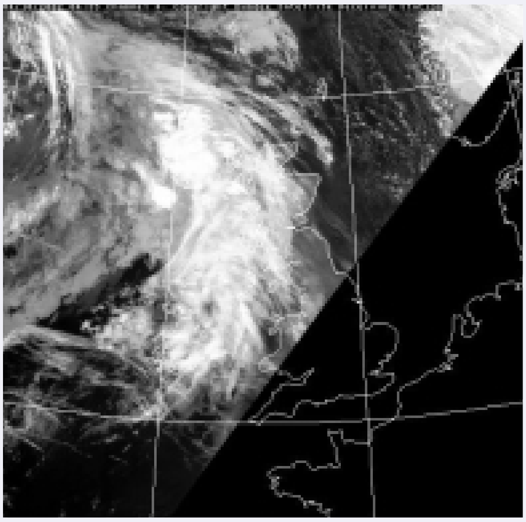
3.10 A 'conservative gas' is one that becomes well mixed throughout the atmosphere so that the point of emission is irrelevant for its impact on climate. The carbon dioxide produced by the combustion of kerosene in aircraft engines behaves as a conservative gas and so becomes well mixed. However, oxides of nitrogen, produced by high temperature burning in the engine, are rapidly involved in chemical reactions that lead to changes in both ozone and ambient methane. These reactions are complex and sensitive. Ozone is generally produced by oxides of nitrogen in the troposphere and destroyed by it in the lower stratosphere. Since the lifetime of ozone is relatively short, its aircraft-induced increase or decrease is restricted in both the vertical and the horizontal. The lifetime of methane, however, is sufficiently long that the reduction in it produced by the emitted oxides of nitrogen becomes distributed throughout the atmosphere.

3.11 In the troposphere the amount of water vapour emitted in aircraft exhaust is negligible compared with the pre-existing concentrations in the atmosphere. However, along with the particles emitted, the water vapour can lead to condensation trails (contrails - see box 3C), some of which can persist for hours and perhaps trigger the development of cirrus clouds. Subsequent cirrus cloud may also be further influenced by particles emitted by aircraft.[24]

Box 3C Contrails



Contrail persists if ambient air is supersaturated (~ 10 – 15% at 10 km)
Contrail can spread to form extensive cirrus cloud



When the moist, high temperature air from a jet engine mixes with the ambient cold air, saturation can occur and the moisture can condense onto particles in the atmosphere, and in particular those present in the exhaust. The result is a condensation trail, or contrail.

On about 10 - 15% of occasions in the upper troposphere in middle latitudes, the ambient air is already supersaturated with respect to ice. In supersaturated conditions contrails will persist and tend to spread. Sometimes they can spread to form or initiate a cirrus cloud, though the amount of such cirrus cloud formed by aviation is currently unknown. The extent of the contrail and cirrus cloud can be striking, those shown in the lower left corner of the plate to the left persist out over the Atlantic.

Contrails and cirrus clouds reflect some solar radiation and therefore act to cool the surface. They also absorb some upwelling thermal radiation, re-emitting it both downwards, which acts to warm the surface, and upwards. On average the latter warming effect is thought to dominate.

Changes in atmospheric ozone and associated surface UV changes

3.13 The total ozone in an atmospheric column above the surface is one determinant of the UV radiation there. Aircraft emissions of oxides of nitrogen in the troposphere will act to increase ozone levels and therefore decrease surface UV radiation, whereas emissions in the stratosphere near 20 km, act in the opposite way.

3.14 In its 1999 report *Aviation and the Global Atmosphere*, the Intergovernmental Panel on Climate Change (IPCC) estimated that in 1992, due to the overwhelming dominance of subsonic transport, the net oxides of nitrogen-induced change in ozone was an increase of about 6% at cruise altitudes in the Northern Hemisphere. They calculated that this ozone increase would rise to 13% by 2050 under their basic reference scenario. The associated increase from 1970 levels in the total ozone in a column of air was calculated to be 0.4% and 1.2% by 1992 and 2050, respectively.[25]

3.15 Increased atmospheric ozone concentrations result in a decrease in the UV reaching the Earth's surface. For 1992, the consequent reduction in erythemal dose rate (surface solar UV radiation weighted according to its sunburn impact) due to aviation was estimated to be about 0.5% in July at 45N. In fact, due to other human activities the column ozone was observed to *decrease* and the dose rate consequently *increased* by 4% in the period from 1970 until 1992. For 2050, the projected decrease in the Northern Hemisphere July erythemal dose rate due to aviation alone was 1.3%. The Southern Hemisphere changes were predicted to be some four times smaller.

3.16 Since, at the stratospheric flight levels of supersonic aircraft, the oxides of nitrogen emissions act to decrease ozone there are competing effects on the column ozone and the surface UV when such aircraft are included in the fleet. In the reference scenario for 2050 with 11% substitution of subsonic by supersonic aircraft, IPCC found that the small number of stratospheric-flying aircraft would dominate to give a projected increase of 0.3% in the Northern Hemisphere July erythemal dose rate.[26]

3.17 The projected changes in damaging UV radiation are very small. Unless there is a major change in the number of supersonic aircraft cruising in the stratosphere, present knowledge suggests that there does not appear to be a significant problem from ozone-related change in surface UV associated with aircraft.

Climate change

3.18 Many of the emissions from aircraft change the absorption of solar radiation and the absorption and emission of thermal radiation. They may, therefore, affect climate. Important aspects of such climate change could be a local change in average precipitation or the frequency and intensity of heat waves. Here, as in other assessments of the potential impact of human activities on climate, discussion of the effects of air transport will largely be restricted to consideration of possible changes in globally averaged surface temperature. However, it should be noted that such a measure of climate change is limited in its scope. Further, the importance of regional and local changes in climate forcing is likely to be particularly underestimated by this global measure.

3.19 Carbon dioxide is a greenhouse gas and emissions of it from aircraft become well mixed (see paragraph 3.10) and act to warm the surface of the Earth globally. The aircraft-induced reduction in the greenhouse gas methane is also well mixed and therefore acts to give a global cooling effect.

3.20 Ozone is also a greenhouse gas and its impact is normally considered in terms of a global warming effect. However, aviation-induced increases remain quite local and impacts on climate from such increases are therefore likely to be more subtle than suggested by its impact on globally averaged temperature. Contrails and cirrus clouds, though even more local, have also usually been considered in terms of a global warming effect.

3.21 To estimate the relative and absolute importance of various activities and emissions on climate, IPCC[ii] has used a globally averaged measure, known as 'radiative forcing', of the imbalance in solar and thermal radiation caused by the sudden addition of the activity or emission (see box 3A). This is a useful concept because models show that the change in globally averaged surface temperature is usually approximately proportional to radiative forcing.

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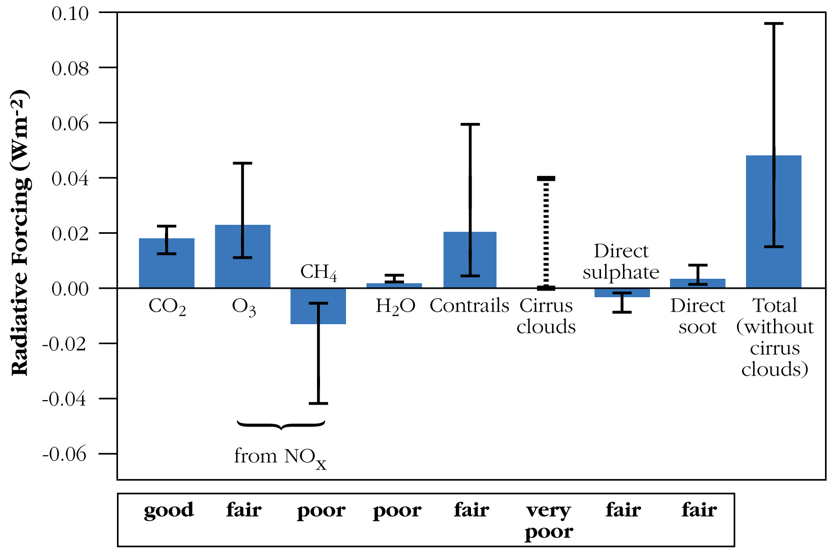
ii In its reports including IPCC (1999). *Aviation and the Global Atmosphere.*

3.22 According to IPCC, in 1992 aviation was responsible for 2% of carbon dioxide emissions due to the total burning of fossil fuel and 13% of that associated with transport. However, the total greenhouse impact was more important than this would suggest (see figure 3-I). Since the vast majority of the flights were subsonic and therefore in the 9 - 13 km height range, the emissions of oxides of nitrogen led, on average, to an increase in ozone as well as a decrease in methane. Relative to carbon dioxide, the radiative forcing factors were estimated to be +1.3 for ozone and -0.8 for methane. The factor +1.1 was given for contrails. The impacts of water vapour, and sulphate and soot particles were given as small and positive. The total radiative forcing was calculated to be about 2.7 times that of the carbon dioxide alone, a factor that compares with numbers generally in the range 1 - 1.5 for most other activities. Consequently, aircraft were seen as being responsible for 3.5% of the total radiative forcing in 1992.

Figure 3-I Radiative forcing from aviation effects in 1992



IPCC's estimates of the radiative forcing in Watts per square meter from subsonic aircraft emissions in 1992. The bars indicate the best estimates of the forcings related to the different aircraft induced effects and their total (apart from cirrus clouds) while the line indicates a range of uncertainty. The evaluations of the relative levels of scientific understanding are indicated below the graph.

3.23 The IPCC indicated for each component the level of scientific understanding and the uncertainty range for its radiative forcing. The range for the total radiative forcing is given by IPCC to be about +1 to +5 times the best estimate for the effect of the carbon dioxide alone. The radiative forcing estimate for carbon dioxide was considered to be fairly robust but for the other emissions and effects there were considerable uncertainties.

3.24 The radiative forcing factor relative to carbon dioxide for ozone was given the range +0.6 to +1.8, and that for methane –0.3 to –2.2. More recent estimates[27] have supported IPCC's best estimate for the positive impact of ozone but suggested that the negative impact of the methane loss should have been at the small end of the range given.

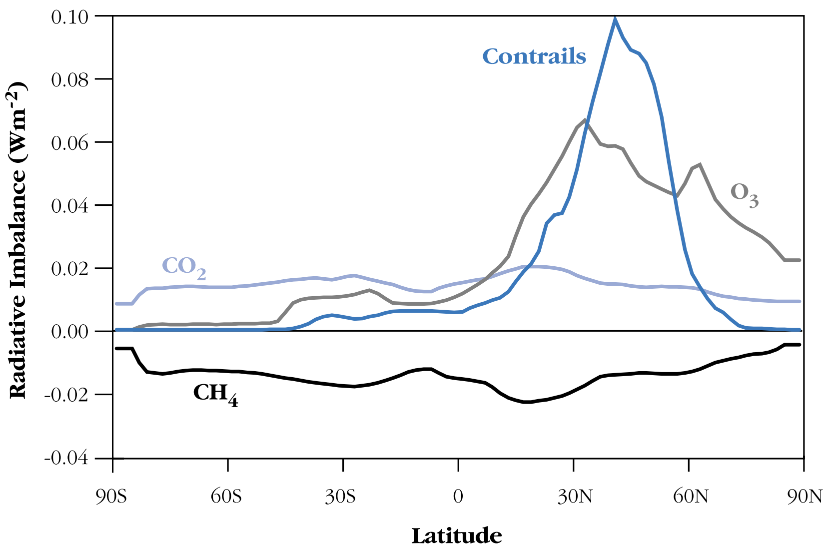
3.25 The uncertainty range given by IPCC for the radiative forcing due to contrails was extremely large, from +0.3 to +3.2 times the impact of the carbon dioxide.[28] For cirrus cloud stimulated by aircraft emissions and the associated contrails, the uncertainty felt by IPCC was such that they did not even give a best estimate, and they did not include it in their total radiative forcing figure for aviation. However, they gave a range of 0 to +2.1 for the factor relative to the carbon dioxide.

3.26 One very recent study has suggested a much smaller best estimate for the contrail impact than IPCC,[29] and other methodologies produce a wide range of answers. Since IPCC's report in 1999, it is apparent that the uncertainties over contrail impacts have increased rather than decreased.[30] However, evidence provided to us in connection with this study suggests that the relationship between air traffic and cirrus cloud is becoming more certain.[31]

3.27 It should be noted that a recent comparison of the three-day period following 11 September 2001, when all commercial aircraft in the United States were grounded, has shown some evidence of a 1°C to 2°C increase in the day-night difference in temperature over the USA.[32] This is consistent with the theoretical proposition that aircraft contrails and related cirrus cloud act to lower day-time temperatures by reducing solar radiation and raising night-time temperatures by reducing heat loss. If the result turns out to be robust it will be the first empirical evidence that aircraft contrails and related cirrus cloud are indeed significant in the Earth's radiation balance.

3.28 The use of the global radiative forcing concept and the opposite signs of the two oxides of nitrogen-related impacts associated with changes in ozone and methane should not be taken to imply that the combined effect is unimportant. An indication of this is given by figure 3-II which shows the radiative imbalance as a function of latitude. The well-mixed gases lead to effects which are almost uniform with latitude and the methane reduction tends to compensate the carbon dioxide increase in the Southern Hemisphere. The radiative imbalance is concentrated in the middle latitudes of the Northern Hemisphere. The contrast between the two hemispheres could have global climate importance and the region with the stronger radiative forcing would be expected to experience larger local climate change.[33]

Figure 3-II Radiative imbalance at the tropopause as a function of latitude

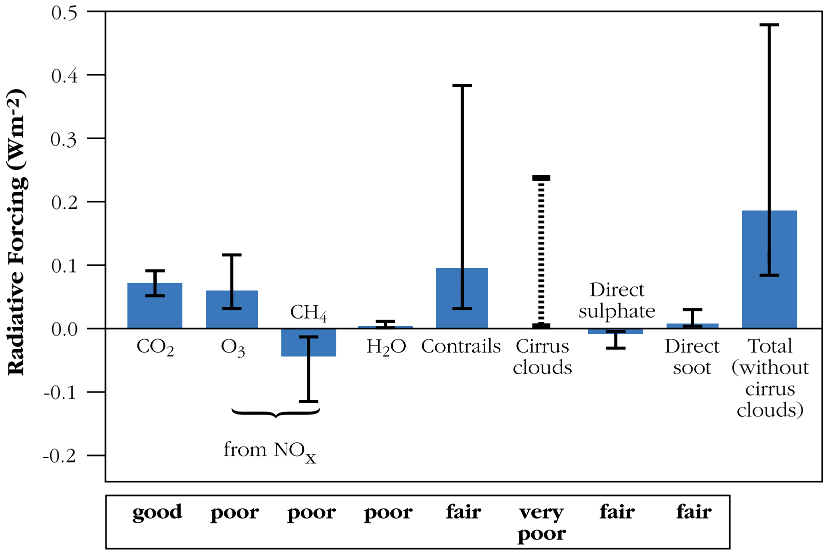


IPCC calculation of the aviation induced 1992 radiative imbalance at the tropopause in Watts per square meter as a function of latitude.

3.29 For the period 1990 to 2050, IPCC introduced various scenarios for traffic growth and two technical scenarios for fuel burn and oxides of nitrogen production, which are discussed further in Section 4. These scenarios gave an increase in carbon dioxide emissions by a factor ranging between 0.5 and 9. The reference scenario used by IPCC and referred to above had a traffic growth of 3.1% per annum (less than that seen in the last decade) and a fuel burn rate growth of 1.7%. Thus by 2050, the traffic would be a factor of 6.4 larger and the fuel burn 2.7 times larger, the difference being because of the large improvements in aircraft efficiency assumed.

3.30 At any time, the radiative forcing associated with a long-lived gas such as carbon dioxide depends on the emissions over the previous period and not just the instantaneous emissions. For its reference scenario IPCC estimated that the radiative forcing by carbon dioxide was about a factor of 4 larger than in 1992 (figure 3-III). Relative to this 2050 carbon dioxide impact, the best estimates for the radiative forcing factors associated with oxides of nitrogen were +0.8 associated with increased ozone and –0.6 associated with decreased methane. The best estimate for contrails was a factor 1.2. The total radiative forcing, not including cirrus cloud, was about 2.6 times that of the carbon dioxide alone and a factor 3.8 larger than its 1992 value.

Figure 3-III Predicted radiative forcing from aviation effects in 2050



IPCC estimates of the radiative forcing in Watts per square meter from subsonic aircraft emissions in 2050 for its reference scenario.

3.31 IPCC considered six aviation emission scenarios constructed from different transport and aircraft construction scenarios. The reference scenario discussed here was at the lower end of the range of radiative forcings, the lowest of which was a factor of 1.5 times smaller and the highest a factor of 3 times larger than the reference scenario. The range of radiative forcings is 2.6 - 11 times that for 1992.

3.32 For a supersonic aircraft flying in the 17 - 20 km range, IPCC suggests that the oxides of nitrogen-induced decrease in ozone gives a radiative forcing that is comparable with that for the carbon dioxide but of the opposite sign. Methane changes are not significant, and contrails and cirrus cloud are not produced. In this case the radiative forcing is totally dominated by the impact of the water vapour emitted: its forcing is positive and 10 times larger than that of the carbon dioxide. This issue is discussed further in Section 4.

3.33 IPCC considered one alteration from their reference scenario, in which 11% of the fleet was replaced by supersonic transports. The radiative forcing of the supersonic aircraft was calculated to be about a factor of 5 larger than that for the subsonic aircraft displaced. Consequently, the total 2050 radiative forcing due to aviation then rose by more than 40% to a figure some 5.4 times its 1992 value.

Implications

3.34 The major, large-scale environmental problem associated with the continuing expansion of aviation is the forcing of climate change. One aspect of climate change is global warming and a convenient, but approximate, measure of the tendency to produce global warming is the concept of radiative forcing. The IPCC's estimates of radiative forcing due to aircraft emissions appear to remain valid, though the uncertainties are still at least as large. The magnitude of the positive impact of increased cirrus cloud remains the major unknown.

3.35 The total radiative forcing due to aviation is probably some 3 times that due to the carbon dioxide emissions alone. This contrasts with factors generally in the range 1 - 1.5 for most other human activities.

3.36 The IPCC reference scenario assumes less aviation growth than seen in the period up to 11 September 2001 and large technology advances. For 2050 the radiative forcing estimate, without a cirrus cloud estimate, is about 3.8 times larger than in 1992 and would correspond to about 14% of the total radiative forcing for 1992. The range of scenarios give 2050 radiative forcings that are 2.6 - 11 times larger than in 1992 and from 10% - 40% of the 1992 total.

3.37 IPCC compared their estimates of aviation radiative forcings with those from a benchmark scenario of future emissions due to all anthropogenic activities as used by them in their *Second Assessment Report - Climate Change 1995*.[34] However, for their *Third Assessment Report - Climate Change 2001*, IPCC developed a new set of emission scenarios up to 2100.[35] We used some of these in our Twenty-second Report as a basis for longer-term scenarios. One scenario (B1 in IPCC 2001 terminology) gives an approach to stabilisation of climate with carbon dioxide capped at about twice the pre-industrial level, consistent with the target recommended by us in our Twenty-second Report. Here we use the 2050 radiative forcings from this scenario as a benchmark for the aviation scenarios. However, we note that this scenario would have all emissions peaked or starting to fall by 2050 whereas the aviation emissions on each scenario would be on a continuing upward trend.

3.38 Compared with this benchmark stabilisation scenario, in 2050 the contribution of aviation to the total radiative forcing would be in the range 4% - 17%, with the reference aviation scenario contribution being 6%.

3.39 Since IPCC's 1999 report, *Aviation and the Global Atmosphere*, research has broadly supported the projections made there, but also suggested a number of adjustments. Some later research has suggested that IPCC may have over-estimated the possible climatic effect of contrails. However, as explained in paragraph 3.25, there is conflicting evidence and huge uncertainty. In any case, three other results from recent research more than compensate any implication that the impact of aviation may be smaller than IPCC suggested. Firstly, there is an increasing indication that aviation-induced cirrus cloud will indeed be a significant contributor to warming. Secondly, recent research suggests that the cooling effect of the aviation-induced methane reduction had previously been over-estimated.

3.40 Finally, recent estimates for the growth of aviation in the period 1992 - 2000 have shown that it is continuing to be larger than the IPCC reference value.[36] The distance travelled in the period was estimated to have risen by 43% and the fuel usage by 33%.[37] These correspond to annual percentage growths of about 5% and 4%, respectively, and follow IPCC's higher growth scenario rather than the more central reference value. As discussed in Section 2, the decrease in passenger transport since 11 September 2001 is widely expected to be only a temporary dip.

3.41 In summary, we consider that the IPCC reference value for the climate impact of aviation is more likely to be an under-estimate rather than over-estimate. We conclude that, unless there is some reduction in the growth in the sector, or technology improves considerably more than was assumed by IPCC, by 2050 aviation will be contributing at least 6% of the total radiative forcing consistent with the necessary stabilisation of climate. A safer working hypothesis is that it will be in the range 6% - 10%. If significant fleets of sonic or supersonic aircraft are flown then the aviation contribution would be higher than this.

3.42 It is likely that the amount of time that subsonic aircraft spend in the stratosphere has been rather underestimated by calculations made using climatological tropopause heights.[38] The current knowledge of the chemistry in this region is such that it is difficult to determine the importance of this. Contrail and cirrus cloud effects would be absent but the radiative forcing due to water vapour emissions would be expected to be significantly more important.

3.43 It is possible that a decrease in cruise level would, because of the higher ambient temperatures, lead to less contrail and cirrus cloud impact. It is also likely that it would lead to less radiative impact from ozone production. Some recent calculations[39] suggest that for radiative forcing these benefits may out-weigh the increased carbon dioxide emissions associated with higher fuel usage. However there is still great scientific uncertainty in this area.

3.44 Modern weather forecasting capabilities are increasingly such that the regions of likely supersaturation in the upper troposphere and the height of the tropopause in any region may be usefully predicted some days in advance. When there is more scientific understanding of the various elements involved in the climatic impact due to aviation, it should be possible to route individual aircraft so that, for example, they spend less time in regions where persistent contrails and enhanced cirrus cloud could be formed, or so that they almost always remained in the troposphere where the water vapour effects are negligible.

3.45 Supersonic aircraft flying at 17 - 20 km have a radiative forcing some 5 times greater than the 9 - 13 km subsonic equivalent. They also contribute to ozone depletion. A subsonic aircraft at 14 - 15 km would be expected to have a radiative forcing between the two values, though again a confident prediction at this time is impossible. Significant fleets of any such higher-flying aircraft would be expected to have very important global environmental impacts.

3.46 Liquid hydrogen as a fuel would clearly remove the carbon dioxide effect at the point of emission. The effects of oxides of nitrogen would still be present, depending on the burn temperature, and because 2.6 times as much water vapour would be produced, other impacts are likely. More water could mean more contrails. However, recent work has suggested that the decrease in emitted particles that act as condensation nuclei might mean that the drop size increases sufficiently to compensate for this effect.[40] If, as appears likely, hydrogen fuelled aircraft were to cruise at higher levels, then the increased water emitted into the stratosphere would suggest larger radiative forcing.

3.47 Since a hydrogen fuelled aircraft produces 2.6 times as much water as a kerosene fuelled aircraft, and since the water vapour produced by the latter cruising at 17 - 20 km gives a radiative forcing some 5 times that of a lower flying subsonic aircraft, a hydrogen fuelled supersonic aircraft flying at stratospheric levels would be expected to have a radiative forcing some 13 times larger than for a standard kerosene fuelled subsonic aircraft. This is discussed further in Section 4.

3.48 Local and regional pollution issues, though not the focus of this report, are also very important. There can be conflict between measures to tackle them and the larger-scale flight-related environmental issues. In particular, both technological and flight routing measures to tackle noise from take-offs and landings, and technological measures to decrease emissions of oxides of nitrogen during these and on the ground can lead to larger radiative forcing associated with carbon dioxide emissions through the entire flight and emissions of oxides of nitrogen at the cruising altitude. This too is discussed further in Section 4.