While the pollutants are known, the effects they have on the atmosphere are not. The effect of aircraft-induced carbon dioxide on the atmosphere is only just beginning to be quantified

ground-level emissions was taken by the USA. Subsequently, ICAO developed international standards and recommended practices for fuel venting and emissions of carbon monoxide, hydrocarbons, nitrogen oxides and smoke from engines operating below 3,000ft.

The only global agreement that could affect aviation emissions in the cruise came with the Kyoto Protocol, signed in 1997, which was aimed at stabilising greenhouse gas concentrations at a level that would prevent dangerous long-term damage to the climatic system. Aviation is not specifically mentioned, but there are two areas which are relevant. Firstly, the protocol requires developed countries to reduce their total national emissions from all sources by an average of about 5% compared to 1990 levels. Secondly, there is a provision calling on developed countries to pursue policies and measures for the limitation or reduction of greenhouse gases from aviation bunker fuels (defined as fuels consumed for international marine and aviation transportation).

A major problem with the first area, which is unresolved, is that once aviation emissions have been quantified, the distinction must be made whether they are from domestic or international flights. If the latter, then how are the emissions allocated to any particular country? Who, for example, is responsible for an aircraft registered in Germany which loads fuel in Montreal and flies to Frankfurt, producing greenhouse gases over several countries on the way?

ICAO has called the Kyoto Protocol a "welcome clarification" of the respective roles of ICAO and the United Nations Framework Convention on Climate Change (UNFCCC). "It is clear that ICAO is the forum where emissions from international aviation are to be addressed," it says. Within ICAO, progress on reducing emissions is the responsibility of its Committee on Aviation Environmental Protection (CAEP), which last year agreed on a revised work programme taking the Kyoto Protocol into account. It has set up groups to study the technical and operational aspects of aircraft emissions and market-based options for reducing them.

THE POLLUTANTS

Aircraft affect the atmosphere by introducing gases and particles into it and by forming contrails. The emissions include greenhouse gases, such as carbon dioxide and water, that trap terrestrial radiation, as well as chemically active gases that alter natural greenhouse gases, such as ozone and carbon monoxide. Particles may interact directly with the earth's radiation balance or influence the formation of clouds.

The IPCC report points out that detecting aircraft-induced climate change is difficult because the proportion of radiative forcing caused by aircraft is tiny. Considerable research is being done to evaluate this contribution.

CARBON DIOXIDE

The largest and the best understood man-produced agent affecting climate change is carbon dioxide, the production of which has increased almost exponentially since the beginning of the industrial revolution. Because of its exceptionally long lifetime in the atmosphere, carbon dioxide becomes thoroughly mixed and evenly distributed around the planet. It is therefore difficult to separate the contribution made by any particular polluter.

Along with water, carbon dioxide is the most abundant of the products of jet fuel combustion, being an unavoidable product of it. Today, aircraft account for 2.4% of the total produced by all man-made sources, a figure which, because of the increase in traffic, is projected to rise to more than 7% by 2050, even though the production per engine has reduced significantly with the introduction of new technology.

WATER

Water emission by aircraft engines leads directly to the formation of the contrails that are characteristic of high-flying aircraft in the cruise.

These emissions are extremely small compared to those from natural atmospheric processes such as convection from land and sea, cloud formation and rainfall, but there is concern that contrails may have a disproportionate effect on global warming. Their effects are only beginning to be understood, even if the amount of global warming they may cause is unclear.

Water remains in the troposphere for around nine days. In the stratosphere it can stay for months and even years, so there is a build-up of aircraft-produced water vapour that might upset the natural hydrological balance. The report highlights two main consequences: a direct effect on the heat exchange process in the atmosphere, and a chemical impact on stratospheric ozone which could increase the occurrence of polar stratospheric clouds at high altitudes.

Contrails are expected to increase more rapidly than fuel consumption because of the rise in the numbers of aircraft flying in the upper troposphere, where they are most likely to form. The IPCC report admits there is still much uncertainty about the increase in greenhouse effect resulting from extra contrail cover. One estimate puts it at around 0.5% of total global coverage (see diagram), six times what it is today. The understanding of the effect on formation of cirrus cloud is even less certain, the best estimate being that it will rise in proportion to the extra fuel burned in the upper troposphere.

NITROGEN OXIDES

Nitrogen oxides are influential in the chemistry of the atmosphere and in the production and destruction of ozone. The processes by which NO_x affects that chemistry are complex and differ according to factors such as season and location. At cruise altitudes, increases in ozone lead to an increased greenhouse effect. The IPCC report found that in 1992, NO_x emissions from subsonic aircraft were estimated to have increased ozone concentrations at cruise altitudes by up to 6% and are projected to grow to about 13% of the total by 2050.

NO_x production by aircraft is related to combustion temperature and has increased as operating temperatures and pressures have gone up. Improved combustor technology has helped reverse the trend, but as the report points out, the production of NO_x is linked to that of carbon dioxide, such that attempts to reduce NO_x can increase the amount of carbon dioxide present in the exhaust. New, dual annular staged combustors provide more control over a greater operating range, but are more expensive and suffer from extra weight and complexity. Further research is under way in the USA and Europe to develop "ultra-low NO_x" engines which retain low emissions of other pollutants.

AEROSOL PARTICLES

Engines emit invisible aerosol particles, including soot, metals, sulphuric acid, water vapour and possibly nitric acid and unburned hydrocarbons. These may stimulate chemical reactions in the atmosphere, absorb or scatter radiation and change cloud properties. They can seed contrails and cirrus clouds and may be a factor in increasing cloud cover. The chemistry of aerosol production and its interaction with the atmosphere is little understood. ❑

Aviation and the Global Atmosphere is published by Cambridge University Press, UK.