

Part 1:

***Calculating the
Environmental Impact of
Aviation Emissions***

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1. Context

It is widely acknowledged that man-made emissions of carbon dioxide and other greenhouse gases are causing major changes to the planet's climate. The global average surface temperature of the earth has increased by 0.6 °C during the 20th century and is predicted to increase by between 1.8 and 5.8 °C by the year 2100.¹ By contrast, the last ice-age was 5 °C cooler than the present 'warm-period'. These future temperature rises will have severe climate impacts, with higher local maximum temperatures, fewer cold days, more heavy rain, summer droughts, decreased snow cover and sea ice, rising sea levels and an increase in storm intensity all deemed likely.¹ The societal impacts of these changes are also likely to be severe.

The acceptance of the fact that much of the observed and predicted future climate change is due to human activity has led to a desire to reduce greenhouse gas emissions, so as to minimise the impacts of climate change on society and individuals. The response has been far-reaching, with the international community, and concerned businesses and individuals, seeking methods to minimise emissions.

At the international level, the Kyoto Protocol² came into force in February 2005, and commits signatories to legally binding emissions targets. Industrialised countries must reduce their total emissions by 5.2% of 1990 levels by 2010 (actually an average of the period 2008-2012). The UK is committed to reducing its emissions by 12.5% below 1990 levels by 2010.

Individuals and businesses have also expressed a desire to reduce their own emissions beyond the requirement of policy, which has led to the principle of offsetting. An individual pays to offset his or her own personal emissions - the money raised will fund energy efficiency or renewable energy projects which lead to a reduction in greenhouse gas emissions equal to the amount offset.

In order for offsetting to be credible, the greenhouse gas emissions to be offset have to be calculated accurately, and the projects require equally rigorous verification to ensure that the savings are in fact made. Carbon dioxide emissions from activities within the home, business, or terrestrial transport can be simply calculated by knowing the amount of fuel burned for the given activity. However, greenhouse gas emissions from flights requires a special approach, which is outlined in this report.

Aviation emissions have a greater climate impact than the same emissions made at ground level.³ This is because emissions at altitude can instigate a host of chemical and physical processes that have climate change consequences (See Appendix). This is identified through the use of a multiplier, known as a 'metric', to account for the greater climate impacts of aviation.

The basic methodology for calculating the impact of aviation emissions is merely the mass of carbon dioxide emitted multiplied by the chosen metric. Once this extra impact has been accounted for, the emissions may be costed in the usual manner. Sections 2-4, below, outline the calculation of carbon dioxide emissions, relevant metrics and pricing strategies, respectively.

2. Calculation of carbon dioxide emissions

Carbon dioxide emissions from aircraft can be calculated from a knowledge of the amount of fuel consumed during the flight. However, unlike terrestrial transport, fuel consumed does not scale linearly with distance travelled due to the extra fuel burn required to lift the plane up to cruising altitude, and the necessity to carry large quantities of fuel for long distance flights. A model has been developed to determine emissions accurately.

The emissions of carbon dioxide from an individual flight will depend on many different factors including distance travelled, weather conditions (head or tail wind), cargo load, passenger load and flight altitude. Obviously, for an individual seeking to offset, these conditions will be unknown. The model therefore uses averaged data to determine emissions. Whilst the emissions from an individual flight may be under or over that determined by the model, any errors will cancel each other out over multiple flight offsets.

Calculating fuel burn

The fuel burn is attributed to different sections of the flight (see Figure 1), which each use fuel at different rates. Emissions occur during:

- The Landing and Take Off cycle (LTO)⁴ which includes all activities near the airport that take place below the altitude of 3000 feet (1000 m). This consists of taxi-out, take-off and climb out, and at the end of the flight, the landing approach and taxi-in. This is the fuel required to get the aircraft into the air (and down again) and are constant irrespective of flight length. Ascents require a much more intense fuel burn than cruising at constant altitude.
- The Climb, Cruise and Descent cycle (CCD) is defined as all activities that take place at altitudes above 3000 feet (1000 m). This fuel use accounts for the bulk of the flight distance, and naturally varies with flight length.

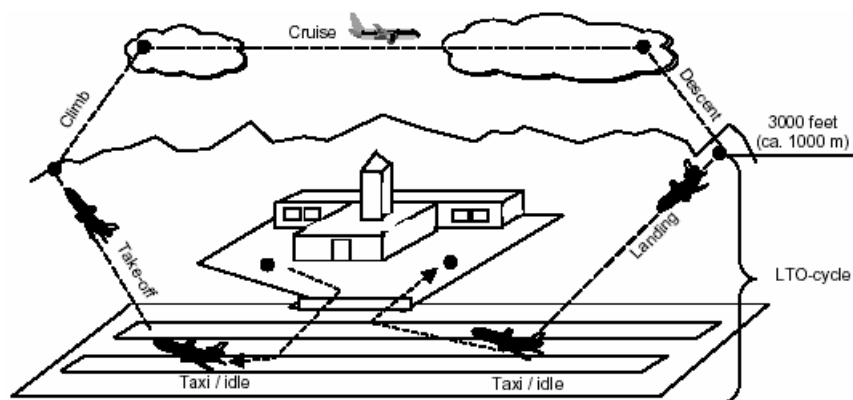


Figure 1. Phases of flight of aircraft⁴

The proportions of LTO to CCD will vary between flights, with short-haul flights (e.g. Heathrow to Amsterdam) having a much larger contribution from LTO than a transatlantic flight (e.g. Heathrow to Tokyo).

For simplicity of calculation, and because most passengers do not know the exact make of aircraft on which they are flying, representative aircraft have been chosen to calculate the fuel burn. Boeing 737s, the most popular aircraft ever produced, flew 14.8% of intra-EU flights in 1998⁴ and so have been chosen as the representative model for short-haul flights. Short-haul flights are defined as those less than 3500 km.

Historically, medium to long-haul flights have been flown on Boeing 747s, but in recent times Airbus A340s have attracted a significant proportion of the market share. The Airbus is newer and more efficient, and so produces less CO₂ per kilometre than the Boeing. The model has assumed that medium- and long-haul flights (>3500 km) are considered as an average of Airbus A340 and Boeing 747 emissions.

Tables of the amount of fuel consumed are available for all major types of aircraft as published by the European Environment Agency (2003).⁴

Table 1. Representative calculations of fuel burn for a Boeing 737⁴

B737 400		Standard flight distances (nm)						
		125	250	500	750	1000	1500	2000
Distance (km)	Climb/cruise/descent	231.5	463	926	1389	1852	2778	3704
Fuel (kg)	Flight total	1603.1	2268.0	3612.8	4960.3	6302.6	9187.7	12167.6
	LTO	825.4	825.4	825.4	825.4	825.4	825.4	825.4
	Taxi out	183.5	183.5	183.5	183.5	183.5	183.5	183.5
	Take off	86.0	86.0	86.0	86.0	86.0	86.0	86.0
	Climb out	225.0	225.0	225.0	225.0	225.0	225.0	225.0
	Climb/cruise/descent	777.7	1442.6	2787.4	4134.9	5477.2	8362.3	11342.2
	Approach landing	147.3	147.3	147.3	147.3	147.3	147.3	147.3
	Taxi in	183.5	183.5	183.5	183.5	183.5	183.5	183.5

Calculating carbon dioxide emissions

When fuel oil is burned, it is converted to carbon dioxide and water vapour. Combustion of one kilogram of fuel oil yields 3.15 kilograms of carbon dioxide gas. Carbon dioxide emissions are therefore 3.15 times the mass of fuel burned.

In an offsetting model such as this, it is important to attribute only the emissions for which the passenger is directly responsible to that passenger. This has two effects:

- The commercial freight load of the plane is ignored. Commercial freight loads are estimated to be 10% of the total weight of the plane for long-haul flights,⁵ so only 90% of emissions are attributed to the passengers.
- Emissions are allocated per seat. The number of seats on standard models of aeroplanes are readily available.^{6,7,8}

Model output

The model gives a series of curves of carbon dioxide emissions per seat as a function of distance travelled. Departure and destination airports are selected from a database, which returns the longitude and latitude of the respective locations. The length of flight is then calculated using trigonometry, and the corresponding emissions determined from the appropriate curve (Figure 2).

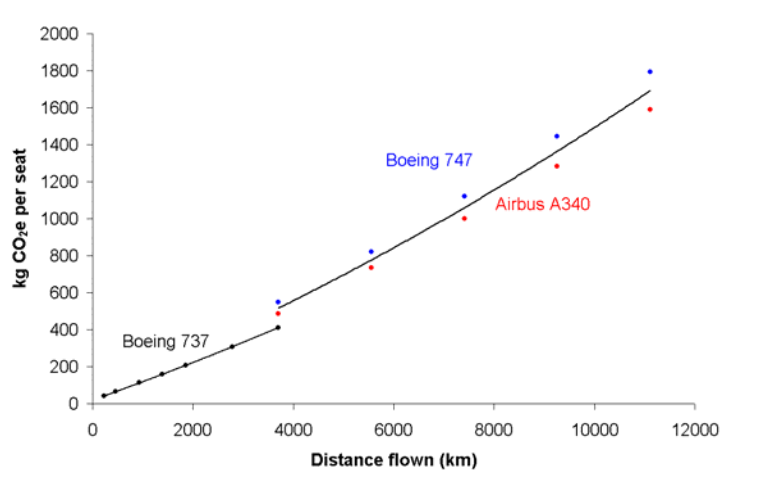


Figure 2. Emissions per seat as a function of flight distance

It can be seen that there is a discontinuity between the aircraft used for short-haul versus medium to long-haul flights. The smaller, lighter Boeing 737's use less fuel per kilometre. As soon as larger heavier aeroplanes with a greater fuel loads are used, flights become less efficient and emissions per seat greater.

This can be seen on a plot of carbon dioxide emissions per seat per kilometre (Figure 3). For very short flights, carbon efficiency is low, as the fuel burn required for the landing and take-off cycle is the major component of emissions. This drops away such that flights over 2000 km in a Boeing 737 are the most efficient flights (of those considered in this model). For larger aircraft on medium and long-haul flights, the landing and take-off cycle is not so critical, and the climb, cruise and descent cycle forms the major part of the fuel burn. There is a slight decrease in flight efficiency with increased distance, due to the greater fuel load that must be carried.

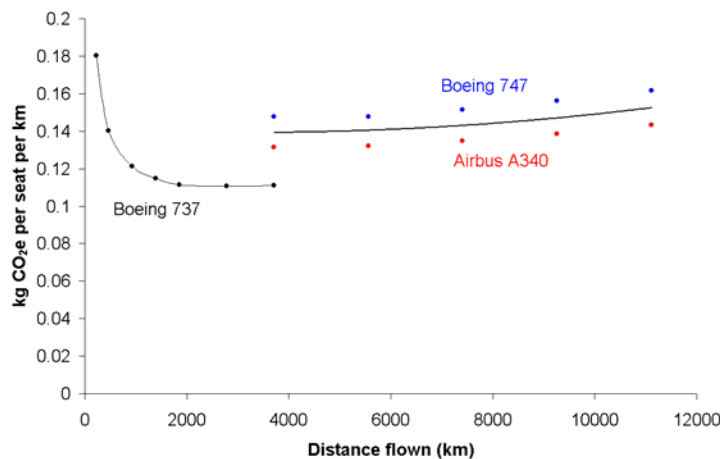


Figure 3. Carbon efficiency per seat as a function of distance travelled

3. Applying a metric for aviation emissions

Now that the carbon dioxide emissions are known, a metric must be applied to account for the full environmental effect of aviation emissions. A metric is a mechanism for transformation of emissions of gases with different effects on climate into one common scale. In simple terms, the metric is a measure of how many tonnes of CO₂ emissions should be avoided at ground level, as opposed to emitting one tonne of aviation emissions at high altitude.

The full climate impact of aviation is deemed to be between 2 and 4 times greater than CO₂ alone,³ but the exact value is dependent on which parameter is chosen to be measured by the metric. There are many different possible metrics for comparing greenhouse gases, some of which have become commonly used (see below). However, it is only possible to use some of these to examine aviation emissions.

What to measure?

The mass of carbon dioxide emissions can be calculated as outlined above, but quantifying their effect on the environment is more complex, and depends on what is used as a measure of the climate impact. This is true for any greenhouse gas emissions, not just the special case of aviation.

The 'chain of influences' shown in Figure 4 gives a range of possible measures of climate impact that could all theoretically be used as the basis for a metric. The greenhouse gas emissions will alter the atmospheric concentration, which in turn alters the energy balance of the atmosphere (known as radiative forcing). The radiative forcing is the driving force behind climate change, but because the atmosphere is a complex system, the effects of radiative forcing on the climate are not linear. Furthermore, there are many measures of climate change including effects on temperature, rainfall, average wind-speed and sea level rise. These changes in climate have impacts on society including agriculture, land use, energy consumption. Ultimately, these societal changes can be quantified in terms of financial impacts.

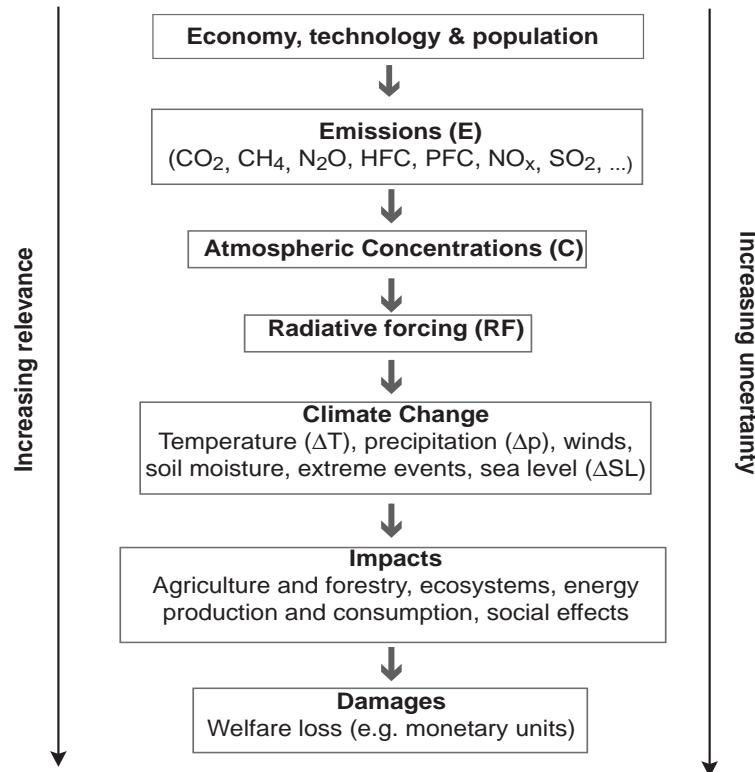


Figure 4. Chain of influences on climate

Any of these parameters can be used as a measure of the environmental influence of greenhouse gas emissions. However, there is a trade-off to be made when determining which of these parameters to utilise as a measure of climate change. The further down the chain one goes, the more relevant it becomes to people and society, but the less well science and computer modelling can quantify it.

To date, science and policy has adopted radiative forcing (and derivatives thereof) as metrics of climate change. However, climate models are becoming sophisticated enough to start quantifying the influence on temperature – a more easily understood parameter for the layperson, and it is expected that metrics based on temperature will become more commonly used in future.

Extent or rate?

Once the measure of environmental impacts has been decided, some assessment must also be made as to whether it is the extent or rate of change that is the most important. For example, the extent of ice-cover will be influenced by the extent of temperature rise. Conversely, the ability of ecosystems to adapt to climate change is determined by the rate of temperature rise. It is becoming increasingly apparent that both extent and rate of climate change are important, and that both are unprecedentedly high. However, it is the extent that has been most widely studied and utilised.

Timeframes

Climate change metrics can operate over different timeframes. Some are instantaneous, whilst others give the summed effect up to a chosen point in the future. Because different greenhouse gases have different lifetimes in the atmosphere, the choice of metric timeframe is critical in determining the relative importance of different gases. Other metrics examine the influence of historical emissions.

Sustained or pulse emissions?

A further difference between metrics is whether they consider a ‘pulse’ emission (*i.e.* the instantaneous emission of 1 tonne of gas) or sustained emissions (emission of a profile of emissions over a specified timeframe). Sustained emissions metrics may be more policy relevant, but pulse emissions are more useful for carbon trading and offsetting projects.

Commonly used metrics

The Intergovernmental Panel on Climate Change has used two different metrics for assessing climate change: radiative forcing and the global warming potential. A newly developed metric - the global temperature potential – is also discussed.

Radiative forcing

The radiative forcing is defined as “the change in the energy balance of the lower atmosphere by a climate change mechanism” and is measured in units of Watts per square metre (W/m^2). The ‘climate change mechanism’ is typically the emission of a greenhouse gas (e.g. CO_2 from human activity), or a collection of different gases (e.g. all greenhouse gases from the agricultural sector). Radiative forcing can therefore be used to examine the influence of the aviation sector as a whole, including all atmospheric effects.

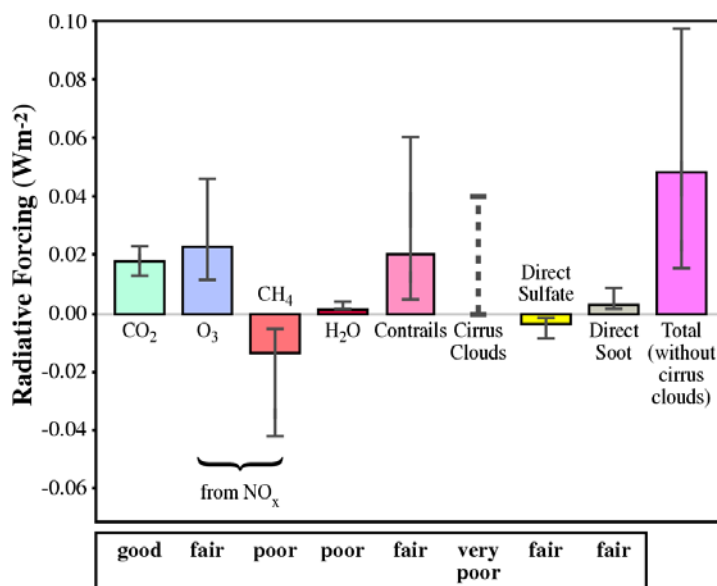
Radiative forcing is usually determined between two different points in time (e.g. the change in the energy balance of the lower atmosphere between pre-industrial times and the present). Carbon dioxide concentrations have increased from 280 ppm in 1750 to 365 ppm in 1998, resulting in an extra $1.46 W/m^2$ being trapped within the earth’s atmosphere.

Radiative forcing does not examine the influence of a single flight in the present day; instead it calculates the total influence of all historic aviation emissions.

Radiative Forcing Index

The radiative forcing index (RFI) is an extension of the concept of radiative forcing, and is simply the radiative forcing of a gas with respect to that of carbon dioxide. For aviation emissions the radiative forcing of the different atmospheric effects can be calculated separately (see Figure 5). The radiative forcing index is the ratio of the total radiative forcing compared to that of carbon dioxide alone. An explanation of the main influences of aviation emissions on the chemistry and physics of the atmospheric is presented in the Appendix.

The IPCC calculate the change in radiative forcing of aviation emissions since pre-aviation times to be $0.049 W/m^2$ (See Figure 5).. This corresponds to a radiative forcing index of 2.7 as the total radiative forcing of 2.7 times that of CO_2 alone ($0.018 W/m^2$). However, a recent study (TRADEOFF⁹) has updated this figure and a value of 1.9 is now the best-quantified estimate of radiative forcing index of aviation emissions.



Note: CO_2 = carbon dioxide, O_3 = ozone, CH_4 = methane, H_2O = water vapour, NO_x = nitrogen oxides

Figure 5. Effect of historic aviation emissions on the heat trapping ability of the atmosphere.³ (See Appendix for explanation of individual effects)

Global Warming Potential

The global warming potential (GWP) is the most commonly used climate change metric and is used for assessing different greenhouse gases under the Kyoto protocol and other international policy instruments.

It is defined as '*the [cumulative] radiative forcing of one kilogram of emitted gas relative to one kilogram of reference gas*'. In practice the reference gas is always carbon dioxide, so the global warming potential is a measure of the warming effect of other greenhouse gases relative to carbon dioxide. Typically, a 100-year time horizon is used although shorter and longer timescales are possible to calculate.

Unfortunately, the global warming potential is not a suitable measure of the influence of aviation emissions. This is because the global warming potential examines the effect of one tonne of emitted gas, yet the climate impacts of one tonne of aviation emissions will depend on other factors due to the impact of short-lived gases (especially nitrogen oxides), formation of contrails at altitude. These effects depend on the location, altitude, temperature, season, light intensity and the concentrations of other pollutants in the atmosphere.

Attempts have been made to quantify the global warming potential of aviation emissions, but results vary widely due to the models used, and assumptions made about the climate impact of emissions of nitrogen oxides (see Appendix). No accurate measure of the global warming potential of aviation emissions has yet been calculated.

Global Temperature Potential

The global temperature potential (GTP) is analogous to the global warming potential, but instead of using radiative forcing as a measure of climate change, it uses the average surface temperature change (See Figure 4). It too considers the influence of a pulse emission of one tonne of gas, and is typically considered over a 100-year timeframe.

The GTP is capable of modelling the influence of short-lived species, and so is applicable for aviation emissions. Emissions of ground-level greenhouse gases have a GTP very similar to the GWP as the temperature response of ground level emissions is directly related to the change in radiative forcing.

Unfortunately, work on this metric is still in its infancy, and more studies will need to be undertaken to quantify the influence of aviation emissions more exactly.

Comparing different metrics

The best-quantified measure of aviation emissions is the use of a radiative forcing metric. However, this does not consider the influence of one tonne of emitted gas, but rather the influence of all historic emissions. It is therefore not ideally suited for use in offsetting methodologies.

The global warming potential is the most commonly used metric for ground level greenhouse gas emissions, but aviation emissions cannot be quantified accurately under this metric.

The global temperature potential is likely to be the first metric capable of examining both ground level greenhouse gas emissions and aviation emissions. As a metric based on pulse emissions it is ideally suited to offsetting methodologies. However, more work needs to be done to improve the accuracy of the modelling before such a metric could be used in practice.

Table 2. Comparison of commonly used metrics.

Metric	Pulse emission?	Value
Radiative Forcing Index	No, historic	2.7 (IPCC) ³ 1.9 (TRADEOFF) ⁹
Global Warming Potential	Yes	Cannot be accurately quantified
Global Temperature Potential	Yes	Can be accurately modelled, but requires more work.

It can be seen that the three most-commonly used metrics has their own advantages and disadvantages. The choice of metric for an offsetting methodology is subjective, but no whatever is used is certain to have a value greater than 1, and almost certainly less than 4.

4. What price is charged?

Charging for aviation emissions or terrestrial greenhouse gas emissions requires a price to be put on the value of one tonne of carbon dioxide. The exact charge for CO₂ emissions levied by an offsetting company is also a subjective matter. There are 3 basic measures of the cost of carbon dioxide emissions:

- The social cost of carbon emissions. This is the economic cost of the climate impacts resulting from the emissions. Such costs are very difficult to calculate, lying at the end of the chain of influences (see Figure 4), and estimates vary considerably. A recent government report suggests a value of £257 per tonne of carbon dioxide (with lower and upper estimates of £128 and £513).¹⁰
- The cost of abatement. This is the cost of offsetting an equivalent amount of emissions. Efficiency measures and changes in operational practice can reduce emissions much more cheaply than the full social cost. (*i.e.* the cost at which an offsetting company can economically offset emissions);
- The market price of carbon. Carbon trading schemes, such as the EU Emissions Trading Scheme (EU ETS), assign an economic value to emissions of carbon dioxide. Under such market based schemes, the price is variable and is strongly influenced by supply and demand. At the time of writing The EU ETS is currently trading at €10 per tonne of carbon dioxide (£6.25).¹¹

For an offsetting company, who are investing in abatement technologies, the cost of abatement is the obvious choice of price of carbon dioxide.

5. Conclusions

A comprehensive model has been developed to estimate emissions arising from individuals taking flights. The model accounts for the distance travelled, likely aircraft used, and freight load, and apportions emissions arising from the flight to each seat in the aeroplane.

The full environmental effect of aviation emissions, compared to terrestrial emissions is accounted for by the use of a metric. All metrics have advantages and drawbacks, so the choice of metric is a subjective matter. The best-quantified metric, radiative forcing index, has an accurately quantified value of 1.9. Older studies estimated a value of between 2 and 4. In future, the global temperature potential may prove to be the most useful metric for determining the influence of aviation emissions but more work needs to be carried out to develop the computer models more fully.

Appendix: Atmospheric Chemistry of Aviation Emissions

Aviation is different from other energy-using activities as the majority of emissions occur at altitude, and their influence on the atmosphere can be highly localised and short-lived. Emissions from aircraft are responsible for other atmospheric chemical processes that also have atmospheric warming consequences. Aviation emissions are therefore more significant contributors to climate change, than an equivalent amount of carbon dioxide emitted at ground level.

Combustion of fuel in aeroplane engines results in emissions of carbon dioxide (CO₂) and nitrogen oxides, (termed NO_x), as well as water vapour and particulates. It is the emission of NO_x, water vapour and particulates at altitude that account for the extra impacts of aviation emissions.

Carbon dioxide

Carbon dioxide is a greenhouse gas and alters the balance of incoming and outgoing radiation from the earth's surface and contributes to warming of the atmosphere. Aviation emissions of carbon dioxide have the same effect on climate as terrestrial emissions, from power stations, industry or transport sources. Carbon dioxide has an atmospheric lifetime of up to 200 years, so ends up well mixed in the lower atmosphere over this timeframe no matter where it is emitted.

Nitrogen oxides

Emissions of nitrogen oxides initiate a series of chemical reactions in the atmosphere. Nitrogen oxides form ozone (O₃) in the presence of light, and light intensity is higher at altitude, so more ozone is formed at altitude than from terrestrial sources of NO_x. Emissions of nitrogen oxides from sub-sonic aircraft accelerate local generation of ozone in the lower atmosphere where aircraft typically fly. The increase in ozone concentration will generally be proportional to the amount of nitrogen oxides emitted from aircraft. Ozone is a potent greenhouse gas whose concentration is highly variable and controlled by atmospheric chemistry and dynamics. The increase in radiative forcing from ozone is greater than carbon dioxide emissions (see Figure 5)

However, the ozone is responsible for the destruction of atmospheric methane (CH₄). Methane is also a potent greenhouse gas, with an atmospheric lifetime of 14 years. The destruction of methane as a direct result of aviation therefore reduces the extent of warming caused by aviation emissions.

Water vapour

Water vapour is also an important greenhouse gas, but emissions of water vapour from aviation only have a minor direct warming effect. Water vapour has a short lifetime in the atmosphere and is controlled by the hydrological cycle. Emission of water vapour at high altitudes will produce contrails – the cloud-like trails behind aircraft that are visible from the ground (Figure 6). These contrails also trap heat in the atmosphere and their warming effect is believed to be equivalent to that of carbon dioxide alone (see Figure 5). Contrails do not form at lower altitudes, so could be avoided by flying lower. In practice this is not done as the fuel burn, and therefore running cost, is greater when flying at lower altitudes where the atmosphere is denser.

The contrails themselves are implicated in the formation of high altitude cirrus clouds, which are believed to have a strong warming effect on the atmosphere (see Figure 5), although quantification remains poorly understood.



Figure 6. Contrails are implicated in the formation of cirrus clouds.¹²

Soot and aerosols

Sulphate aerosols and soot from combustion also have small temperature effects on the atmosphere. Traces of sulphur are present in fuel oil, and form aerosols of sulphate compounds. These reflect incoming solar radiation back into space and so have a small cooling effect. Conversely, small particulates produced from combustion (soot) trap outgoing infra-red radiation within the atmosphere and so have a small warming effect. These are both poorly quantified but are believed to be small effects that roughly cancel each other out.

Level of our understanding

The level of understanding of each of these effects varies. The influence of carbon dioxide is well understood, ozone and methane progressively less so, and contrails and cirrus clouds poorly understood. Therefore the more effects that are included, the more complete the scientific picture, but the greater the uncertainty in values adopted.

Part 2:

Making Sense of the Science: A review of Climate Care's approach to accounting for aviation emissions

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Context

The study “Calculating the Environmental Impact of Aviation Emissions” has developed a methodology for calculating aviation emissions from flights and attributing those emissions to individuals. It also outlines a range of scientific techniques, known as metrics, for accounting for the greater impact of all aviation emissions compared to carbon dioxide only.

International greenhouse gas accounting does not yet include aviation emissions, mainly because it is complex to attribute emissions from flights to a particular country, but also which metric to apply to account for the extra climate warming effect of aviation.

However, Climate Care does feel it is important to acknowledge the greater impact of aviation emissions, and so applies a metric in its calculations. The choice of metric is a subjective one, and at present none is ideal. This paper explains Climate Care’s approach to this issue, as well as explaining the other key assumptions made in the model.

Applying a metric

Climate Care has chosen to use a multiplier of 2 to take account of the enhanced climatic effects of aviation. As discussed in “Calculating the Environmental Impact of Aviation Emissions”, none of the major metrics are ideal for describing the extra influence of aviation emissions:

- The Global Warming Potential cannot be calculated accurately for the short-lived species, so no multiplier has been calculated as yet.
- The Radiative Forcing Index has been quantified, but does not examine the influence of one tonne of aviation emissions emitted in the present day. Instead it is a measure of the influence of all historic aviation emissions, irrespective of their lifetime in the atmosphere. Because offsetting procedures undertake projects to offset a given mass of emissions, the metric used should ideally examine the effect of ‘pulse emissions’.
- The Global Temperature Potential will have the capability to account for short lived species, and for terrestrial emissions of greenhouse gases will be virtually identical to the Global Warming Potential. However, work on this metric is still being developed and no quantification of aviation emissions has been made as yet.

The radiative forcing of aviation has been described by the IPCC¹ as 2.7 times greater than that of carbon dioxide only. The report gives confidence limits lying between 2 and 4. A more recent study (TRADEOFF)⁹ has revised this value to 1.9.

In the absence of an ideal metric, Climate Care has chosen a multiplier slightly higher than that given by the most recent research on radiative forcing - on the basis that the IPCC’s values remain the most widely cited in this arena. Climate Care has chosen to use a conservative radiative forcing of 2 as the multiplier for aviation emissions relative to carbon dioxide alone.

Climate Care will review their policy on metrics periodically to ensure the metric used is representative of current scientific knowledge.

Other Assumptions

A number of other assumptions are made in the model for calculating the carbon dioxide emissions from a flight.

- Emissions are calculated per seat rather than per person on the flight. Climate Care does not believe that customers should be charged depending on the occupancy of the flight. The number of seats per plane depends on the configuration chosen by each operator, so Climate Care has taken a number typical for the three representative aeroplanes used in the model (Boeing 737 – 180 seats, Boeing 747-400 seats, and Airbus A340 – 295 seats).

- For long haul flights, 10% of the fuel burn is attributed to freight, leading to a slight reduction in emissions per seat.
- Short-haul flights (<3500 km) are assumed to be flown by Boeing 737s. Long haul flights are taken as an average of Airbus A340 and Boeing 747s.

Climate Care will review these assumptions on a periodic basis to ensure the assumptions made reflect the aeroplane stock in use.

References

¹ Houghton *et al.* "Climate Change 2001 – The Scientific Basis", IPCC, Cambridge University Press, Cambridge, 2001.

² <http://unfccc.int/resource/docs/convkp/kpeng.html>

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⁵ Andrew Kershaw, BA, personal communication

⁶ <http://www.airliners.net/info/stats.main?id=27>

⁷ <http://www.airliners.net/info/stats.main?id=93>

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¹⁰ <http://www.defra.gov.uk/environment/climatechange/carbon-cost/index.htm>

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¹² Courtesy of David Lee, Manchester Metropolitan University.