The current state of scientific understanding of the non-CO_2 effects of aviation on climate

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Summary

Aviation has impacts on climate change through both its carbon dioxide (CO_2) emissions and non-CO_2 effects. The non-CO_2 emissions of gases and aerosol particles affect atmospheric composition and cloudiness, adding to the overall climate impact from the sector's CO_2 emissions. Climate impacts can be measured with a metric known as 'radiative forcing' (RF) and the total RF of aviation has been estimated to be around 5% of global anthropogenic forcing (2 – 14% uncertainty range), of which the non-CO_2 effects comprise 50 – 60% of this 5% fraction. However, these non-CO_2 impacts have a larger scientific uncertainty than the CO_2 impacts, particularly for impacts on cloudiness.

Many improvements have been made to the science over the last 5 years since the publication of the DfT Aviation Policy Framework in 2013, which pointed to these uncertainties. Nonetheless, the uncertainties remain large, and new effects have been identified that potentially have large impacts but for which no best estimates are available. Firstly, in the case of soot emission impacts on high altitude cirrus cloud formation, both the magnitude and sign (warming or cooling) of the forcing are uncertain; secondly, in the case of the impact of aviation sulphur compound emissions on low-level clouds, the sign of the impact is known (cooling) but the magnitude is uncertain. Significant progress has been made on modelling the emission impacts of aviation oxides of nitrogen (NO_x), and the formation and impacts of linear contrails and contrail-cirrus. However, a large uncertainty remains as to whether contrails and contrail-cirrus warm the Earth's surface as much as other aviation effects, per unit forcing.

Mitigation strategies have been suggested that potentially have technological or operational trade-offs, whereby non-CO_2 impacts might be reduced, but at the expense of additional CO_2 emissions. Weighing the costs and benefits of these trade-offs is complex, involving both uncertainties in the non-CO_2 impacts and the choice and usage of metrics to compare the impacts.

1 Introduction

Aviation has impacts on climate through its emissions of gases and particles that change the ‘greenhouse’ properties of the atmosphere, contributing to climate warming and climate change (IPCC, 1999). The principle metric used for describing the contribution of these changes that affect global mean surface temperature is ‘radiative forcing’ (RF), measured in watts per square metre ($W\ m^{-2}$) since changes in RF are approximately proportional to changes in the expected (equilibrium) global mean surface temperature (see Key Concepts Box).

A key pollutant from aviation is CO_2, which is a well-understood and quantified greenhouse gas that overall, has been assigned a ‘very high’ level of confidence in its contribution to net anthropogenic forcing (IPCC, 2013). However, aviation has a number of significant non-CO_2 impacts[1] through its emissions of particles, water vapour and NO_x,[2] affecting aerosols, clouds and atmospheric composition (IPCC, 1999). These non-CO_2 pollutants can have both positive and negative RF effects (warming and cooling) although scientific consensus puts the overall non-CO_2 effects of aviation as having a net positive (warming) RF effect, which in terms of RF is thought to be approximately two to three times that of the RF effect from aviation’s historical CO_2 emissions (IPCC, 1999; Lee et al., 2009). This ratio is sometimes referred to as the ‘Radiative Forcing Index’ (RFI), introduced by the Intergovernmental Panel on Climate Change (IPCC) in their 1999 Special Report, ‘*Aviation and the Global Atmosphere*’ (IPCC, 1999). However, it should be noted that the RFI is not an emissions metric for comparing effects of equivalent emissions to CO_2, such as e.g., the Global Warming Potential (GWP) (see Key Concepts Box) (Wuebbles et al., 2010).

For a baseline of 2005 data, Lee et al. (2009) calculated that aviation CO_2 was responsible for 1.6% (0.8–2.3%, 90% likelihood range) of the total global anthropogenic CO_2 RF in 2005. The net RF from aviation (CO_2 plus non-CO_2 impacts) was calculated to represent 4.9% (2–14%, 90% likelihood range) of the total anthropogenic RF.

In the next section, the CO_2 and non-CO_2 radiative effects of aviation are considered in detail.

2 Overall radiative forcing from aviation

Since the seminal IPCC Special Report (IPCC, 1999) ‘*Aviation and the Global Atmosphere*’, aviation’s impacts have been represented graphically and quantitatively by a bar chart of the RF terms, along with additional information such as geographic scope, uncertainties, level of scientific understanding etc. – similar to RF charts of overall climate forcing agents presented in the periodic IPCC Assessment Reports. The IPCC’s (1999) chart of 1992 impacts was updated in 2005 and 2009 by Sausen et al. (2005) and Lee et al. (2009) for base years of 2000 and 2005, respectively. Since 2009, there has been no update chart published although such an initiative is known to be underway. Figure 1 reproduces the Lee et al. (2009) RF bar chart for a base year of impacts in 2005 and this chart been widely used, both nationally and internationally (e.g. by the Committee on Climate Change (UKCCC, 2009) and referred to by the IPCC, 2013).

The overall RF from aviation (including induced cirrus cloudiness) in 2005 was calculated to be 78 $mW\ m^{-2}$ ($0.078\ W\ m^{-2}$), which represented ~5% of the total anthropogenic RF calculated by IPCC (2007) in the Fourth Assessment Report (Lee et al., 2009).

The chart in Figure 1 still represents valid information but requires updating, since some additional effects need to be represented and the underlying science for some of the effects has subsequently

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[1] Other sectors also have significant non-CO_2 impacts, e.g. shipping (through enhanced lower-level cloudiness, a large negative RF impact), agriculture (through nitrous oxide and methane)

[2] where NO_x = nitric oxide [NO] + nitrogen dioxide [NO_2]

been substantially improved (Fahey and Lee, 2016). Figure 1 should be examined in conjunction with the next section, which details the CO_2 and non-CO_2 radiative impacts, term by term.

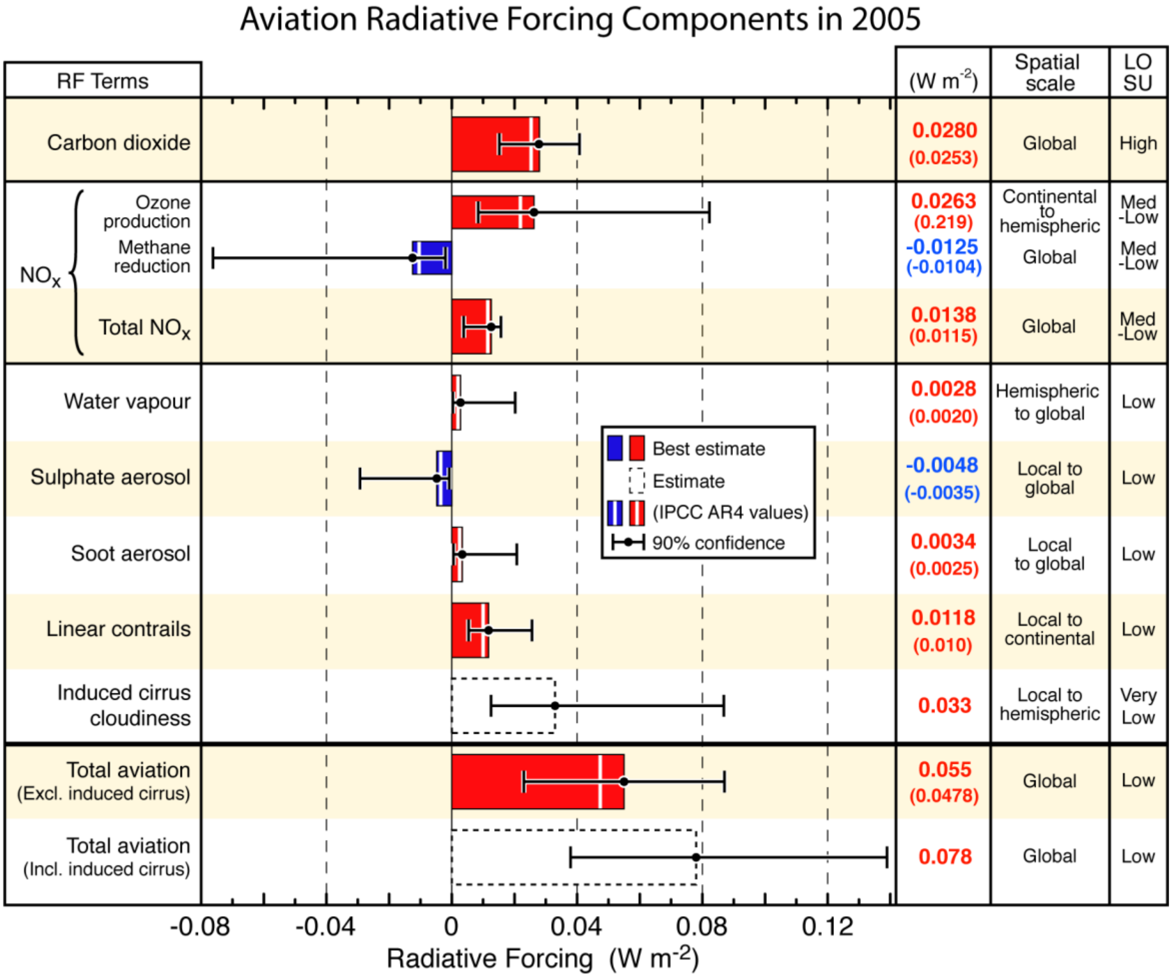

Figure 1 (reproduced from Lee et al., 2009). Radiative forcing components in Watts per square metre[3] from global aviation as evaluated from preindustrial times until 2005. Bars represent updated best estimates or an estimate in the case of aircraft-induced cirrus cloudiness (AIC). IPCC AR4 values are indicated by the white lines in the bars as reported by Forster *et al.* (2007). The aviation induced cirrus cloudiness (AIC) estimate includes linear contrails. Numerical values are given on the right for both IPCC AR4 (in parentheses) and updated values. Error bars represent the 90% likelihood range for each estimate. The median value of total radiative forcing from aviation is shown with and without AIC. The median values and uncertainties for the total NO_x RF and the two total aviation RFs are calculated using a Monte Carlo simulation. The 'Total NO_x' RF is the combination of the methane (CH_4) and ozone (O_3) RF terms, which are also shown here. The geographic spatial scale of the radiative forcing from each component and the level of scientific understanding (LOSU) are also shown on the right.

3 Individual radiative forcing terms from aviation

3.1 Carbon dioxide

Emissions of CO_2 are directly related to fuel burn. Although the emission rate is often referred to (the total mass emitted per year), it is the *cumulative* emissions over time that determine the change in CO_2 concentrations in the atmosphere and thus the RF term and temperature response (see Key Concepts Box), since CO_2 accumulates in the atmosphere. Hence, aviation CO_2 RF is determined from its whole history of emissions back to 1940 (taken as the start of significant aviation activity (Sausen and Schumann, 2000).

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[3] Note that elsewhere in this report, the RF values are given in milli-Watts per square metre (i.e. Watts/1000)

The last RF assessment of aviation (Lee et al., 2009) included cumulative emissions of CO_2 from 1940 – 2005 of ~21,830 Mt[4] CO_2; over the period 2006 – 2015, an additional ~7,900 Mt CO_2 were emitted, some 27% of the total cumulative emissions over the period until 2015, or a 21% increase as an annual emission rate in 2015 over 2005 (International Energy Agency online data).

The RF term for aviation CO_2 is well-quantified and most uncertainty will arise from quantification of historical emissions and our basic understanding of CO_2 biogeochemical cycling, which determines CO_2 concentrations in the atmosphere, an uncertainty not unique to aviation CO_2 RF. Nonetheless, it will have a high confidence level in terms of its contribution to overall aviation RF.

3.2 Nitrogen oxides

Emissions of NO_x arise from the combustion process in which atmospheric nitrogen is fixed with oxygen under the high temperature and pressure conditions of the gas turbine combustor (Bowman, 1992). The emission index (EI) for the overall global fleet is around 15 g NO_x per kg fuel combusted (ICAO, 2016). Emissions of aircraft NO_x lead to the formation of atmospheric ozone (O_3), a radiatively active gas (a 'greenhouse' gas), via complex atmospheric chemistry. In addition, the NO_x emissions result in the formation of the short-lived hydroxyl radical (OH), which is the principle reactant that results in the removal of ambient methane (CH_4) by about 1 – 2%. Methane is a greenhouse gas in its own right that principally arises from anthropogenic (e.g. agriculture and industry – but not from aircraft engines) and natural sources (e.g. wetlands). Thus, the formation of O_3 results in a positive RF (warming) and the destruction of ambient CH_4 represents a negative RF (cooling). The net NO_x RF term is a combination of these two terms, but overall is a positive RF (Lee et al., 2009).

These chemical reactions are not unique to aviation NO_x; however, the altitude at which most of aviation's NO_x is emitted is in the upper troposphere and lower stratosphere (approximately 8 – 12 km), and leads to a larger impact on O_3 formed per unit emission of NO_x than that from surface emissions, partly because of the efficiency of the chemistry and partly because of the differential radiative effect of O_3 with height (Forster and Shine, 1997), which peaks at aircraft cruise altitudes.

In addition, recent investigations have shown that there are additional negative RF terms associated with the CH_4 destruction arising from NO_x emissions. Methane destruction via OH is a major anthropogenic source of water vapour in the stratosphere[5]. The stratosphere is very dry, so any additional water vapour there represents an additional positive RF and is a secondary effect of warming from CH_4 (Myhre et al., 2007). If the amount of CH_4 in the stratosphere is reduced from aircraft NO_x emissions, then this represents a negative RF. A further secondary effect of reducing CH_4 levels in the atmosphere is that CH_4 contributes (along with NO_x, carbon monoxide and non-methane hydrocarbons) to background O_3 formation, such that a small long-term reduction in background O_3 results from the CH_4 change attributable to aviation NO_x emissions (Holmes et al., 2011). Lastly, there may also be some impact of cooling from nitrate-containing particles, although this effect is poorly understood and quantified (Pitari et al., 2015).

In total, the net NO_x RF from aviation is a positive forcing, from short-term O_3 formation, which is not completely counterbalanced by CH_4 reduction, stratospheric water vapour (SWV) reduction, and long-term reductions in O_3. In the shorter term, increasing emissions of aircraft NO_x will likely increase overall RF.

The main limitations in quantification of the above effects of NO_x are the available modelling tools, input data, and their validation. These modelling tools require a representation of the 3D flow fields (atmospheric transport) of the atmosphere, complex chemical reaction schemes, and emission fields, and to be time-integrated. Such global chemistry-transport models are often integrated into climate models and are research tools that generally require supercomputing power. A further

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[4] Mt = mega tonne, 1 million tonnes, or 1×10^{12} grams

[5] CH_4 has a lifetime of around 8 – 12 years, so is mixed globally and into the stratosphere, although it exhibits a significant north-south hemispheric gradient, as land-based sources dominate

limitation to quantification of future effects of NO_x from aviation is the assumptions regarding background emissions. The chemistry involved is non-linear, such that there is no single quantifiable RF effect per unit aviation NO_x emission over the longer term, since background conditions and emissions can have a large impact on aviation's net NO_x RF. Having said this, the modelling tools are quite mature although by the inherently varied nature of the data and parameterizations, they produce a range of estimates.

3.3 Water vapour

Water vapour is a product of hydrocarbon fuel combustion. Water vapour is mostly a natural greenhouse gas, the natural hydrological cycle and the radiative properties of water being responsible for Earth's habitable temperatures. The additional amount of water emitted from aviation from combustion is tiny compared with the hydrological cycle and is therefore only a very small positive RF. Note that this is true for the current-day civil fleet which is exclusively subsonic: any future supersonic fleet would fly at higher altitudes than current subsonic aircraft and emit water vapour into the dry stratosphere, which depending on the total mass emission, could be a significant perturbation of the stratosphere and could result in an additional positive RF (IPCC, 1999).

3.4 Sulphate aerosol

Sulphate particles originate from sulphur (S) in aviation kerosene fuel which is oxidised to sulphur dioxide (SO_2) during the combustion process (Brown et al., 1996), and then to sulphuric acid to a minor extent in the combustor and to a major part, in the ambient atmosphere (Tremmel and Schumann, 1999). Sulphuric acid can form, or coat pre-existing particles (Petzold et al., 2005). These particles reflect solar radiation back to space as a 'direct effect' and thus have a negative RF (cooling). Aviation kerosene is regulated to have a maximum S content of 3000 parts per million by mass (0.3%)[6] although most aviation fuels have a S content in the range 600 – 800 ppm (by mass) (IPCC, 1999). Thus, the overall mass emission of S from aviation is small (relative to other anthropogenic sources) and has a small direct negative radiative effect. However, the indirect effects on clouds (also negative) may be more significant (see below).

3.5 Soot aerosol

'Soot' emissions refer to the non-volatile black-carbon content of aircraft particle emissions. Other volatile particle emissions exist (e.g. those arising from the S emissions) and can contribute towards changes in the radiative properties of clouds (dealt with in below section 3.7). Soot emissions are the result of incomplete combustion of aviation kerosene and have previously been measured as a 'smoke number' in quantifying emissions for regulation by ICAO. The measurement technique for smoke number involves an optical measurement of the change in reflectance of filter paper, through which emissions of soot have been drawn. This technique has proven to be inadequate as soot mass emissions have fallen dramatically since early jet engines and developments are underway within ICAO to supersede this with a more accurate measurement technique. Soot has a so-called 'direct' effect of a positive RF, since small 'black' particles trap infrared radiation (Bond et al., 2013) leading to warming. However, the emissions index of soot for aircraft engines is rather small and the overall global fleet emission and direct RF effect from these particles is small (Lee et al., 2009; 2010). The 'indirect' effects on cirrus cloud formation and aviation-induced cloudiness may be rather large and therefore these emissions should not be dismissed as unimportant for climate. The main limitation to quantification of this effect is a reliable assessment of aircraft black carbon emissions, and also a more complete understanding of how these particles interact with clouds and the radiation budget[7].

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[6] From UK Defence Standard 91-91 and ASTM D1655 Standard Specification for Aviation Turbine Fuels

[7] The balance of incoming solar radiation, solar radiation reflected back to space, long-wave (infrared) radiation emitted from the earth's surface and trapping of long-wave radiation that ultimately warms the atmosphere.

3.6 Aviation impacts on high-level clouds; formation of linear contrails and contrail-cirrus

Aviation contrails are linear ice cloud structures formed in the exhaust and wake of cruising aircraft (Schumann, 1996). Their formation can be thermodynamically predicted from temperature, water vapour emission, pressure and the overall efficiency of the aircraft (Schumann, 1996). This process is enhanced by the emission of soot aerosol particles combined with the emission of water vapour, providing an initial 'pulse' that allows background water vapour from a super-saturated atmosphere to condense on the particles to form ice crystals (Jensen et al., 1998). By visual experience, this can be seen not to occur uniformly in time and space, which shows the dependence of this effect on the combined conditions of temperature and humidity (strictly, the ice-supersaturation) of the background atmosphere. When the atmosphere is cold and ice-supersaturated, contrails may form and can be persistent (long-lived) and spread to form extensive heterogeneous cloud structures, merging into one another (Schumann, 2002). This is termed 'contrail-cirrus', as the clouds formed have similar properties and characteristics to natural cirrus clouds.

Both individual linear contrails and contrail-cirrus can have both positive and negative impacts on the radiative budget: at the relevant height in the atmosphere, these ice cloud structures both reflect solar radiation back to space (less radiation to the Earth) and infrared radiation back down into the Earth's atmosphere (more radiation) (Meerkötter et al., 1999). The balance and strength of the local forcing depends on the ice crystal size distribution, density, time of day, and the albedo (or reflectivity) of the surface over which the cloud structures are formed (IPCC, 1999). Overall, and globally, the RF is calculated to be positive for both linear contrails and contrail-cirrus (Burkhardt and Kärcher, 2011). The distinction between the two is somewhat artificial – however, linear contrails are relatively easily detected by satellite instrumentation and can be related to known flight paths and trajectories, whereas contrail-cirrus is less easily traced in the same manner because of its departure from distinctive line-shaped structures and similarity to natural cirrus. Thus, estimates of the RF from contrail-cirrus generally have to be made with climate models with a good representation of contrails and contrail-cirrus.

The IPCC re-assessed contrail and contrail-cirrus RF for the Fifth Assessment Report (IPCC 2013), accounting for newer literature and modelling approaches of contrail-cirrus (e.g. Burkhardt and Kärcher, 2011; Schumann and Graf, 2013). The IPCC estimated that linear persistent contrails had an RF of around 10 mW m^{-2} (range 5 – 30 mW m^{-2}) and the combined forcing with contrail-cirrus has an Effective Radiative Forcing (ERF – see Key Concepts, 'Efficacy') of ~50 mW m^{-2} (range 20 – 150 mW m^{-2} such that contrail cirrus is the larger signal (Burkhardt and Kärcher, 2011, Bock and Burkhardt, 2016, Schumann et al., 2015). This value is not dissimilar to the value estimated by Lee et al. (2009) scaled with volumes of air traffic, and as such still represents the largest component of aviation RF (approximately 50 – 60%)

The uncertainties of the RF associated with linear contrails and in particular, contrail-cirrus are still relatively large. This is because of a lack of extensive measurements of ice-crystal properties and the optical properties of linear contrails; moreover, for contrail-cirrus (which requires large-scale dynamical models) certainty is limited by these factors plus the ability of the model to represent the amount of water vapour available in the ice-clouds and predict conditions of ice-supersaturation (Kärcher, 2017).

3.7 Aviation impacts on high-level clouds and lower-level cloud modification

A third effect of aviation soot aerosol emissions beyond the formation of linear contrails, and contrail-cirrus at cruising altitudes is sometimes termed 'soot cirrus' where this is defined as the formation of additional high-level cirrus clouds caused by aircraft emissions of particles (largely soot particles) that have not gone through the linear contrail to cirrus-cloud spreading mechanism (or that have, and the contrail-cirrus ice crystals have evaporated, leaving the soot particles). Aviation particles can be emitted into an atmosphere whose conditions preclude linear contrails, and therefore contrail-cirrus formation: however, these particles have a residence time in the atmosphere of approximately days to weeks before removal by subsidence or rain-out, and therefore represent additional particles in the atmosphere for cirrus clouds to form on (i.e. 'condensation nuclei' – generally, most clouds are formed by condensation of water onto particles of both natural and anthropogenic origin, other than some tropical clouds).

This process cannot be easily observed although it is conceivable that it might be, under controlled and carefully instrumented conditions away from main air traffic corridors, with an experimental aircraft 'seeding' the upper atmosphere with soot emissions. In the absence of such experimental data, the effect can, at present, only be modelled. Such modelling is in its infancy and has produced a wide range of impacts from a large positive RF (+90 mW m^{-2}) though to a large negative RF (-350 mW m^{-2}) (Zhou and Penner et al., 2014; Zhou et al., 2016), with other estimates providing very small positive RF impacts (Gettelman and Chen, 2013; Pitari et al., 2015) of 8 mW m^{-2} and 4.9 mW m^{-2}, respectively. Owing to the lack of consistency and consensus, no best estimate can be given for this effect, and no assessment of even its sign with good confidence.

In addition to the above effect on high-level clouds, the S in aircraft exhaust may also have an effect on lower-level clouds (Righi et al., 2013). In this lower-level cloud modification effect, the sulphate particles, as they descend to lower levels in the troposphere, may interact with warmer water-droplet clouds. Additional sulphate, primarily sulphuric acid (H_2SO_4) or the neutralized salt, ammonium sulphate (formed from the reaction of sulphuric acid with ambient ammonia from ground-level sources), is known to modify cloud droplet size distributions, shifting the mean droplet size to smaller values. The smaller droplet size distribution makes the cloud optically brighter, and therefore reflects more solar radiation back to space than an unperturbed cloud. This is sometimes referred to as the 'first indirect aerosol effect' (see IPCC, 2007). Initial assessments of the effect of global aviation emissions of S on this effect put this somewhere between zero and several tens of mW m^{-2} (negative), such that the effect may be significant (Righi et al., 2013; Kapadia et al., 2016). Note that the sign of this effect is known with certainty, but there is not a good evaluation of its magnitude.

4 A summary of known and likely changes between the aviation 2005 RF bar chart and knowledge today

A key piece of information is that global fuel usage by the aviation sector has continued to increase since 2005, so all other things being equal, the individual RF terms will have increased (positively and negatively) and the net RF increased. However, new knowledge on certain terms may tend to counter this tendency. Changes may be summarized as follows:

CO_2 – fuel usage has continued and increased since 2005, resulting in an increased RF (certain);

Net NO_x effects – fuel usage has increased and the emission index of NO_x of the global fleet has increased, with a likely increase in net NO_x RF. However, additional negative terms associated with CH_4 destruction may counter this tendency;

Water vapour – a smaller term (RF per unit emission) from updated scientific studies (Wilcox et al., 2012), possibly countered by an increase in fuel usage;

Sulphate aerosol – no significant change to the S direct effect other than a likely decrease in RF (more negative) from increased fuel usage;

Soot aerosol - no significant change to the soot direct effect other than a likely increase in RF from increased fuel usage;

Linear contrails and 'contrail cirrus' – most recent studies (e.g. Boucher et al., 2013; De León et al., 2018) have reduced the RF per unit distance (a better measure than fuel usage) over earlier studies. The terminology has changed by separating 'aviation induced cloudiness' to 'contrail-cirrus' and 'soot-cirrus' (see below). Improved contrail-cirrus estimates have been made that often include the smaller linear contrail element and are of a similar order (per unit distance) to the Lee et al., 2009 estimate (Burkardt and Kärcher, 2011; Chen et al., 2013). However, the 'Effective Radiative Forcing' may downscale these RF estimates. An important likely development is that because of the improvements in the science of contrail-cirrus modelling, future assessments are unlikely to provide total aviation RF estimates "with and without contrail-cirrus" and estimates of total RF from aviation will include contrail-cirrus.

Additional RF terms: **effects on cloudiness from soot (soot-cirrus); effects on cloudiness from sulphate** – these effects were not explicitly considered in the Lee et al. (2009) RF chart, although the data from which the 'aviation induced cloudiness' may have contained an element of the impact on high-level clouds (it was based, in part, on rather speculative interpretation of satellite cloud observational data that could have included this effect) (Stordal et al., 2005). The effect of sulphate aerosols on lower level clouds was not considered in the Lee et al., 2009 RF chart. Neither of these effects can be reliably assessed in the same way that other bars on the RF chart are as the science is simply too immature.

5 Key developments in the available evidence of aviation's non-CO_2 effects since the DfT's previous 2013 Aviation Policy Framework

The state of knowledge was very briefly summarized in the 2013 DfT Aviation Policy Framework in Chapter 2 (DfT, 2013), paragraphs 2.2 and 2.3 reproduced verbatim, below:

> 2.2 Aviation's most significant contribution to climate change in the longer term is through emissions of carbon dioxide (CO_2), which make up about 99% of the sector's Kyoto basket of greenhouse gas emissions,[58] and this has therefore been the focus of government action. But we recognise that the complexities of atmospheric chemistry mean that the total climate change impacts of aviation are greater than those from its CO_2 emissions alone. Non-CO_2 emissions from aviation can have both cooling and warming effects on the climate, with a likely overall warming impact on the atmosphere. Nitrogen oxides (NO_x), sulphur oxides (SO_x) and water vapour all contribute to the overall effect, with NO_x emissions resulting in the production of ozone, a greenhouse gas and air pollutant with harmful health and ecosystem effects. However, despite advances over the past decade, considerable scientific uncertainty remains about the scale of the effect on climate change of non-CO_2 emissions. As a consequence there is no consensus on whether and how to mitigate them.
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> 2.3 Our focus will remain on actions to target CO_2 emissions, which may also help to reduce some of the non-CO_2 emissions. We will continue to support efforts to improve the understanding of non-CO_2 impacts of aviation. The UK is participating in and helping to fund a number of projects investigating non-CO_2 impacts such as the effects of contrails and NO_x on atmospheric warming. As scientific understanding improves and evidence of the effects of non-CO_2 emissions becomes clearer, we will adapt our approach as necessary to ensure our strategy addresses aviation's total climate change impacts effectively
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> 58 ibid
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> *[footnote 57 says: Domestic and international aviation emissions on the basis of bunker fuel sales in the UK to the aviation sector. UK Greenhouse Gas Emissions, Department of Energy and Climate Change, 2011, available through https://www.gov.uk/government/publications/final-uk-emissions-estimates]*

The summary of scientific knowledge contained in para 2.2 of DfT (2013) largely remains a reasonable summary. Some aspects of non-CO_2 impacts have considerably improved in terms of certainty (NO_x – more assessments; revision of water vapour RF/unit emission; contrail-cirrus modelling), whereas new uncertainties have been introduced, i.e. effects of soot and sulphur on high-level and low-level clouds, respectively.

A key uncertainty not mentioned in the 2013 Aviation Policy Framework on non-CO_2 impacts was the 'trade-off' aspects of potential mitigation approaches. Some trade-off aspects were known at the time but given the overall assessment of non-CO_2 effects ("*considerable scientific uncertainty remains*..."), this was not explored. Trade-offs essentially involve mitigating one effect at the expense of another, which can occur through both technological and operational developments.

6 Emission mitigation by technological and operational means, and trade-offs between CO_2 and non-CO_2 effects

CO_2 and NO_x

Reductions of NO_x are required in international regulation by ICAO for air quality purposes. However, the technological trade-off between NO_x and CO_2 whereby NO_x can be reduced but at the expense of fuel and therefore CO_2, is a well-known phenomenon in combustion technology (Sehra and Whiltlow, 2004) but one that is poorly understood in terms of environmental impacts. Conversely, efforts to reduce fuel consumption and, as a consequence, CO_2 emissions (reducing fuel consumption is a high priority to engine and airframe manufacturers since it is a major cost consideration to operators) will increase NO_x emissions without further combustor technology development. The development of second-generation turbo-fan engines on modern jet aircraft in efforts to increase fuel efficiency has led to ever increasing temperatures and pressures in the combustor. This results in 'cleaner' less fuel-consuming and soot-emitting aircraft engines[8] but tends to *increase* NO_x emissions without additional combustor design technology to reduce the NO_x. The scientific guidance within ICAO has always been "to reduce both CO_2 and NO_x". However, the question arises as to the overall environmental costs and benefits of technology development; so, for example, large reductions in NO_x might be envisaged (e.g. 10s of percent) at the cost of slightly increased CO_2 emission (1 to a few percent). Very few studies have attempted to address this trade-off in terms of climate impacts. Freeman et al. (2018) undertook a parametric study of this and showed in case studies that for a scenario of a 20% reduction in NO_x emissions the consequential CO_2 penalty of 2% actually *increased* the total radiative forcing (RF) for a constant emission scenario, after 100 years. For a 2% fuel penalty, NO_x emissions needed to be reduced by >43% to realise an overall benefit. Conversely, to ensure that the fuel penalty for a 20% NO_x emission reduction did not increase overall forcing, a 0.5% increase in CO_2 was found to be the "break even" point, i.e. no net change in impact, implying that for a 20% NO_x reduction, the CO_2 penalty needed to be minimal to produce a net environmental climate benefit. The timescales of the climate effects of NO_x and CO_2 are quite different, necessitating careful analysis of proposed emissions trade-offs.

As mentioned above, the overall state of scientific knowledge has improved – there are many more assessments of aviation NO_x impacts in the literature (e.g. Holmes et al., 2011; Skowron et al., 2015; Pitari et al., 2015; Olsen et al., 2013) that are largely in agreement on sign and magnitude. The additional negative RF effects associated with the CH_4 destruction have been identified and quantified. However, more detailed analyses of future scenarios have identified that background conditions can also make a significant impact on the effect of the same aircraft NO_x emission. In terms of future mitigation strategies and technology development (for climate impacts of NO_x), this requires more investigation to understand costs and benefits of NO_x reductions.

CO_2 and contrails and contrail-cirrus

Operational measures to avoid contrails and contrail-cirrus (Matthes et al., 2017) may result in reductions in the associated marginal[9] RF. However, avoidance by deviation from optimal flight altitudes and trajectories will result in a small increase in fuel and therefore CO_2. The basis of the operational changes proposed is that the properties of temperature and in particular ice-supersaturation in the upper troposphere and lower stratosphere are highly heterogeneous (Gierens

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[8] Engines are cleaner in terms of *mass*, however, number concentrations of soot may have increased as many small particles are emitted

[9] i.e. the additional RF arising from the flight following the new operational measures

and Spichtinger, 2000; Gettelman et al., 2006) such that contrails might be avoided by flying under, over or around areas with high potential for contrail formation.

Early studies concentrated on simple parametric operational changes, e.g. changing the overall global fleet cruise altitudes with subsequent contrail reductions, and fuel (CO_2) increases (generally lower altitudes that are less aerodynamically efficient) (Frömming et al., 2012). Such studies showed the possibility for contrail RF reductions at the expense of CO_2 emissions, but did not go on to quantify like-for-like impacts. This was because of large uncertainties in emission equivalence metrics (GWP, GTP – see Key Concepts Box) and the inherent use of time-horizons, repeatedly emphasized in the literature as a 'user choice' and therefore having a degree of subjectivity (Fuglestvedt et al., 2010). Neither are emission metrics straightforward for contrails/contrail-cirrus as they are not an 'emission'; whilst they may be very roughly equated with fuel usage, this is a very poor proxy (e.g. a small low-fuel burning single aisle twin aircraft might make an equivalent linear contrail to a large one, burning much more fuel), whereas 'distance travelled' (through contrail-forming conditions) is a much better measure (Gierens et al., 1999).

Whilst it has been shown that contrail/contrail-cirrus RF might be realistically reduced by altering flight trajectories, given a good knowledge of potential contrail-forming areas from predictive meteorological models (this is a requirement that cannot as yet be fulfilled), the trade-off aspect has not been fully explored; i.e. it can be done, but is it worth the extra fuel burn in term of long-term climate impacts from extra CO_2?

Complications in comparing short-lived climate forcers with long-lived greenhouse gases

In addition, relevant to any CO_2 vs non-CO_2 RF trade-off, which is effectively a comparison of a long-lived greenhouse gas with short-lived climate forcers, is the issue of long-term impacts vs short-term impacts, since emission equivalence metrics have an inherent time horizon (which represents a calculation 'cut-off' after which further impacts are neglected). Thus, for example, for a GWP of 100 years, the longer-term impacts of CO_2 will be underestimated, and it is potentially possible to reduce non-CO_2 aviation forcings such that the net forcing (non-CO_2 + CO_2) is decreased. However, beyond the time horizon of e.g. 100 years, the consequential increase in fuel, and therefore CO_2 RF may increase the net RF in the longer term. This, in essence, was what Freeman et al. (2018) found could happen in NO_x vs CO_2 'trades'.

Temperature change is often considered to be a better choice for short-term vs long-term effects as an integrated RF on short-term effects imposes an 'artificial memory' of the effect which has effectively been 'forgotten' by the climate system (Fuglestvedt et al., 2010). More recent work shows promising results for comparing short-lived climate forcers with long-lived greenhouse gases with a modification of the GWP, termed GWP* (Allen et al., 2017; 2018).

Radiative forcing, Effective Radiative Forcing, Efficacy of forcing

One remaining and highly significant uncertainty with non-CO_2 effects is actually the underlying assumptions within the RF metric used. This is the assumption that the temperature response to a given forcing does not vary across the forcing agents from that for CO_2, i.e. in the case of aviation, the non-CO_2 effects. This inequality of a temperature change per unit forcing has been found by e.g. Joshi et al. (2013), Hansen et al. (2005), and has been termed the 'efficacy' of forcing (see Key Concepts Box).

This may be particularly important in the case of contrail-cirrus. Ponater et al. (2006) found an efficacy of 0.59 for linear contrails. In other words, contrails produced only ~60% of the temperature signal per unit forcing, compared with that of CO_2. Rap et al. (2010) found an even smaller efficacy of 0.31. This aspect has been recently discussed by Schumann and Mayer (2017) who also found that contrail-cirrus may not heat the Earth's surface as effectively as CO_2, per unit forcing. This means that a straightforward RF term may be misleading, and a significant correction to an RF may be appropriate. The ERF metric (see Key Concepts), goes some way to correcting the RF but a value for contrail-cirrus is not well-established.

7 How may CO_2 effects be compared with non-CO_2 effects?

The comparison of CO_2 effects with non-CO_2 effects of aviation as emission equivalences is a complex topic. The way emissions equivalences (CO_2-e) were calculated for the Kyoto Protocol was by the use of Global Warming Potentials (see Key Concepts box) for a 100 year time horizon (the length of time over which the calculation is made). Comparing short-lived climate forcers, such as the non-CO_2 effects of aviation with a long-lived greenhouse gas makes the use of GWPs more difficult because of the disparity in lifetimes of the gases/emission effects. Alternative metrics, such as the Global Temperature change Potential (GTP, Shine et al., 2005) and derivatives such as the Average Temperature Response (ATR) (Dallara et al., 2011) are also available but require the same user choice of a time horizon, which is not a scientific choice (Fuglestvedt et al., 2010).

As mentioned in the introduction the RFI is not a suitable metric to calculate CO_2 emission equivalents (Wuebbles et al., 2010; Fuglestvedt et al., 2010; Myhre et al., 2013).

Using RF values calculated by Lee et al. (2009) and the methods described by Fuglestvedt et al. (2010), Lee et al. (2010) calculated composite (net) aviation non-CO_2 GWPs and GTPs for a range of time horizons. The total aviation GWP was estimated to be ~2 and the total aviation GTP to be 1.1, both for 100 year time horizons.

8 What new evidence is expected to become available on non-CO_2 effects in the future?

Since the publication of the DfT's Aviation Policy Framework in 2013, much scientific study has been committed to aviation effects on NO_x emission impacts, contrails and contrail-cirrus, and the impact of aviation aerosols on clouds. Some of this has improved knowledge; some of this has opened up new and significant questions. No new bar chart of the overall effects has been published since 2009 (which was for a base year of 2005), and this is urgently required, although efforts are underway within the scientific community to produce such an assessment.

There has been an emphasis in recent years as to whether aviation's overall impact can be reduced through targeting some of the non-CO_2 effects, e.g. NO_x emissions, contrails and contrail-cirrus. This can be done through both technological and operational means. However, a likely consequence in both cases is a small increase in fuel usage, which will increase CO_2 emissions. Thus, complex trade-off arguments are invoked, whereby assessments have to be made of the benefits of reducing short-lived climate forcers (the non-CO_2 effects) against an increase in CO_2, a long-lived greenhouse gas. The answers to such 'scenario' type questions are not clearly established yet, and require more assessment of the pros and cons. The ERF of contrails may also mean that the effect of contrails/contrail-cirrus is significantly smaller than their RFs, also affecting 'tradeoffs'.

With promising new work on operational possibilities to reduce contrail-cirrus (Grewe et al., 2017), and new work on emission metrics that focus on comparing short-lived climate forcers with long-lived greenhouse gases (Allen et al., 2016, 2018), better assessments of potential mitigation strategies might be expected in the coming years.

However, the clear message is that mitigation of non-CO_2 impacts tends to raise complex questions regarding both scientific uncertainty and trade-off (with CO_2) consequences, whereas reducing CO_2 emissions has clear and long-term benefits, and does not suffer from the same levels of scientific uncertainty.

Acknowledgements

The author would like to express thanks to reviewers of the document from DfT, BEIS, and an independent scientific peer-reviewer for constructive comments and suggestions.

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KEY CONCEPTS

Radiative forcing (RF) in units of watts per square metre is the change in the Earth's radiation energy balance since pre-industrialization (taken as 1750) and is used as there is an approximately linear relationship between a change in global mean radiative forcing (RF) and a change in global mean surface temperature (ΔT_s), when the system has reached a new equilibrium, with some proportionality constant, i.e.

$$\Delta T_s \approx \lambda \mathrm{RF} \qquad [1]$$

where λ is the climate sensitivity parameter (K (W m^{-2})$^{-1}$) (IPCC, 2007). Positive values of RF imply warming and negative values, cooling. In the Fifth Assessment Report of the IPCC (IPCC, 2013) a new metric, the '**Effective Radiative Forcing**' (ERF) was introduced, which includes rapid adjustments of changes of the Earth's surface and troposphere and is a better indicator of changes in ΔT_s. Aerosols and cloud changes show the largest differences between RF and ERF. RF and ERF are largely comparable for greenhouse gases (see IPCC, 2013 Technical Summary, for further details).

The **Radiative Forcing Index** (RFI), is a dimensionless ratio and was introduced as a measure of the strength of CO_2 vs non-CO_2 radiative impacts from aviation, defined as the total RF from aviation divided by the RF from historical aviation CO_2 emissions (IPCC, 1999). This has often been misunderstood as a CO_2 equivalence emissions metric (or 'multiplier') (Wuebbles et al., 2010). To multiply CO_2 emissions by the RFI to account for non-CO_2 radiative effects is an entirely incorrect calculation. Since CO_2 emissions accumulate and are persistent in the atmosphere for many thousands of years, the RF of CO_2 from any source can only be calculated from a knowledge of a complete history of those emissions over time. For the non-CO_2 effects of aviation, these are generally much shorter term and the RF can be calculated from a year's emissions. The effect of aircraft NO_x on ambient methane (CH_4) and associated effects has a longer timescale of 8 – 12 years but can be calculated from a year's emissions via a parameterization of the effect (Fuglestvedt et al., 1999).

The **Global Warming Potential** (GWP) is a means of comparing emission equivalences on a kg for kg basis and is defined as the integrated forcing from a unit emission of interest divided by the integrated forcing from a unit emission of CO_2 over some time horizon, often taken as 100 years, e.g. in the Kyoto Protocol (although the time horizon represents a user choice) (e.g. Fuglestvedt et al., 2010). Alternative emission equivalence metrics exist, for example the Global Temperature change Potential (GTP) (Shine et al., 2005) and others (see Shine, 2009; Dallara et al., 2011).

The **Cumulative Emissions of CO_2** are what determines the CO_2 RF response and ultimately the temperature response. There is an approximately linear relationship between the amount of cumulative CO_2 emissions and the change in global mean surface temperature. The biogeochemical cycling of CO_2 is complex, and it has no single lifetime. The IPCC (2007) gave a simplified summary of the characteristics of CO_2 in that 50% of an increase will be removed from the atmosphere in around 30 years, and a further 30% is removed within a few centuries. The remaining 20% can stay in the atmosphere for many thousands of years. The IPCC (2013) further discriminated between two conceptual domains; a fast domain with relatively rapid reservoir turnovers that include CO_2 in the atmosphere, the ocean, C in surface ocean sediments and on land in vegetation, soils and freshwaters – the turnover times range from decades to millennia. The second domain is a slow one of the massive C reservoirs in rocks and sediments. It is the 'unlocking' of C through fossil fuel extraction from this second domain that perturbs the natural cycle of CO_2 in the atmosphere, resulting in rising CO_2 concentrations and ultimately, warming.

The **'Efficacy'** of forcing is a modification to equation [1] and defined as the ratio of the climate sensitivity parameter for a specific forcing relative to that of CO_2:

$$r_i = \frac{\lambda_i}{\lambda_{CO_2}} \qquad [2]$$

where λ_i and λ_{CO2} are the climate sensitivity parameters associated with perturbations of the climate change agent *i* and of CO_2, respectively, with perturbations of the climate change agent *i* and of CO_2, respectively.

The IPCC introduced the **Effective Radiative Forcing** (ERF) to incorporate some improvements over the RF metric in the Fifth Assessment Report (Myhre et al., 2013), particularly for some of the short-lived climate forcer effects (aerosols and clouds) (Boucher et al., 2013). Earlier, the concept of 'efficacy' had been introduced as a correction to the RF term (Hansen et al., 2005; Joshi et al., 2003). The ERF largely captures this effect but the use of 'fixed' sea-surface temperatures of the calculation may not fully capture the effect. Earlier work had suggested that contrail RF may have an efficacy of between 0.31 (Rap et al., 2010) and 0.59 (Ponater et al., 2006) – in other words, the RF could be scaled down by these factors; in contrast short-term O_3 and CH_4 forcing terms were calculated by Ponater et al. (2006) to have efficacies of >1 (a more powerful effect than the RF would suggest). The IPCC (Boucher et al., 2013) noted with 'medium confidence' that studies supported that the ERF from contrail-cirrus did not produce observable regional effects on either mean or diurnal range of surface temperature. More recently, attention has again been brought to the possibility that contrail-cirrus may not effectively heat the Earth's surface as might be expected from its RF (Schumann and Mayer, 2017).

Calculation of efficacies is a difficult task, as it can only be done with a coupled ocean-atmosphere climate model. Computing any small climate forcing signal, such as those from aviation (compared to the larger background terms), requires much computing power and careful experimental design to overcome signal-to-noise issues. The existing but small amount of evidence for efficacies applying to some aviation non-CO_2 terms represents a large uncertainty in suggesting mitigation measures that will have large technological or operational costs involved.