View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Central Archive at the University of Reading

Radiative forcing and climate change

Book or Report Section

Accepted Version

Shine, K. (2015) Radiative forcing and climate change. In: Blockley, R. and Shyy, W. (eds.) Encyclopedia of Aerospace Engineering. John Wiley & Sons, Ltd., pp. 1-11. ISBN 9780470686652 doi: https://doi.org/10.1002/9780470686652.eae526.pub2 Available at http://centaur.reading.ac.uk/40552/

It is advisable to refer to the publisher's version if you intend to cite from the work.

To link to this article DOI: http://dx.doi.org/10.1002/9780470686652.eae526.pub2

Publisher: John Wiley & Sons, Ltd.

Publisher statement: This is the submitted version of K. Shine "Radiative Forcing and Climate Change" in Encyclopedia of Aerospace Engineering, eds R. Blockley and W. Shyy, John Wiley: Chichester. DOI: 10.1002/9780470686652.eae526.pub2 which has been published in final form on http://onlinelibrary.wiley.com/book/10.1002/9780470686652

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the End User Agreement.

www.reading.ac.uk/centaur

CentAUR

Central Archive at the University of Reading

Reading's research outputs online

Submitted 27 November 2014

Prepared for the Encylopedia of Aerospace Engineering

Reference: EAE526.PUB2

Professor Keith P Shine FRS, Department of Meteorology, University of Reading, Earley Gate, Reading RG6 6BB, UK

email: k.p.shine@reading.ac.uk   Tel: 0118 378 8405   Fax: 0118 378 8905

Prepared in Microsoft Word 2007
Figure files:
aerospace_aea526_pub2_fig1.tif
aerospace_aea526_fub2_fig2.gif

This is the submitted version of
K. Shine "Radiative Forcing and Climate Change" in Encyclopedia of Aerospace Engineering, eds R. Blockley and W. Shyy, John Wiley: Chichester. DOI: 10.1002/9780470686652.eae526.pub2 which has been published in final form on http://onlinelibrary.wiley.com/book/10.1002/9780470686652

RADIATIVE FORCING AND CLIMATE CHANGE

Keith P. Shine
Department of Meteorology
University of Reading
Reading, United Kingdom

Keywords: Radiative forcing, carbon dioxide, climate change, global warming potential, global temperature-change potential

Abstract

Aviation causes climate change as a result of its emissions of CO_2, oxides of nitrogen, aerosols and water vapour. One simple method of quantifying the climate impact of past emissions is radiative forcing. The radiative forcing due to changes in CO_2 is best characterised, but there are formidable difficulties in estimating the non-CO_2 forcings – this is particularly the case for possible aviation-induced changes in cloudiness (AIC). The most recent comprehensive assessment gave a best-estimate of the 2005 total radiative forcing due to aviation of about 55 to 78 mW m^{-2} depending on whether AIC were included or not, with an uncertainty of at least a factor of two,. The aviation CO_2 radiative forcing represents about 1.6% of the total CO_2 forcing from all human activities. It is estimated that, including the non-CO_2 effects, aviation contributes between 1.3 and 14% of the total radiative forcing due to all human activities. Alternative methods for comparing the future impact of present-day aviation emissions are presented – the perception of the relative importance of the non-CO_2 emissions, relative to CO_2, depends considerably on the chosen method and the parameters chosen within those methods.

1. INTRODUCTION

The possibility that aviation could contribute to climate change was considered in the earliest assessments of the climate impact of human activity (e.g., Matthews, Kellogg and Washington, 1971). In the subsequent period, considerable attention focused on examining the impact of possible future supersonic fleets on stratospheric ozone; aviation's impact on climate took a back seat. The European assessment by Brasseur *et al.* (1998) gave renewed vigour to the appraising the climate influence. This was followed by the wider-ranging report on "Aviation and the Global Atmosphere" by the Intergovernmental Panel on Climate Change (IPCC, 1999), which remains a basic reference. Lee *et al*. (2009, 2010) have provided updated assessments.

2. CONCEPTUAL FRAMEWORK

2.1 Radiative forcing

The planetary energy balance can be characterised as a balance between two components: solar radiation (which is mostly at wavelengths less than 4 μm) absorbed or reflected back to space by the Earth and its atmosphere, and longwave (thermal-infrared) radiation (which is mostly at wavelengths greater than 4 μm) emitted and absorbed by the Earth's surface and atmosphere.

At the top of the atmosphere, averaged over the globe and over a year, there is a close balance between the absorbed solar radiation (ASR) by the Earth system and the outgoing longwave radiation (OLR), so that the net radiation (NET)

$$\mathrm{NET} = \mathrm{ASR} - \mathrm{OLR} \approx 0. \qquad (1)$$

Satellite observations show that the global and annual mean ASR and OLR are both about 240 W m^{-2} (e.g., Hartmann, 1996).

The main mechanisms which drive climate change perturb either or both the ASR or the OLR, so that NET≠0. More precise definitions are available (e.g., Myhre *et al.*, 2013), but the size of the initial perturbation of NET, say following a change in CO_2 concentration, is a useful working definition of the radiative forcing (RF) of climate change. RF provides a useful first-order indication of the size of different climate change mechanisms and it will be a major focus here.

Unless otherwise stated, RF is taken here to refer to its global-average value. RF can refer to the change in NET over any specified period of time. Forcing due to human activity is often reported as the total change since some "pre-industrial" time, for example since 1750. For aviation, the total present-day forcing has occurred over a much shorter period, as emissions were negligible prior to 1940 (e.g., Lee *et al.*, 2009).

2.2 Temperature response and climate sensitivity

When RF is positive the planet is absorbing more energy than it is emitting (and vice versa if RF is negative); the climate system responds by warming, leading to more infrared emission and hence a higher OLR. Given sufficient time (and assuming that

RF is not time varying), the system will reach a new equilibrium, where NET is once again close to zero.

The simplest representation of the response of the climate system to a radiative forcing is given by Hartmann (1996) and Fuglestvedt *et al*., (2010)

$$C\frac{d\Delta T(t)}{dt} = RF(t) - \frac{\Delta T(t)}{\lambda} \quad (2)$$

where t is time, C is the heat capacity of the climate system (most of which is contained within the ocean) [J K^{-1} m^{-2}], ΔT is the departure of the global-mean surface temperature [K] from its unperturbed value, and λ is the climate sensitivity parameter [K (W m^{-2})$^{-1}$].

A useful special case is when RF is independent of time. The solution to Equation (2) is then

$$\Delta T(t) = \lambda RF[1 - \exp(-t/\lambda C)]. \quad (3)$$

As t tends to infinity, the equilibrium surface temperature ΔT_{eq} is given by

$$\Delta T_{eq} = \lambda \mathrm{RF}. \quad (4)$$

Hence, Equation (4) tells us that ΔT_{eq} resulting from a (constant) radiative forcing is simply the product of that forcing and the climate sensitivity parameter. This equation provides much of the justification for using RF as an indicator of climate change.

Equation (3) shows that the product of λ and *C* defines a time constant for the climate system to respond to an RF and is of order a few decades; a precise number cannot be given, because of uncertainties in the value of λ (see below) and the value of *C* is not well-defined, as it depends on the rate at which heat is transferred from the surface layers of the ocean to the deep ocean.

2.3 Climate feedbacks

The value of λ is a chronic uncertainty in climate change science. If the Earth and atmosphere emitted to space as a black-body, Stefan's Law would give the OLR as σT_e^4 where σ is the Stefan-Boltzmann constant and T_e is an effective emitting temperature of the climate system. In this case, the first derivative of Stefan's Law is $4\sigma T_e^3$, and its reciprocal would give λ. For an OLR of 240 W m^{-2}, λ would be about 0.3 K (W m^{-2})$^{-1}$, indicating that the planet would warm up by 0.3 K for each W m^{-2} of forcing. This is sometimes referred to as the "black-body" or "no-feedback" response.

However, as the Earth warms (or cools) a number of feedback processes occur that alter the radiative properties of the atmosphere and surface. For example, in response to a positive RF, a warmer atmosphere can contain more water vapour; water vapour is a greenhouse gas and hence this further enhances the warming – giving a positive feedback. Similarly, a warmer planet would be expected to have a decreased extent of snow and ice – this would decrease the amount of solar radiation reflected back to space leading to a further warming. These two feedbacks are believed to be relatively well understood (e.g., IPCC, 2013); together they approximately double the value of λ from its black-body value.

From the late 1970s it was recognised that numerical climate models developed in different laboratories gave significantly different values for λ. It is now understood that the prime reason for this is the way that these models represent the response of clouds to climate change. A principal difficulty is that climate models represent the Earth's climate on a horizontal grid of order of 100 km spacing – many important climate processes, including those that control clouds, occur on much smaller spatial scales, and these have to be related in some way to the variables (such as temperature and humidity) that are represented on the model grid. An additional difficulty has been that many important parameters describing clouds (such as the amount of cloud ice) had not been observed globally; it had been difficult to verify the quality of a climate model's representation of clouds. A new generation of satellite instruments is starting to greatly improve this situation (e.g., Boucher *et al.*, 2013).

Clouds strongly influence OLR and ASR and have the potential to be a powerful feedback mechanism. Many cloud characteristics influence OLR and ASR – for example, cloud amount, height, thickness, and the proportion that is ice or water. Any or all these could change as climate changes and even if climate models have a faithful representation of present-day clouds, this does not guarantee that they can faithfully represent changes in properties. The most recent IPCC scientific assessment (IPCC, 2013) reports that λ is likely to lie in the range from about 0.4 to 1.2 K (W $m^{-2})^{-1}$; this indicates that climate models vary from having a weak to a strong positive cloud feedback.

There are many other possible climate feedbacks (IPCC, 2013) – for example, climate change can impact the way the oceans and land take up CO_2. The so-called carbon-climate feedback is an important focus of current research, and may be a significant positive feedback.

2.4 Limitations in the use of radiative forcing

Several caveats are necessary in using Equation (4) (see also Myhre *et al.*, (2013)). It was originally thought that the value of λ was approximately independent of the nature of the climate change mechanism. So, for example, if RF was due to a change in the output of the Sun (which influences the ASR) the value of λ would be the same as for changes in CO_2 (which mainly influences the OLR). More recent calculations now show that λ varies significantly amongst climate change mechanisms. This effect can be characterised by an "efficacy", defined as the ratio of λ for the given climate change mechanism, to λ for a CO_2 doubling. Ponater *et al.* (2006) present efficacies for a range of aviation-induced RFs. To be confident that efficacies are robustly known, careful comparison of results from similar experiments with different climate models is necessary – no consensus yet exists; it is assumed here that all climate change mechanisms possess the same value of efficacy. Once a consensus emerges, it would be better to compare climate change mechanisms using the product of efficacy and RF, or else (as proposed in Myhre *et al.*, (2013)) to use a variant of the RF called the "effective RF".

A second caveat is that Equation (4) refers strictly to global-mean quantities. This is important, for two reasons. Firstly, Equation (4) cannot be applied locally – the value of RF at a given location is not a good indicator of the temperature response at that location. This is because winds and ocean currents transport heat around the planet – the geographical pattern of response is more strongly determined by the nature of the feedbacks than the distribution of the forcing (e.g., Boer and Yu, 2003; IPCC, 2013). For example, snow/ice feedback leads to a greater response at higher latitudes. Secondly, it is easy to imagine cases where the global-mean RF is zero (due to chance compensation between mechanisms causing positive and negative RF) – even though the global-mean temperature change may be close to zero, significant local climate change could still occur.

The final caveat discussed here, is that there are *many* other dimensions to climate change beyond RF and ΔT – for example, changes in precipitation, extreme storms, sea level rise, which are also important in terms of impact on society. These are represented in the more complex models, but not in the simpler representations encapsulated by Equation (2).

Most of the work on aviation and climate change has concentrated on calculating RF and hence RF will be the focus here.

3. RADIATIVE FORCING DUE TO AVIATION

The RF due to the accumulated emissions from aviation is summarized in Figure 1, from Lee *et al.* (2009), the most recent detailed assessment. The total size of each bar gives the best estimate RF for 2005, relative to pre-industrial times, with the numerical value shown in the first column on the right hand side. The white line shows the value estimated in Forster *et al.* (2007) (which is repeated in parentheses in the first column on the right hand side). The error bar represents the 90% likelihood range, which comes from a mixture of the range of published values and expert judgement. The middle column on the right hand side indicates the spatial scale of the forcing. The final column gives the level of scientific understanding (LOSU), based on expert judgement, taking into account the difficulties in calculating the forcing. Figure 2 illustrates typical latitudinal distributions of many of these forcings.

It would, of course, be desirable if these RFs could be observed directly. It is only rarely that this is possible (for example, the effect of large volcanic eruptions or changes in the sun's output, which has only become possible relatively recently with the advent of satellite-based observations). There are various reasons for this. Firstly, the deviations in NET due to RF are relatively small and their detection would require a long sequence of well-calibrated satellite observations. Secondly, any observed variation in NET is due to both RF and the response of the climate to that forcing and it is difficult to untangle these. Thirdly, in this context, even if RF could be observed, it would be difficult to unravel how much is due to aviation and how much is due to other human activity – as will be shown, the effects of aviation are only a small percentage of the total. As a result, RF calculations generally depend heavily on computer simulations – in addition to uncertainties due to an incomplete understanding of atmospheric processes, calculations are reliant on assumed distributions of emissions of CO_2 and other gases and particles from aviation – there are significant differences in these distributions in recent inventories (e.g., Wilcox *et al.*, 2013).

It is important to note that aviation-induced effects have a wide variety of different timescales. For CO_2, a significant fraction (several 10's of %) of any perturbation, as a result of an aviation (or any other) emission, persists in the atmosphere for thousands of years (Archer and Brovkin, 2008; IPCC, 2013) – this is because of the way CO_2 changes lead to changes in the oceanic carbon cycle. Hence, the CO_2 RF in Figure 1 results from emissions over the entire time-period that aircraft have been emitting. At the other extreme, contrails typically persist for at most a few hours. Hence the entire RF due to linear contrails is a result of *very* recent aviation activity. One consequence of these different timescales is to consider the hypothetical case in which all aviation emissions suddenly cease. The RF due to linear contrails would disappear almost immediately; the CO_2 RF would persist for centuries. These issues of timescale will be considered again in Section 4. There has been no consolidated update of Figure 1 in the recent literature, but changes due to improved understanding will be indicated in the sections below.

3.1 Carbon dioxide

CO_2 is an effective greenhouse gas as it possesses strong absorption bands at thermal-infrared wavelengths, notably near 15 μm. On a per molecule basis, CO_2 is relatively weak, partially because of the large natural CO_2 concentrations. However, this relative weakness is compensated by the fact that the absolute changes in CO_2 concentration are much higher than those of other greenhouse gases emitted by human activity.

CO_2 is the easiest of all aviation forcings to consider; its lifetime in the atmosphere (decades to millennia) is so long, that there is essentially no climate difference between CO_2 produced from burning kerosene in a jet engine to CO_2 produced from burning any fossil fuel, anywhere else in the globe. The timescales over which the winds spread out any CO_2 emission across the planet (many months) are much shorter than the lifetime of the CO_2 in the atmosphere.

Figure 1 shows that the estimated CO_2 RF from aviation emissions up to 2005 is 28 mW m^{-2}, with a high LOSU and it is clearly one of the largest single components. The value for 2011 is likely to be about 10-15% higher because of growth in emissions. Figure 2 shows that the forcing is global in extent.

3.2 Oxides of nitrogen

The emission of oxides of nitrogen (NO_x) by aviation leads to a complex chain of chemical effects (see eae347.pub2), making the evaluation of the net RF challenging. NO_x causes an increase in ozone. Ozone absorbs ultra-violet and visible radiation and has thermal-infrared absorption bands, notably at wavelengths near 10 μm. This ozone forcing is positive; Figure 1 shows this forcing is, within the uncertainty bars, the same size as the CO_2 forcing, although more recent analyses indicate that it may be around 20% smaller (e.g., Søvde *et al.*, 2014).

The ozone change has a knock-on effect in increasing the concentration of the hydroxyl radical, OH, which plays a key role in controlling the concentrations of many atmospheric species. In the context of climate change, the most important is methane (CH_4), which is a powerful greenhouse gas (about 24 times CO_2 on a per molecule basis) – more OH means that CH_4 is more readily destroyed, and hence CH_4 concentrations are reduced. (Methane concentrations have increased since pre-industrial times (e.g., Myhre *et al.*, 2013) as a result of all human activity, but NO_x emissions are believed to have reduced that rate of increase.) Hence the CH_4 reduction by aviation causes a negative RF which Figure 1 shows to be around 50% of, but opposite in sign to, the ozone forcing.

There are several further consequences of the CH_4 reduction (e.g., Myhre *et al.*, 2013). One of these is that methane itself is important for ozone formation; the loss of methane leads to an ozone reduction which offsets the ozone increase generated by the NO_x increase. Several recent publications (e.g., Søvde *et al.*, 2014) indicate the net effect of aviation NO_x emissions is smaller than indicated in Figure 1, at around 5(±4) mW m^{-2}, because of improved understanding of atmospheric processes.

There are additional complications concerning NO_x. Firstly, the impact on ozone depends strongly on the altitude and latitude where NO_x is emitted. The values in Figure 1 refer to the present-day fleet, concentrated as it is in the northern mid-latitudes in the upper troposphere and lower stratosphere. If the height or geographical distribution of emissions changes, so too could the NO_x RF. Secondly, while the O_3 and CH_4 forcings cancel to some extent in the global mean, they do not do so locally. Figure 2 shows that the ozone forcing, for the present-day fleet, is concentrated in northern mid-latitudes; by contrast, because CH_4 is relatively long lived (with a lifetime of 10 years), the reduction spreads across the globe, and is roughly equal in both hemispheres. Hence, in the northern hemisphere, the positive ozone forcing dominates, while in the southern, the negative CH_4 forcing dominates. This is an example of where an apparently small global-mean forcing may still lead to a significant regional climate impact.

3.3 Water vapour

Burning kerosene leads to water vapour being emitted by aviation. Water vapour is a strong greenhouse gas and the main contributor to the natural greenhouse effect. Aviation water vapour emissions within the troposphere are not believed to lead to any significant concentration changes – the vigour of the natural hydrological cycle is such that the lifetime of water vapour molecules is around 7 days, and it is not possible to accumulate large changes in concentration. However, in the stratosphere, the lifetime is considerably longer (many months) allowing more marked changes to occur. The tropopause, which separates the troposphere from the stratosphere, varies with location, season and with particular weather systems, but broadly varies from around 8 km in high latitudes to 16 km in the tropics. The civil aviation fleet spends a considerable amount of time in the lower stratosphere (e.g., Gauss *et al.*, 2003) especially during northern-hemisphere winter when, on average, the tropopause is lower in altitude.

Figure 1 shows that the water vapour RF to be modest (3 mW m^{-2}) and an order of magnitude smaller than CO_2. More recent assessments (e.g., Wilcox *et al.*, 2012) indicate it could be smaller still (1 mW m^{-2}, with a likely upper limit of 1.4 mW m^{-2}). However, as discussed in IPCC (1999), were future fleets of supersonic aircraft to fly in the stratosphere, water vapour might become the dominant RF, as most of the emissions would occur at altitudes where its lifetime is long.

3.4 Aerosol

Aerosol particles emitted by aircraft engines, or forming within the exhaust plume, can influence RF by absorbing and/or scattering solar radiation; they are generally too small (being sub-micron in size) to significantly influence thermal-infrared radiation.

Sulphate aerosols are generally non-absorbing, especially at visible wavelengths; they cause an RF by scattering solar radiation, and hence exert a negative RF. Figure 1 shows a small RF (-5 mW m^{-2}). By contrast, soot particles are highly absorbing at visible wavelengths and absorb solar radiation that would otherwise be scattered to space. Hence they exert a positive RF which is roughly equal in size (3 mW m^{-2}), but opposite in sign to the sulphate forcing. Recent simulations (Gettelman and Chen, 2013; Righi *et al.*, 2013) are broadly supportive of values of around this size.

This indicates that aerosols are not a major direct contributor to aviation RF. Nevertheless, they play an important role in contrail formation (see eae352.pub2) and may significantly alter the properties of natural clouds. These topics are covered in the following sub-sections.

3.5 Contrails

Aircraft contrails are, arguably, the most obvious visible sign of human activity on the atmosphere, especially for those living beneath busy flight tracks. Of interest here are so-called persistent contrails, which form when an aircraft flies through a sufficiently cold layer which is supersaturated with respect to ice (see eae352.pub2). These contrails may last for a few hours.

There are many difficulties in estimating the RF due to contrails. Firstly, although contrails can be clearly seen in satellite images, reliable global climatologies of their horizontal coverage have not yet been developed. This requires pattern-recognition techniques that can reliably distinguish contrails from other clouds. To date detailed analysis of satellite images are available over more restricted areas and time periods. These are then used together with modelling techniques (which combine meteorological data and flight inventories) to provide a global estimate of contrail occurrence. Typical estimates are that, on a global average, about 0.05 to 0.1% of the sky is covered by contrails at any one time (e.g. Myhre and Stordal, 2001; Spangenberg *et al.*, 2013).

A second difficulty is that RF calculations require additional information on contrail properties, such as their thickness, and the number, size and shape of the ice crystals that make up the contrail. Data is available only for a limited number of case studies and many assumptions must be made for global calculations.

The final difficulty discussed here concerns the fact that the net contrail RF is a small residual of opposing longwave and shortwave RF. Contrails reflect solar radiation, causing a negative RF, and trap thermal-infrared radiation decreasing the *OLR* and causing a positive RF.

On an annual and global average, it is believed that the thermal-infrared RF dominates – Figure 1 indicates a global and annual mean RF of around 12 mW m^{-2}; a number of other recent studies have derived values of 10 mW m^{-2} or less (e.g., Boucher *et al.,* 2013; Burkhardt and Kärcher 2011; Spangenberg *et al.,* 2013).

Because contrails are so short-lived, they persist only in areas of high aircraft traffic, and hence the resulting forcing is also very inhomogeneous (Figure 2). Also, the contrail forcing varies significantly during the day, as the compensation between the thermal-infrared and the shortwave RF depends on the availability of sunlight (Myhre and Stordal 2001; Stuber et al., 2006). Thus at night, the thermal-infrared RF is the only component, whilst in the day, the net forcing can be negative, if the shortwave RF dominates. It has not yet been established whether this day-night difference significantly influences the climatic effect of contrails.

The simulations of Ponater *et al.* (1996) and Rap *et al.* (2010) indicate that contrail RF may be less effective at causing a surface temperature change because their efficacy (see Section 2.4) may be significantly less (0.6 and 0.3 respectively) than that of CO_2. It will be important to see if further simulations find similarly low values.

There were claims of a clear climatic effect, resulting from the absence of contrails, following the grounding of US civil aircraft, after the 9/11 terrorist attacks (Travis *et al.,* 2004). These conclusions have been robustly challenged by a number of studies (e.g., Deitmuller *et al.,* 2008).

3.6 Aviation-induced cloud changes

Aviation-induced cloud (AIC) changes are probably the most uncertain aviation RF but have the potential to be one of the most important.

Following Lee *et al.* (2009), two distinct AIC effects are discussed. First, persistent contrails (see Section 3.5) can spread to form cirrus-like clouds which seem indistinguishable from natural cirrus clouds – this is referred to here as the direct AIC forcing. There is clear evidence that contrails do evolve into cirrus-like clouds (e.g., Minnis *et al.,* 1998). The many difficulties in quantifying this forcing include the problem of knowing whether natural cirrus clouds would have formed in any case, whether the aviation emissions impact on natural cirrus, and defining the properties of the AIC (e.g., Burkhardt and Kärcher, 2011). The mid-range estimate for this RF of 30 mW m^{-2} (see Figure 1) has been revised upwards to 40 mW m^{-2} for 2011, in IPCC's recent assessment (Boucher *et al.,* 2013) making it the largest single aviation-induced RF. However the uncertainty in this estimate is around a factor of three, indicating low confidence.

Second, sulphate aerosols due to surface-based emissions may cause a significant negative RF by influencing the properties of low-altitude clouds (e.g. Boucher *et al.,* 2013). Sulphate and black carbon aerosols from aviation could have a similar effect. There are formidable difficulties in performing such calculations because of uncertainties in microphysical processes in clouds and how they are affected by changing aerosol concentrations. Nevertheless recent modelling studies indicate that the effect of sulphate emissions on clouds might cause a negative RF of several tens of mW m^{-2} (Righi *et al*., 2013; Gettelman and Chen, 2013). This would make it almost as important as, but opposite in sign to, the direct AIC RF; much further work is clearly necessary.

3.7 Summary and comparison with the total impact of human activity.

Figure 1 shows the total RF in 2005 due to aviation both excluding (55 mW m^{-2}) and including (78 mW m^{-2}) the central estimate for the direct AIC RF. This indicates that the total aviation RF is between 2 or 3 times the aviation CO_2 RF alone, although the level of scientific understanding is low for the total forcing. Growth in aviation emissions and recent research on the RF due to NO_x and the effect of sulphate emissions on clouds, would likely lead to broadly similar figures for the 2011 RF but a detailed assessment is not yet available.

These numbers can be compared to estimates of the total RF due to human activity (Myhre *et al.*, 2013) for 2011 relative to pre-industrial times. The total CO_2 RF is estimated to be 1.8 W m^{-2} (±10%, with high level of scientific understanding), with the total RF due to human activity of about 2.3 W m^{-2}; the uncertainty in this value is about 50%.

Lee *et al.* (2009) estimate that aviation CO_2 currently contributes around 1.6% of the total anthropogenic CO_2 RF, while the total aviation RF is 3.5% without or 4.9% with the direct AIC RF. Lee *et al.* (2009) present results from Monte Carlo simulations using uncertainty estimates and find the 90% uncertainty ranges of the contribution of aviation to the total anthropogenic RF range from 1.3 to 10% if direct AIC RF is excluded, and from 2 to 14% if the direct AIC RF is included.

No attempt is made here to provide projections of the future contribution of aviation to total RF but this is discussed in Lee *et al.* (2009). Many factors inhibit a confident prediction. The total anthropogenic RF depends heavily on future changes in population, economic growth and technological developments and the extent to which any international climate treaties influence emissions. The aviation RF depends on such developments and also depends on whether any changes to the operation of the present and future fleets (e.g. cruise altitude) occur.

4. EMISSION INDICES

4.1 General considerations

The diverse range of aviation emissions leads to questions about whether they can be placed on a common scale for comparison. There are several possible reasons for doing this. One is a technological – if there is a change in design or operation of an aircraft, does this change its climate impact? For example, contrails could be avoided by flying lower, but this would likely entail increased fuel use and increased CO_2 emissions. Is this desirable? A second purpose might be in a legislative context, where the effects of non-CO_2 emissions of aviation (or any other sector) are required to be taken into account to provide a fuller picture of the total impact. A related purpose is where companies provide consumers with the opportunity to pay towards schemes to offset the climate impact of their air travel, which could include the effect of non-CO_2 emissions.

RF is one potential index for making comparisons – indeed, one index is the ratio of the total forcing to the CO_2-only forcing – this is sometimes called the Radiative Forcing Index (RFI) or, simply, a CO_2 multiplier. In this usage, the climate impact of the CO_2 is then multiplied by the RFI (which, according to Lee *et al.*'s (2009) estimates would be about 2 or 3) to get a total climate impact. RF and RFI are useful for looking at the cumulative effect of past aviation emissions, but less suited for looking at the future effects of current emissions. Hence, the use of the RFI has been heavily criticised (see e.g. Fuglestvedt *et al.* 2010) as it fails to account for the different lifetimes of the emissions (ranging from hours for contrails to millennia for much of the CO_2 emitted); also it represents a fixed tax on fuel use (and hence CO_2 emissions) which might encourage perverse behaviour whereby attempts are made to decrease CO_2 emissions regardless of the impact on the non-CO_2 emissions.

There are many difficulties in constructing a robust index (e.g., Fuglestvedt *et al.* (2010)). These include: (i) exactly what climate parameter should be compared? The RF, the temperature change or perhaps some time-integral of these effects? (ii) Over what period should the parameters be calculated? Is it the climate impact in the decade or so following an emission, or should some longer-term impact be considered? (iii) How are the uncertainties in the effect of emissions taken into account? As will be shown, answers to (i) and (ii) have a profound influence on the perception of the relative importance of the CO_2 and non-CO_2 emissions. There is as yet no widely accepted way of comparing the climate effect of aircraft emissions and some choices, such as the time period of calculation, are value-laden decisions that must be made by policymakers.

4.2 The Global Warming Potential and the Global Temperature-change Potential

IPCC has, since its early assessments, presented an emissions index called the Global Warming Potential (GWP). If a pulse emission of, say, 1 kg of a gas is emitted into the atmosphere, the pulse decays (exponentially for many emissions) over some time period as it is removed from the atmosphere. The GWP represents the time-integral of the RF due of this decaying pulse – this means that the lifetimes of the gas, as well as its radiative strength are taken into account. It is normally presented as the ratio of a gas's GWP to that of CO_2. The GWP (integrated over a 100 year "time horizon") was adopted for the Kyoto Protocol to the United Nations Framework Convention on Climate Change, to allow Protocol signatories to decide which, of a range of greenhouse gases, to control to meet its commitments. So, for example, the mass of methane emitted in a given year can be cast in "CO_2-equivalence" terms by multiplying it by 28, the current estimate for methane's100-year GWP (Myhre *et al.*, 2013). There have been a range of criticisms of the GWP as a concept and recognition of particular difficulties in calculating its values for short-lived species such as NO_x (see Fuglestvedt *et al.* 2010 and references therein), but nevertheless it is widely used.

An alternative index, called the Global Temperature-change Potential (GTP) has also been proposed – this gives the temperature change at some specified time after a pulse emission into the atmosphere. The GTP has not achieved the level of acceptance of the GWP, but it may be more suited to certain types of climate policy (see Myhre *et al.*, 2013) although it is also subject to criticism; nevertheless, it illustrates the influence of different choices in the design of emission indices. Because it looks at the temperature change some time after an emission, rather than integrating the effect of an emission over time, in general it indicates a lesser impact for the short-lived non-CO_2 emissions from aviation. The actual values of the GTP depend on the assumptions about the values of λ and C (see Section 2).

Tables 1 and 2 illustrate typical GWP and GTP values for aviation emissions, based on values in Fuglestvedt *et al.* (2010). It is emphasized that these values refer to the average effect of the present-day aircraft fleet – they cannot be applied to the effect of a single flight (for which, for example, the meteorological conditions may not allow contrail formation) and cannot be applied if there were significant changes to, for example, the altitudes or latitudes at which the fleet flies – the effect of NO_x and contrails are highly dependent on where the emissions occur. Some information on the height and latitude dependence can be found in, for example, Grewe and Stenke (2007), Rädel and Shine (2009) and Søvde *et al.* (2014). Finally, the values presented in the Tables are subject to significant revisions as scientific understanding increases.

Each Table shows the values relative to CO_2. The GWP is presented for three time horizons (20, 100, 500 years) which are the conventional values presented by IPCC. The GTP is presented for 20, 50 and 100 years, as this is felt to be more appropriate for such an index; in any case, for longer time periods, the non-CO_2 emissions from aviation would quickly decay to zero, as they are so short-lived compared to CO_2.

The values are presented as the effect of burning 1 kg of fuel, relative to the effect of the CO_2 from this 1 kg of fuel. For each kg burnt, 3.16 kg of CO_2, 1.23 kg of H_2O and 0.015 kg of NO_2 are assumed to be emitted – the NO_2 number is the most uncertain, as it is dependent on the way kerosene is burnt. Values are presented for "high NO_x" and "low NO_x" to reflect the range of RF values currently in the literature. The bottom 4 lines in the Tables show how much the CO_2 effect has to be multiplied to incorporate the non-CO_2 effects; it is given for the two NO_x cases and with and without AIC, because of the particularly high uncertainty. These rows could be considered as an analogue for the RFI, but posed in terms of the future effect of present-day emissions.

Table 1 shows that for all components, the GWP decreases with time horizon – this is because the values are referenced to CO_2, a significant component of which remains in the atmosphere for much longer than 500 years; hence the part of the CO_2 pulse that remains in the atmosphere even at 500 years continues to contribute to (the integral of) RF, whereas the RF from the short-lived components have long since decayed to zero. It can be seen that the sign of the NO_x component changes, as this is determined by the relative balance of the effect of the created ozone and the destroyed methane. The CO_2 multiplier rows show different combinations of the total effect. This clearly illustrates that the multiplier to be applied to CO_2 to account for the non-CO_2 emissions varies greatly depending on the chosen time horizon, and on which effects are considered, from 1.1 to 4.9.

Table 2 shows the GTP drops off much more quickly with time horizon than the GWP (compare the 20 and 100 year values in Tables 1 and 2); because of the nature of the GTP, it retains less memory of short-lived effects than the GWP. NO_x values are generally negative, because the cooling due to methane dominates over the warming due to ozone. Fuglestvedt *et al.* (2010) discuss the reasons for the behaviour of these values. In general, the CO_2 multiplier values are much smaller than for the GWP and indeed, can be less than unity for some cases, where the methane-induced cooling has a strong influence. In the cases given, the multiplier ranges from 0.4 to 1.6.

5. CONCLUSION

Aviation causes climate change as a result of its emissions of CO_2, oxides of nitrogen, aerosols and water vapour. While the RF due to changes in CO_2 is as well-characterised as those from other sources due to human activity, there are formidable difficulties in estimating the non-CO_2 forcings – this is particularly the case for the aviation-induced changes in cloudiness (AIC). The best-estimate of total radiative forcing to 2005, from aviation, using values from the most recent comprehensive assessment (Lee *et al.* 2009) is 55 mW m^{-2} excluding AIC and 78 mW m^{-2} including it, with an uncertainty of at least a factor of two; these values are likely broadly appropriate for 2011 given recent developments in understanding. The 2005 aviation CO_2 RF represents about 1.6% of the total CO_2 forcing from all human activities. It is estimated that, including the non-CO_2 effects, aviation contributes between 1.3 and 14% of the total RF due to all human activities.

Two distinct methods for comparing the future impact of present-day aviation emissions are presented – the Global Warming Potential and the Global Temperature-change Potential. The perception of the relative importance of the non-CO_2 emissions, relative to CO_2 depends considerably on the chosen method and the parameters chosen within that method. Of particular importance is the choice of the time-scale over which the effects are compared – in general, the longer the time scale that is chosen, the more important CO_2 becomes, relative to the non-CO_2 emissions.

Improvement in estimates of RF will require advances in our understanding of atmospheric processes, better techniques for numerical modelling of these processes and more detailed, and sustained, observations, using both *in situ* and remote sensing techniques.

REFERENCES

Archer D and Brovkin V. The millennial atmospheric lifetime of anthropogenic CO_2 *Climatic Change* 2008; **90**:283–297.

Boer GJ and Yu B. Climate sensitivity and response. *Climate Dynamics* 2003; **21**:415–429.

Boucher O, Randall D, Artaxo P, Bretherton C, Feingold G, Forster P, Kerminen V-M, Kondo Y, Liao H, Lohmann U, Rasch P, Satheesh SK, Sherwood S, Stevens B and Zhang XY. Clouds and Aerosols. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V and Midgley PM (eds.)) . Cambridge University Press, Cambridge UK, 2013.

Brasseur GP, Cox RA, Hauglustaine D, Isaksen I, Lelieveld J, Lister DH, Sausen R, Schumann U, Wahner A and Wiesen P. European scientific assessment of the atmospheric effects of aircraft emissions. *Atmos. Environ.* 1998; **32**:2329–2418.

Burkhardt U and Kärcher B. Global radiative forcing from contrail cirrus. Nature Climate Change. 2011; 1:54-58.

Dietmuller S, Ponater M, Sausen R, Hoinka KP and Pechtl S. Contrails, natural clouds, and diurnal temperature range. J.Climate. 2008; **21**: 5061-5075.

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M and Van Dorland R. Changes in atmospheric constituents and in radiative forcing. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M and Miller HL (Eds.)], Cambridge University Press, Cambridge, United Kingdom 2007.

Fuglestvedt JS, Shine KP, Berntsen T, Cook J, Lee DS, Stenke A, Skeie RB, Velders GJM and Waitz IA. Transport Impacts on Atmosphere and Climate: Metrics. *Atmos. Environ*. 2010; **44:**4648-4677.

Gauss M, Isaksen ISA, Wong S and Wang W.-C. Impact of H_2O emissions from cryoplanes and kerosene aircraft on the atmosphere. *J. Geophys. Res.*, 2003; **108**:4304.

Gettelman A and Chen C. The climate impact of aviation aerosols, *Geophys. Res. Lett.*, 2013; **40**:2785–2789.

Grewe V and Stenke A. AirClim: an efficient tool for climate evaluation of aircraft technology. Atmos. Chem. Phys. 2008; **8**:4621–4639.

Hartmann DL. Global Physical Climatology. Academic 1996.

IPCC. *Aviation and the global atmosphere*. Penner JE, Lister DH, Griggs DJ, Dokken DJ and McFarland M (Eds.), Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK 1999.

IPCC. *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change . Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V and Midgley PM (eds.). Cambridge University Press, Cambridge, UK. 2013.

Lee DS, Fahey DW, Forster PM, Newton PJ, Wit RCN, Lim LL, Owen B and Sausen R. Aviation and global climate change in the 21st century. *Atmos. Environ.* 2009; **43**:3520-3537

Lee DS, Pitari G, Berntsen T., Grewe V, Gierens K, Penner JE, Petzold A, Prather M, Schumann U, Bais A, Iachetti D and Lim LL. Transport impacts on atmosphere and climate: aviation, *Atmos. Environ*. 2010; **44**:4678-4734.

Matthews WH, Kellogg WW and Robinson GD (Eds). Man's impact on climate, MIT Press, Cambridge Mass, 1971.

Minnis P, Young DF, Garber DP, Nguyen L, Smith WLJ and Palikonda R. Transformation of contrails into cirrus during SUCCESS. *Geophys. Res. Lett.* 1998; **25**:1157–1160.

Myhre G and Stordal F. On the tradeoff of the solar and thermal infrared radiative impact of contrails. *Geophys. Res. Lett.* 2001; **28**:3119–3122.

Myhre G, Shindell D, Bréon F-M, Collins W, Fuglestvedt J, Huang J, Koch D, Lamarque J-F, Lee D, Mendoza B, Nakajima T, Robock A, Stephens G, Takemura T and Zhang H. Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V and P.M. Midgley PM (eds.)) . Cambridge University Press, Cambridge UK, 2013.

Ponater M, Pechtl S, Sausen R, Schumann U and Hüttig G. Potential of the cryoplane technology to reduce aircraft climate impact: A state-of-the-art assessment. *Atmos. Environ*. 2006; **40**:6928–6944.

Rädel G and Shine KP. Radiative forcing by persistent contrails and its dependence on cruise altitudes. *J. Geophys. Res*. 2008; **113**:D07105.

Rap A, Forster PM, Haywood JM, Jones A and Boucher O. Estimating the climate impact of linear contrails using the UK Met Office climate model. *Geophys. Res. Lett.* 2010; **37**:L20703.

Righi M, Hendricks J and Sausen R. The global impact of the transport sectors on atmospheric aerosol: simulations for year 2000 emissions. *Atmos. Chem. Phys.* 2013; **13**:9939-9970.

Søvde OA, Matthes S, Skowron A, Iachetti D, Lim L, Owen B, Hodnebrog Ø, Di Genova G, Pitari G, Lee DS, Myhre G and Isaksen ISA. Aircraft emission mitigation by changing route altitude: A multi-model estimate of aircraft NOx emission impact on O_3 photochemistry, *Atmos. Environ.* 2014; **95**:468-479.

Spangenberg DA, Minnis P, Bedka ST, Palikonda R, Duda DP and Rose FG. Contrail radiative forcing over the Northern Hemisphere from 2006 Aqua MODIS data, *Geophys. Res. Lett.* 2013; **40**:595–600.

Stuber N, Forster P, Rädel G and Shine KP. The importance of the diurnal and annual cycle of air traffic for contrail radiative forcing. *Nature* 2006; **441**:864–867.

Travis DJ, Carleton AM and Lauritsen RG. Regional variations in US diurnal temperature range for the 11-14 September 2001 aircraft groundings: Evidence of jet contrail influence on climate. *J. Climate* 2004; **17**:1123-1134.

Wilcox LJ, Shine KP and Hoskins BJ. Radiative forcing by aviation water vapour emissions. *Atmos. Environ.* 2012; **63**:1-13.

Table 1: Estimates of the Global Warming Potential for three time horizons for aviation emissions, relative to CO_2 for the present-day aviation fleet for each kg of fuel burnt. The bottom 4 rows show how much the CO_2 effect, for each kg of fuel burnt, should be multiplied to account for the non-CO_2 effects.

	Time Horizon (years)		
	20	**100**	**500**
NO_x (high estimates)	0.68	0.10	0.03
NO_x (low estimates)	0.17	-0.003	-0.001
Contrails	0.74	0.21	0.064
Aviation-induced cloud (AIC)	2.2	0.63	0.19
Water vapour	0.27	0.078	0.023
CO_2-multiplier (NO_x high, no AIC)	2.7	1.4	1.1
CO_2-multiplier (NO_x high, including AIC)	4.9	2.0	1.3
CO_2-multiplier (NO_x low, no AIC)	2.2	1.3	1.1
CO_2-multiplier (NO_x low, including AIC)	4.4	1.9	1.3

Table 2: Estimates of the Global Temperature-change Potential for three time horizons for aviation emissions, relative to CO_2 for the present-day aviation fleet for each kg of fuel burnt. The bottom 4 rows show how much the CO_2 effect, for each kg of fuel burnt, should be multiplied to account for the non-CO_2 effects.

	Time Horizon (years)		
	20	**50**	**100**
NO_x (high estimates)	-0.29	-0.09	0.01
NO_x (low estimates)	-0.85	-0.30	-0.01
Contrails	0.21	0.04	0.03
Aviation-induced cloud (AIC)	0.64	0.11	0.09
Water vapour	0.08	0.01	0.01
CO_2-multiplier (NO_x high, no AIC)	1.0	1.0	1.1
CO_2-multiplier (NO_x high, including AIC)	1.6	1.1	1.1
CO_2-multiplier (NO_x low, no AIC)	0.4	0.7	1.0
CO_2-multiplier (NO_x low, including AIC)	1.1	0.9	1.1

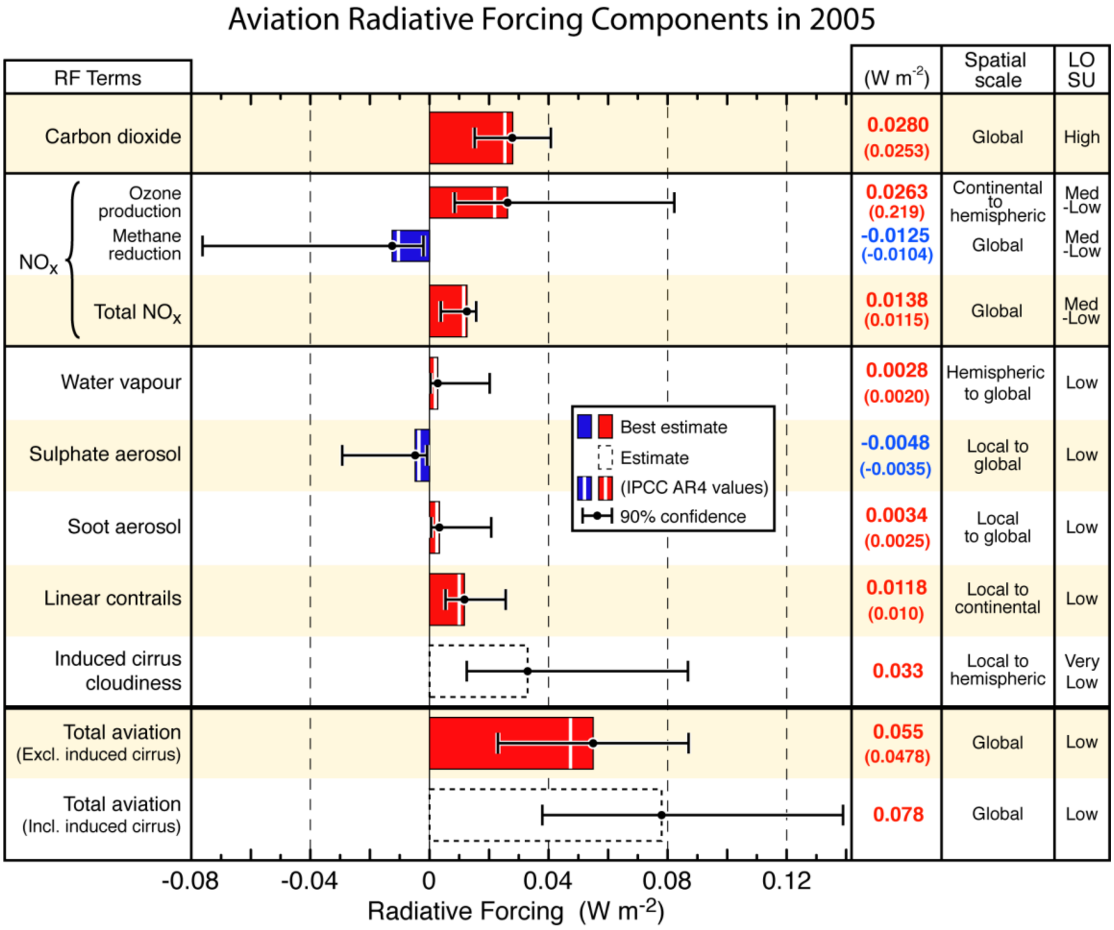

Figure 1. Global-mean radiative forcing components due to aviation for 2005, relative to preindustrial times. Coloured bars represent best estimates (except for the case of aviation-induced cloud changes (AIC) where a best-estimate cannot be given). Values indicated by the white lines within the bars are from Forster *et al.* (2007). The induced cloudiness (AIC) estimate includes linear contrails. Numerical values are given on the right for both Forster *et al.* (2007) (in parentheses) and for Lee *et al.* (2009). Error bars represent the 90% likelihood range for each estimate. The best estimate value of total radiative forcing from aviation is shown with and without AIC. The spatial scale of each radiative forcing and its level of scientific understanding (LOSU) are shown in the columns on the right. Reproduced from Lee *et al.* (2009) © Elsevier.

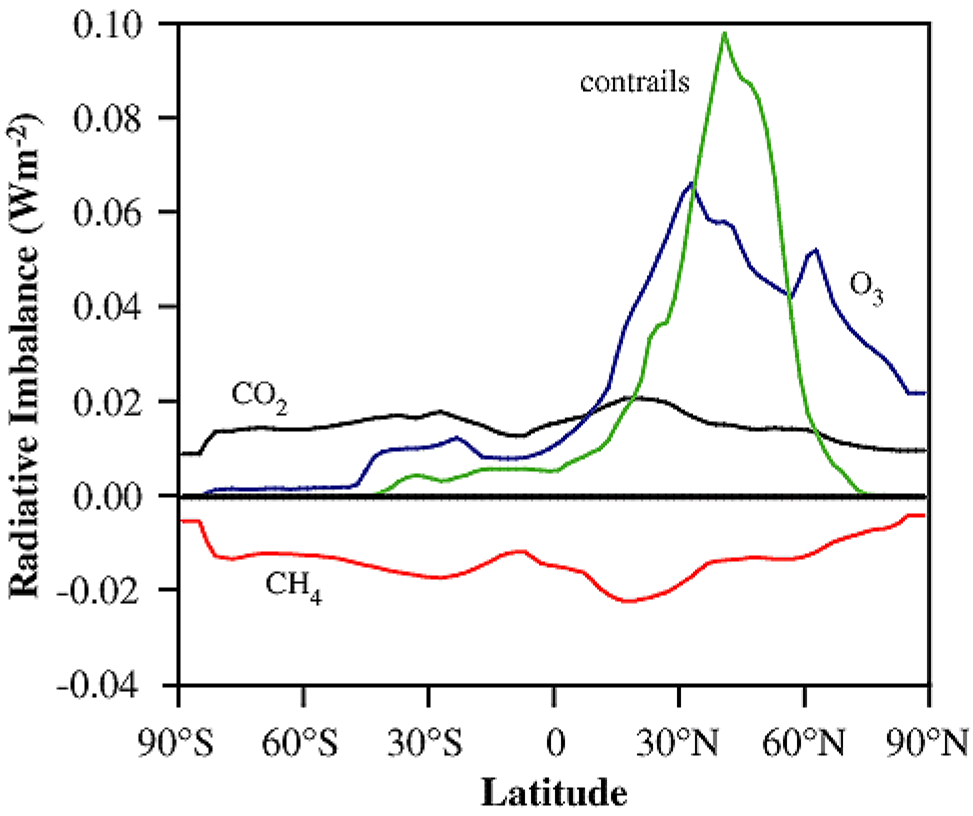

Figure 2: Radiative forcing as a function of latitude for global aviation in 1992, relative to pre-industrial times, for a number of aviation-induced forcings. Note that the global-mean of these values will not correspond to those in Figure 1, as they are for a different period and because of improvements in understanding. Reproduced from IPCC (1999) © Cambridge University Press.