

# *Radiative forcing and climate change*

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19

## 20 **RADIATIVE FORCING AND CLIMATE CHANGE**

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26

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29

30 Abstract

31

32 Aviation causes climate change as a result of its emissions of CO<sub>2</sub>, oxides of nitrogen,  
33 aerosols and water vapour. One simple method of quantifying the climate impact of  
34 past emissions is radiative forcing. The radiative forcing due to changes in CO<sub>2</sub> is best  
35 characterised, but there are formidable difficulties in estimating the non-CO<sub>2</sub> forcings  
36 – this is particularly the case for possible aviation-induced changes in cloudiness  
37 (AIC). The most recent comprehensive assessment gave a best-estimate of the 2005  
38 total radiative forcing due to aviation of about 55 to 78 mW m<sup>-2</sup> depending on whether  
39 AIC were included or not, with an uncertainty of at least a factor of two,. The aviation  
40 CO<sub>2</sub> radiative forcing represents about 1.6% of the total CO<sub>2</sub> forcing from all human  
41 activities. It is estimated that, including the non-CO<sub>2</sub> effects, aviation contributes  
42 between 1.3 and 14% of the total radiative forcing due to all human activities.

43 Alternative methods for comparing the future impact of present-day aviation  
44 emissions are presented – the perception of the relative importance of the non-CO<sub>2</sub>  
45 emissions, relative to CO<sub>2</sub>, depends considerably on the chosen method and the  
46 parameters chosen within those methods.

47

## 1 **1. INTRODUCTION**

2  
3 The possibility that aviation could contribute to climate change was considered in the  
4 earliest assessments of the climate impact of human activity (e.g., Matthews, Kellogg  
5 and Washington, 1971). In the subsequent period, considerable attention focused on  
6 examining the impact of possible future supersonic fleets on stratospheric ozone;  
7 aviation's impact on climate took a back seat. The European assessment by Brasseur  
8 *et al.* (1998) gave renewed vigour to the appraising the climate influence. This was  
9 followed by the wider-ranging report on "Aviation and the Global Atmosphere" by  
10 the Intergovernmental Panel on Climate Change (IPCC, 1999), which remains a basic  
11 reference. Lee *et al.* (2009, 2010) have provided updated assessments.

## 12 **2. CONCEPTUAL FRAMEWORK**

### 13 **2.1 Radiative forcing**

14  
15  
16  
17 The planetary energy balance can be characterised as a balance between two  
18 components: solar radiation (which is mostly at wavelengths less than 4  $\mu\text{m}$ )  
19 absorbed or reflected back to space by the Earth and its atmosphere, and longwave  
20 (thermal-infrared) radiation (which is mostly at wavelengths greater than 4  $\mu\text{m}$ )  
21 emitted and absorbed by the Earth's surface and atmosphere.

22  
23 At the top of the atmosphere, averaged over the globe and over a year, there is a close  
24 balance between the absorbed solar radiation (ASR) by the Earth system and the  
25 outgoing longwave radiation (OLR), so that the net radiation (NET)

$$26 \quad \quad \quad \text{NET} = \text{ASR} - \text{OLR} \approx 0. \quad (1)$$

27  
28  
29 Satellite observations show that the global and annual mean ASR and OLR are both  
30 about 240  $\text{W m}^{-2}$  (e.g., Hartmann, 1996).

31  
32 The main mechanisms which drive climate change perturb either or both the ASR or  
33 the OLR, so that  $\text{NET} \neq 0$ . More precise definitions are available (e.g., Myhre *et al.*,  
34 2013), but the size of the initial perturbation of NET, say following a change in  $\text{CO}_2$   
35 concentration, is a useful working definition of the radiative forcing (RF) of climate  
36 change. RF provides a useful first-order indication of the size of different climate  
37 change mechanisms and it will be a major focus here.

38  
39 Unless otherwise stated, RF is taken here to refer to its global-average value. RF can  
40 refer to the change in NET over any specified period of time. Forcing due to human  
41 activity is often reported as the total change since some "pre-industrial" time, for  
42 example since 1750. For aviation, the total present-day forcing has occurred over a  
43 much shorter period, as emissions were negligible prior to 1940 (e.g., Lee *et al.*,  
44 2009).

### 45 **2.2 Temperature response and climate sensitivity**

46  
47  
48 When RF is positive the planet is absorbing more energy than it is emitting (and vice  
49 versa if RF is negative); the climate system responds by warming, leading to more  
50 infrared emission and hence a higher OLR. Given sufficient time (and assuming that

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

3  
4 The simplest representation of the response of the climate system to a radiative  
5 forcing is given by Hartmann (1996) and Fuglestedt *et al.*, (2010)

$$6 \quad C \frac{d\Delta T(t)}{dt} = RF(t) - \frac{\Delta T(t)}{\lambda} \quad (2)$$

7  
8 where  $t$  is time,  $C$  is the heat capacity of the climate system (most of which is  
9 contained within the ocean) [ $\text{J K}^{-1} \text{m}^{-2}$ ],  $\Delta T$  is the departure of the global-mean surface  
10 temperature [K] from its unperturbed value, and  $\lambda$  is the climate sensitivity parameter  
11 [ $\text{K} (\text{W m}^{-2})^{-1}$ ].

12  
13 A useful special case is when RF is independent of time. The solution to Equation (2)  
14 is then

$$15 \quad \Delta T(t) = \lambda RF [1 - \exp(-t/\lambda C)]. \quad (3)$$

16  
17 As  $t$  tends to infinity, the equilibrium surface temperature  $\Delta T_{eq}$  is given by

$$18 \quad \Delta T_{eq} = \lambda RF. \quad (4)$$

19  
20 Hence, Equation (4) tells us that  $\Delta T_{eq}$  resulting from a (constant) radiative forcing is  
21 simply the product of that forcing and the climate sensitivity parameter. This equation  
22 provides much of the justification for using RF as an indicator of climate change.

23  
24 Equation (3) shows that the product of  $\lambda$  and  $C$  defines a time constant for the climate  
25 system to respond to an RF and is of order a few decades; a precise number cannot be  
26 given, because of uncertainties in the value of  $\lambda$  (see below) and the value of  $C$  is not  
27 well-defined, as it depends on the rate at which heat is transferred from the surface  
28 layers of the ocean to the deep ocean.

### 29 30 31 32 **2.3 Climate feedbacks**

33  
34 The value of  $\lambda$  is a chronic uncertainty in climate change science. If the Earth and  
35 atmosphere emitted to space as a black-body, Stefan's Law would give the OLR as  
36  $\sigma T_e^4$  where  $\sigma$  is the Stefan-Boltzmann constant and  $T_e$  is an effective emitting  
37 temperature of the climate system. In this case, the first derivative of Stefan's Law is  
38  $4\sigma T_e^3$ , and its reciprocal would give  $\lambda$ . For an OLR of  $240 \text{ W m}^{-2}$ ,  $\lambda$  would be about  
39  $0.3 \text{ K} (\text{W m}^{-2})^{-1}$ , indicating that the planet would warm up by 0.3 K for each  $\text{W m}^{-2}$  of  
40 forcing. This is sometimes referred to as the "black-body" or "no-feedback" response.

41  
42 However, as the Earth warms (or cools) a number of feedback processes occur that  
43 alter the radiative properties of the atmosphere and surface. For example, in response  
44 to a positive RF, a warmer atmosphere can contain more water vapour; water vapour  
45 is a greenhouse gas and hence this further enhances the warming – giving a positive  
46 feedback. Similarly, a warmer planet would be expected to have a decreased extent of  
47 snow and ice – this would decrease the amount of solar radiation reflected back to  
48 space leading to a further warming. These two feedbacks are believed to be relatively

1 well understood (e.g., IPCC, 2013); together they approximately double the value of  $\lambda$   
2 from its black-body value.

3  
4 From the late 1970s it was recognised that numerical climate models developed in  
5 different laboratories gave significantly different values for  $\lambda$ . It is now understood  
6 that the prime reason for this is the way that these models represent the response of  
7 clouds to climate change. A principal difficulty is that climate models represent the  
8 Earth's climate on a horizontal grid of order of 100 km spacing – many important  
9 climate processes, including those that control clouds, occur on much smaller spatial  
10 scales, and these have to be related in some way to the variables (such as temperature  
11 and humidity) that are represented on the model grid. An additional difficulty has  
12 been that many important parameters describing clouds (such as the amount of cloud  
13 ice) had not been observed globally; it had been difficult to verify the quality of a  
14 climate model's representation of clouds. A new generation of satellite instruments is  
15 starting to greatly improve this situation (e.g., Boucher *et al.*, 2013).

16  
17 Clouds strongly influence OLR and ASR and have the potential to be a powerful  
18 feedback mechanism. Many cloud characteristics influence OLR and ASR – for  
19 example, cloud amount, height, thickness, and the proportion that is ice or water. Any  
20 or all these could change as climate changes and even if climate models have a  
21 faithful representation of present-day clouds, this does not guarantee that they can  
22 faithfully represent changes in properties. The most recent IPCC scientific assessment  
23 (IPCC, 2013) reports that  $\lambda$  is likely to lie in the range from about 0.4 to 1.2 K (W  
24 m<sup>-2</sup>)<sup>-1</sup>; this indicates that climate models vary from having a weak to a strong positive  
25 cloud feedback.

26  
27 There are many other possible climate feedbacks (IPCC, 2013) – for example, climate  
28 change can impact the way the oceans and land take up CO<sub>2</sub>. The so-called carbon-  
29 climate feedback is an important focus of current research, and may be a significant  
30 positive feedback.

## 31 **2.4 Limitations in the use of radiative forcing**

32  
33  
34 Several caveats are necessary in using Equation (4) (see also Myhre *et al.*, (2013)). It  
35 was originally thought that the value of  $\lambda$  was approximately independent of the  
36 nature of the climate change mechanism. So, for example, if RF was due to a change  
37 in the output of the Sun (which influences the ASR) the value of  $\lambda$  would be the same  
38 as for changes in CO<sub>2</sub> (which mainly influences the OLR). More recent calculations  
39 now show that  $\lambda$  varies significantly amongst climate change mechanisms. This effect  
40 can be characterised by an “efficacy”, defined as the ratio of  $\lambda$  for the given climate  
41 change mechanism, to  $\lambda$  for a CO<sub>2</sub> doubling. Ponater *et al.* (2006) present efficacies  
42 for a range of aviation-induced RFs. To be confident that efficacies are robustly  
43 known, careful comparison of results from similar experiments with different climate  
44 models is necessary – no consensus yet exists; it is assumed here that all climate  
45 change mechanisms possess the same value of efficacy. Once a consensus emerges, it  
46 would be better to compare climate change mechanisms using the product of efficacy  
47 and RF, or else (as proposed in Myhre *et al.*, (2013)) to use a variant of the RF called  
48 the “effective RF”.

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

12  
13 The final caveat discussed here, is that there are *many* other dimensions to climate  
14 change beyond RF and  $\Delta T$  – for example, changes in precipitation, extreme storms,  
15 sea level rise, which are also important in terms of impact on society. These are  
16 represented in the more complex models, but not in the simpler representations  
17 encapsulated by Equation (2).

18  
19 Most of the work on aviation and climate change has concentrated on calculating RF  
20 and hence RF will be the focus here.

### 21 22 **3. RADIATIVE FORCING DUE TO AVIATION**

23  
24 The RF due to the accumulated emissions from aviation is summarized in Figure 1,  
25 from Lee *et al.* (2009), the most recent detailed assessment. The total size of each bar  
26 gives the best estimate RF for 2005, relative to pre-industrial times, with the  
27 numerical value shown in the first column on the right hand side. The white line  
28 shows the value estimated in Forster *et al.* (2007) (which is repeated in parentheses in  
29 the first column on the right hand side). The error bar represents the 90% likelihood  
30 range, which comes from a mixture of the range of published values and expert  
31 judgement. The middle column on the right hand side indicates the spatial scale of the  
32 forcing. The final column gives the level of scientific understanding (LOSU), based  
33 on expert judgement, taking into account the difficulties in calculating the forcing.  
34 Figure 2 illustrates typical latitudinal distributions of many of these forcings.

35  
36 It would, of course, be desirable if these RFs could be observed directly. It is only  
37 rarely that this is possible (for example, the effect of large volcanic eruptions or  
38 changes in the sun's output, which has only become possible relatively recently with  
39 the advent of satellite-based observations). There are various reasons for this. Firstly,  
40 the deviations in NET due to RF are relatively small and their detection would require  
41 a long sequence of well-calibrated satellite observations. Secondly, any observed  
42 variation in NET is due to both RF and the response of the climate to that forcing and  
43 it is difficult to untangle these. Thirdly, in this context, even if RF could be observed,  
44 it would be difficult to unravel how much is due to aviation and how much is due to  
45 other human activity – as will be shown, the effects of aviation are only a small  
46 percentage of the total. As a result, RF calculations generally depend heavily on  
47 computer simulations – in addition to uncertainties due to an incomplete  
48 understanding of atmospheric processes, calculations are reliant on assumed  
49 distributions of emissions of CO<sub>2</sub> and other gases and particles from aviation – there

1 are significant differences in these distributions in recent inventories (e.g., Wilcox *et*  
2 *al.*, 2013).

3  
4 It is important to note that aviation-induced effects have a wide variety of different  
5 timescales. For CO<sub>2</sub>, a significant fraction (several 10's of %) of any perturbation, as a  
6 result of an aviation (or any other) emission, persists in the atmosphere for thousands  
7 of years (Archer and Brovkin, 2008; IPCC, 2013) – this is because of the way CO<sub>2</sub>  
8 changes lead to changes in the oceanic carbon cycle. Hence, the CO<sub>2</sub> RF in Figure 1  
9 results from emissions over the entire time-period that aircraft have been emitting. At  
10 the other extreme, contrails typically persist for at most a few hours. Hence the entire  
11 RF due to linear contrails is a result of *very* recent aviation activity. One consequence  
12 of these different timescales is to consider the hypothetical case in which all aviation  
13 emissions suddenly cease. The RF due to linear contrails would disappear almost  
14 immediately; the CO<sub>2</sub> RF would persist for centuries. These issues of timescale will be  
15 considered again in Section 4. There has been no consolidated update of Figure 1 in  
16 the recent literature, but changes due to improved understanding will be indicated in  
17 the sections below.

### 18 19 **3.1 Carbon dioxide**

20  
21 CO<sub>2</sub> is an effective greenhouse gas as it possesses strong absorption bands at thermal-  
22 infrared wavelengths, notably near 15 μm. On a per molecule basis, CO<sub>2</sub> is relatively  
23 weak, partially because of the large natural CO<sub>2</sub> concentrations. However, this relative  
24 weakness is compensated by the fact that the absolute changes in CO<sub>2</sub> concentration  
25 are much higher than those of other greenhouse gases emitted by human activity.

26  
27 CO<sub>2</sub> is the easiest of all aviation forcings to consider; its lifetime in the atmosphere  
28 (decades to millennia) is so long, that there is essentially no climate difference  
29 between CO<sub>2</sub> produced from burning kerosene in a jet engine to CO<sub>2</sub> produced from  
30 burning any fossil fuel, anywhere else in the globe. The timescales over which the  
31 winds spread out any CO<sub>2</sub> emission across the planet (many months) are much shorter  
32 than the lifetime of the CO<sub>2</sub> in the atmosphere.

33  
34 Figure 1 shows that the estimated CO<sub>2</sub> RF from aviation emissions up to 2005 is 28  
35 mW m<sup>-2</sup>, with a high LOSU and it is clearly one of the largest single components. The  
36 value for 2011 is likely to be about 10-15% higher because of growth in emissions.  
37 Figure 2 shows that the forcing is global in extent.

### 38 39 **3.2 Oxides of nitrogen**

40  
41 The emission of oxides of nitrogen (NO<sub>x</sub>) by aviation leads to a complex chain of  
42 chemical effects (see eae347.pub2), making the evaluation of the net RF challenging.  
43 NO<sub>x</sub> causes an increase in ozone. Ozone absorbs ultra-violet and visible radiation and  
44 has thermal-infrared absorption bands, notably at wavelengths near 10 μm. This  
45 ozone forcing is positive; Figure 1 shows this forcing is, within the uncertainty bars,  
46 the same size as the CO<sub>2</sub> forcing, although more recent analyses indicate that it may  
47 be around 20% smaller (e.g., Søvde *et al.*, 2014).

48  
49 The ozone change has a knock-on effect in increasing the concentration of the  
50 hydroxyl radical, OH, which plays a key role in controlling the concentrations of



1 many atmospheric species. In the context of climate change, the most important is  
2 methane (CH<sub>4</sub>), which is a powerful greenhouse gas (about 24 times CO<sub>2</sub> on a per  
3 molecule basis) – more OH means that CH<sub>4</sub> is more readily destroyed, and hence CH<sub>4</sub>  
4 concentrations are reduced. (Methane concentrations have increased since pre-  
5 industrial times (e.g., Myhre *et al.*, 2013) as a result of all human activity, but NO<sub>x</sub>  
6 emissions are believed to have reduced that rate of increase.) Hence the CH<sub>4</sub> reduction  
7 by aviation causes a negative RF which Figure 1 shows to be around 50% of, but  
8 opposite in sign to, the ozone forcing.

9  
10 There are several further consequences of the CH<sub>4</sub> reduction (e.g., Myhre *et al.*, 2013).  
11 One of these is that methane itself is important for ozone formation; the loss of  
12 methane leads to an ozone reduction which offsets the ozone increase generated by  
13 the NO<sub>x</sub> increase. Several recent publications (e.g., Søvde *et al.*, 2014) indicate the net  
14 effect of aviation NO<sub>x</sub> emissions is smaller than indicated in Figure 1, at around 5(±4)  
15 mW m<sup>-2</sup>, because of improved understanding of atmospheric processes.

16  
17 There are additional complications concerning NO<sub>x</sub>. Firstly, the impact on ozone  
18 depends strongly on the altitude and latitude where NO<sub>x</sub> is emitted. The values in  
19 Figure 1 refer to the present-day fleet, concentrated as it is in the northern mid-  
20 latitudes in the upper troposphere and lower stratosphere. If the height or geographical  
21 distribution of emissions changes, so too could the NO<sub>x</sub> RF. Secondly, while the O<sub>3</sub>  
22 and CH<sub>4</sub> forcings cancel to some extent in the global mean, they do not do so locally.  
23 Figure 2 shows that the ozone forcing, for the present-day fleet, is concentrated in  
24 northern mid-latitudes; by contrast, because CH<sub>4</sub> is relatively long lived (with a  
25 lifetime of 10 years), the reduction spreads across the globe, and is roughly equal in  
26 both hemispheres. Hence, in the northern hemisphere, the positive ozone forcing  
27 dominates, while in the southern, the negative CH<sub>4</sub> forcing dominates. This is an  
28 example of where an apparently small global-mean forcing may still lead to a  
29 significant regional climate impact.

### 30 31 **3.3 Water vapour**

32  
33 Burning kerosene leads to water vapour being emitted by aviation. Water vapour is a  
34 strong greenhouse gas and the main contributor to the natural greenhouse effect.  
35 Aviation water vapour emissions within the troposphere are not believed to lead to  
36 any significant concentration changes – the vigour of the natural hydrological cycle is  
37 such that the lifetime of water vapour molecules is around 7 days, and it is not  
38 possible to accumulate large changes in concentration. However, in the stratosphere,  
39 the lifetime is considerably longer (many months) allowing more marked changes to  
40 occur. The tropopause, which separates the troposphere from the stratosphere, varies  
41 with location, season and with particular weather systems, but broadly varies from  
42 around 8 km in high latitudes to 16 km in the tropics. The civil aviation fleet spends a  
43 considerable amount of time in the lower stratosphere (e.g., Gauss *et al.*, 2003)  
44 especially during northern-hemisphere winter when, on average, the tropopause is  
45 lower in altitude.

46  
47 Figure 1 shows that the water vapour RF to be modest (3 mW m<sup>-2</sup>) and an order of  
48 magnitude smaller than CO<sub>2</sub>. More recent assessments (e.g., Wilcox *et al.*, 2012)  
49 indicate it could be smaller still (1 mW m<sup>-2</sup>, with a likely upper limit of 1.4 mW m<sup>-2</sup>).  
50 However, as discussed in IPCC (1999), were future fleets of supersonic aircraft to fly

1 in the stratosphere, water vapour might become the dominant RF, as most of the  
2 emissions would occur at altitudes where its lifetime is long.

### 3 4 **3.4 Aerosol**

5  
6 Aerosol particles emitted by aircraft engines, or forming within the exhaust plume,  
7 can influence RF by absorbing and/or scattering solar radiation; they are generally too  
8 small (being sub-micron in size) to significantly influence thermal-infrared radiation.

9  
10 Sulphate aerosols are generally non-absorbing, especially at visible wavelengths; they  
11 cause an RF by scattering solar radiation, and hence exert a negative RF. Figure 1  
12 shows a small RF ( $-5 \text{ mW m}^{-2}$ ). By contrast, soot particles are highly absorbing at  
13 visible wavelengths and absorb solar radiation that would otherwise be scattered to  
14 space. Hence they exert a positive RF which is roughly equal in size ( $3 \text{ mW m}^{-2}$ ), but  
15 opposite in sign to the sulphate forcing. Recent simulations (Gettelman and Chen,  
16 2013; Righi *et al.*, 2013) are broadly supportive of values of around this size.

17  
18 This indicates that aerosols are not a major direct contributor to aviation RF.  
19 Nevertheless, they play an important role in contrail formation (see eae352.pub2) and  
20 may significantly alter the properties of natural clouds. These topics are covered in the  
21 following sub-sections.

### 22 23 **3.5 Contrails**

24  
25 Aircraft contrails are, arguably, the most obvious visible sign of human activity on the  
26 atmosphere, especially for those living beneath busy flight tracks. Of interest here are  
27 so-called persistent contrails, which form when an aircraft flies through a sufficiently  
28 cold layer which is supersaturated with respect to ice (see eae352.pub2). These  
29 contrails may last for a few hours.

30  
31 There are many difficulties in estimating the RF due to contrails. Firstly, although  
32 contrails can be clearly seen in satellite images, reliable global climatologies of their  
33 horizontal coverage have not yet been developed. This requires pattern-recognition  
34 techniques that can reliably distinguish contrails from other clouds. To date detailed  
35 analysis of satellite images are available over more restricted areas and time periods.  
36 These are then used together with modelling techniques (which combine  
37 meteorological data and flight inventories) to provide a global estimate of contrail  
38 occurrence. Typical estimates are that, on a global average, about 0.05 to 0.1% of the  
39 sky is covered by contrails at any one time (e.g. Myhre and Stordal, 2001;  
40 Spangenberg *et al.*, 2013).

41  
42 A second difficulty is that RF calculations require additional information on contrail  
43 properties, such as their thickness, and the number, size and shape of the ice crystals  
44 that make up the contrail. Data is available only for a limited number of case studies  
45 and many assumptions must be made for global calculations.

46  
47 The final difficulty discussed here concerns the fact that the net contrail RF is a small  
48 residual of opposing longwave and shortwave RF. Contrails reflect solar radiation,  
49 causing a negative RF, and trap thermal-infrared radiation decreasing the *OLR* and  
50 causing a positive RF.

1  
2 On an annual and global average, it is believed that the thermal-infrared RF dominates  
3 – Figure 1 indicates a global and annual mean RF of around  $12 \text{ mW m}^{-2}$ ; a number of  
4 other recent studies have derived values of  $10 \text{ mW m}^{-2}$  or less (e.g., Boucher *et al.*,  
5 2013; Burkhardt and Kärcher 2011; Spangenberg *et al.*, 2013).

6  
7 Because contrails are so short-lived, they persist only in areas of high aircraft traffic,  
8 and hence the resulting forcing is also very inhomogeneous (Figure 2). Also, the  
9 contrail forcing varies significantly during the day, as the compensation between the  
10 thermal-infrared and the shortwave RF depends on the availability of sunlight (Myhre  
11 and Stordal 2001; Stuber *et al.*, 2006). Thus at night, the thermal-infrared RF is the  
12 only component, whilst in the day, the net forcing can be negative, if the shortwave  
13 RF dominates. It has not yet been established whether this day-night difference  
14 significantly influences the climatic effect of contrails.

15  
16 The simulations of Ponater *et al.* (1996) and Rap *et al.* (2010) indicate that contrail RF  
17 may be less effective at causing a surface temperature change because their efficacy  
18 (see Section 2.4) may be significantly less (0.6 and 0.3 respectively) than that of  $\text{CO}_2$ .  
19 It will be important to see if further simulations find similarly low values.

20  
21 There were claims of a clear climatic effect, resulting from the absence of contrails,  
22 following the grounding of US civil aircraft, after the 9/11 terrorist attacks (Travis *et al.*,  
23 2004). These conclusions have been robustly challenged by a number of studies  
24 (e.g., Deitmüller *et al.*, 2008).

### 25 26 **3.6 Aviation-induced cloud changes**

27  
28 Aviation-induced cloud (AIC) changes are probably the most uncertain aviation RF  
29 but have the potential to be one of the most important.

30  
31 Following Lee *et al.* (2009), two distinct AIC effects are discussed. First, persistent  
32 contrails (see Section 3.5) can spread to form cirrus-like clouds which seem  
33 indistinguishable from natural cirrus clouds – this is referred to here as the direct AIC  
34 forcing. There is clear evidence that contrails do evolve into cirrus-like clouds (e.g.,  
35 Minnis *et al.*, 1998). The many difficulties in quantifying this forcing include the  
36 problem of knowing whether natural cirrus clouds would have formed in any case,  
37 whether the aviation emissions impact on natural cirrus, and defining the properties of  
38 the AIC (e.g., Burkhardt and Kärcher, 2011). The mid-range estimate for this RF of  
39  $30 \text{ mW m}^{-2}$  (see Figure 1) has been revised upwards to  $40 \text{ mW m}^{-2}$  for 2011, in  
40 IPCC's recent assessment (Boucher *et al.*, 2013) making it the largest single aviation-  
41 induced RF. However the uncertainty in this estimate is around a factor of three,  
42 indicating low confidence.

43  
44 Second, sulphate aerosols due to surface-based emissions may cause a significant  
45 negative RF by influencing the properties of low-altitude clouds (e.g. Boucher *et al.*,  
46 2013). Sulphate and black carbon aerosols from aviation could have a similar effect.  
47 There are formidable difficulties in performing such calculations because of  
48 uncertainties in microphysical processes in clouds and how they are affected by  
49 changing aerosol concentrations. Nevertheless recent modelling studies indicate that  
50 the effect of sulphate emissions on clouds might cause a negative RF of several tens

1 of  $\text{mW m}^{-2}$  (Righi *et al.*, 2013; Gettelman and Chen, 2013). This would make it  
2 almost as important as, but opposite in sign to, the direct AIC RF; much further work  
3 is clearly necessary.

### 4 **3.7 Summary and comparison with the total impact of human activity.**

6  
7 Figure 1 shows the total RF in 2005 due to aviation both excluding ( $55 \text{ mW m}^{-2}$ ) and  
8 including ( $78 \text{ mW m}^{-2}$ ) the central estimate for the direct AIC RF. This indicates that  
9 the total aviation RF is between 2 or 3 times the aviation  $\text{CO}_2$  RF alone, although the  
10 level of scientific understanding is low for the total forcing. Growth in aviation  
11 emissions and recent research on the RF due to  $\text{NO}_x$  and the effect of sulphate  
12 emissions on clouds, would likely lead to broadly similar figures for the 2011 RF but  
13 a detailed assessment is not yet available.

14  
15 These numbers can be compared to estimates of the total RF due to human activity  
16 (Myhre *et al.*, 2013) for 2011 relative to pre-industrial times. The total  $\text{CO}_2$  RF is  
17 estimated to be  $1.8 \text{ W m}^{-2}$  ( $\pm 10\%$ , with high level of scientific understanding), with  
18 the total RF due to human activity of about  $2.3 \text{ W m}^{-2}$ ; the uncertainty in this value is  
19 about 50%.

20  
21 Lee *et al.* (2009) estimate that aviation  $\text{CO}_2$  currently contributes around 1.6% of the  
22 total anthropogenic  $\text{CO}_2$  RF, while the total aviation RF is 3.5% without or 4.9% with  
23 the direct AIC RF. Lee *et al.* (2009) present results from Monte Carlo simulations  
24 using uncertainty estimates and find the 90% uncertainty ranges of the contribution of  
25 aviation to the total anthropogenic RF range from 1.3 to 10% if direct AIC RF is  
26 excluded, and from 2 to 14% if the direct AIC RF is included.

27  
28 No attempt is made here to provide projections of the future contribution of aviation  
29 to total RF but this is discussed in Lee *et al.* (2009). Many factors inhibit a confident  
30 prediction. The total anthropogenic RF depends heavily on future changes in  
31 population, economic growth and technological developments and the extent to which  
32 any international climate treaties influence emissions. The aviation RF depends on  
33 such developments and also depends on whether any changes to the operation of the  
34 present and future fleets (e.g. cruise altitude) occur.

## 35 **4. EMISSION INDICES**

### 36 **4.1 General considerations**

37  
38  
39  
40 The diverse range of aviation emissions leads to questions about whether they can be  
41 placed on a common scale for comparison. There are several possible reasons for  
42 doing this. One is a technological – if there is a change in design or operation of an  
43 aircraft, does this change its climate impact? For example, contrails could be avoided  
44 by flying lower, but this would likely entail increased fuel use and increased  $\text{CO}_2$   
45 emissions. Is this desirable? A second purpose might be in a legislative context, where  
46 the effects of non- $\text{CO}_2$  emissions of aviation (or any other sector) are required to be  
47 taken into account to provide a fuller picture of the total impact. A related purpose is  
48 where companies provide consumers with the opportunity to pay towards schemes to  
49 offset the climate impact of their air travel, which could include the effect of non- $\text{CO}_2$   
50 emissions.

1  
2 RF is one potential index for making comparisons – indeed, one index is the ratio of  
3 the total forcing to the CO<sub>2</sub>-only forcing – this is sometimes called the Radiative  
4 Forcing Index (RFI) or, simply, a CO<sub>2</sub> multiplier. In this usage, the climate impact of  
5 the CO<sub>2</sub> is then multiplied by the RFI (which, according to Lee *et al.*'s (2009)  
6 estimates would be about 2 or 3) to get a total climate impact. RF and RFI are useful  
7 for looking at the cumulative effect of past aviation emissions, but less suited for  
8 looking at the future effects of current emissions. Hence, the use of the RFI has been  
9 heavily criticised (see e.g. Fuglestedt *et al.* 2010) as it fails to account for the  
10 different lifetimes of the emissions (ranging from hours for contrails to millennia for  
11 much of the CO<sub>2</sub> emitted); also it represents a fixed tax on fuel use (and hence CO<sub>2</sub>  
12 emissions) which might encourage perverse behaviour whereby attempts are made to  
13 decrease CO<sub>2</sub> emissions regardless of the impact on the non-CO<sub>2</sub> emissions.

14  
15 There are many difficulties in constructing a robust index (e.g., Fuglestedt *et al.*  
16 (2010)). These include: (i) exactly what climate parameter should be compared? The  
17 RF, the temperature change or perhaps some time-integral of these effects? (ii) Over  
18 what period should the parameters be calculated? Is it the climate impact in the  
19 decade or so following an emission, or should some longer-term impact be  
20 considered? (iii) How are the uncertainties in the effect of emissions taken into  
21 account? As will be shown, answers to (i) and (ii) have a profound influence on the  
22 perception of the relative importance of the CO<sub>2</sub> and non-CO<sub>2</sub> emissions. There is as  
23 yet no widely accepted way of comparing the climate effect of aircraft emissions and  
24 some choices, such as the time period of calculation, are value-laden decisions that  
25 must be made by policymakers.

## 26 27 **4.2 The Global Warming Potential and the Global Temperature-change** 28 **Potential**

29  
30 IPCC has, since its early assessments, presented an emissions index called the Global  
31 Warming Potential (GWP). If a pulse emission of, say, 1 kg of a gas is emitted into  
32 the atmosphere, the pulse decays (exponentially for many emissions) over some time  
33 period as it is removed from the atmosphere. The GWP represents the time-integral of  
34 the RF due of this decaying pulse – this means that the lifetimes of the gas, as well as  
35 its radiative strength are taken into account. It is normally presented as the ratio of a  
36 gas's GWP to that of CO<sub>2</sub>. The GWP (integrated over a 100 year “time horizon”) was  
37 adopted for the Kyoto Protocol to the United Nations Framework Convention on  
38 Climate Change, to allow Protocol signatories to decide which, of a range of  
39 greenhouse gases, to control to meet its commitments. So, for example, the mass of  
40 methane emitted in a given year can be cast in “CO<sub>2</sub>-equivalence” terms by  
41 multiplying it by 28, the current estimate for methane's 100-year GWP (Myhre *et al.*,  
42 2013). There have been a range of criticisms of the GWP as a concept and recognition  
43 of particular difficulties in calculating its values for short-lived species such as NO<sub>x</sub>  
44 (see Fuglestedt *et al.* 2010 and references therein), but nevertheless it is widely used.

45  
46 An alternative index, called the Global Temperature-change Potential (GTP) has also  
47 been proposed – this gives the temperature change at some specified time after a pulse  
48 emission into the atmosphere. The GTP has not achieved the level of acceptance of  
49 the GWP, but it may be more suited to certain types of climate policy (see Myhre *et*  
50 *al.*, 2013) although it is also subject to criticism; nevertheless, it illustrates the

1 influence of different choices in the design of emission indices. Because it looks at the  
2 temperature change some time after an emission, rather than integrating the effect of  
3 an emission over time, in general it indicates a lesser impact for the short-lived non-  
4 CO<sub>2</sub> emissions from aviation. The actual values of the GTP depend on the  
5 assumptions about the values of  $\lambda$  and C (see Section 2).

6  
7 Tables 1 and 2 illustrate typical GWP and GTP values for aviation emissions, based  
8 on values in Fuglestvedt *et al.* (2010). It is emphasized that these values refer to the  
9 average effect of the present-day aircraft fleet – they cannot be applied to the effect of  
10 a single flight (for which, for example, the meteorological conditions may not allow  
11 contrail formation) and cannot be applied if there were significant changes to, for  
12 example, the altitudes or latitudes at which the fleet flies – the effect of NO<sub>x</sub> and  
13 contrails are highly dependent on where the emissions occur. Some information on the  
14 height and latitude dependence can be found in, for example, Grewe and Stenke  
15 (2007), Rädcl and Shine (2009) and Søvde *et al.* (2014). Finally, the values presented  
16 in the Tables are subject to significant revisions as scientific understanding increases.

17  
18 Each Table shows the values relative to CO<sub>2</sub>. The GWP is presented for three time  
19 horizons (20, 100, 500 years) which are the conventional values presented by IPCC.  
20 The GTP is presented for 20, 50 and 100 years, as this is felt to be more appropriate  
21 for such an index; in any case, for longer time periods, the non-CO<sub>2</sub> emissions from  
22 aviation would quickly decay to zero, as they are so short-lived compared to CO<sub>2</sub>.

23  
24 The values are presented as the effect of burning 1 kg of fuel, relative to the effect of  
25 the CO<sub>2</sub> from this 1 kg of fuel. For each kg burnt, 3.16 kg of CO<sub>2</sub>, 1.23 kg of H<sub>2</sub>O  
26 and 0.015 kg of NO<sub>2</sub> are assumed to be emitted – the NO<sub>2</sub> number is the most  
27 uncertain, as it is dependent on the way kerosene is burnt. Values are presented for  
28 “high NO<sub>x</sub>” and “low NO<sub>x</sub>” to reflect the range of RF values currently in the  
29 literature. The bottom 4 lines in the Tables show how much the CO<sub>2</sub> effect has to be  
30 multiplied to incorporate the non-CO<sub>2</sub> effects; it is given for the two NO<sub>x</sub> cases and  
31 with and without AIC, because of the particularly high uncertainty. These rows could  
32 be considered as an analogue for the RFI, but posed in terms of the future effect of  
33 present-day emissions.

34  
35 Table 1 shows that for all components, the GWP decreases with time horizon – this is  
36 because the values are referenced to CO<sub>2</sub>, a significant component of which remains  
37 in the atmosphere for much longer than 500 years; hence the part of the CO<sub>2</sub> pulse  
38 that remains in the atmosphere even at 500 years continues to contribute to (the  
39 integral of) RF, whereas the RF from the short-lived components have long since  
40 decayed to zero. It can be seen that the sign of the NO<sub>x</sub> component changes, as this is  
41 determined by the relative balance of the effect of the created ozone and the destroyed  
42 methane. The CO<sub>2</sub> multiplier rows show different combinations of the total effect.  
43 This clearly illustrates that the multiplier to be applied to CO<sub>2</sub> to account for the non-  
44 CO<sub>2</sub> emissions varies greatly depending on the chosen time horizon, and on which  
45 effects are considered, from 1.1 to 4.9.

46  
47 Table 2 shows the GTP drops off much more quickly with time horizon than the GWP  
48 (compare the 20 and 100 year values in Tables 1 and 2); because of the nature of the  
49 GTP, it retains less memory of short-lived effects than the GWP. NO<sub>x</sub> values are  
50 generally negative, because the cooling due to methane dominates over the warming

1 due to ozone. Fuglestad *et al.* (2010) discuss the reasons for the behaviour of these  
2 values. In general, the CO<sub>2</sub> multiplier values are much smaller than for the GWP and  
3 indeed, can be less than unity for some cases, where the methane-induced cooling has  
4 a strong influence. In the cases given, the multiplier ranges from 0.4 to 1.6.

## 5 6 **5. CONCLUSION**

7  
8 Aviation causes climate change as a result of its emissions of CO<sub>2</sub>, oxides of nitrogen,  
9 aerosols and water vapour. While the RF due to changes in CO<sub>2</sub> is as well-  
10 characterised as those from other sources due to human activity, there are formidable  
11 difficulties in estimating the non-CO<sub>2</sub> forcings – this is particularly the case for the  
12 aviation-induced changes in cloudiness (AIC). The best-estimate of total radiative  
13 forcing to 2005, from aviation, using values from the most recent comprehensive  
14 assessment (Lee *et al.* 2009) is 55 mW m<sup>-2</sup> excluding AIC and 78 mW m<sup>-2</sup> including  
15 it, with an uncertainty of at least a factor of two; these values are likely broadly  
16 appropriate for 2011 given recent developments in understanding. The 2005 aviation  
17 CO<sub>2</sub> RF represents about 1.6% of the total CO<sub>2</sub> forcing from all human activities. It is  
18 estimated that, including the non-CO<sub>2</sub> effects, aviation contributes between 1.3 and  
19 14% of the total RF due to all human activities.

20  
21 Two distinct methods for comparing the future impact of present-day aviation  
22 emissions are presented – the Global Warming Potential and the Global Temperature-  
23 change Potential. The perception of the relative importance of the non-CO<sub>2</sub> emissions,  
24 relative to CO<sub>2</sub> depends considerably on the chosen method and the parameters  
25 chosen within that method. Of particular importance is the choice of the time-scale  
26 over which the effects are compared – in general, the longer the time scale that is  
27 chosen, the more important CO<sub>2</sub> becomes, relative to the non-CO<sub>2</sub> emissions.

28  
29 Improvement in estimates of RF will require advances in our understanding of  
30 atmospheric processes, better techniques for numerical modelling of these processes  
31 and more detailed, and sustained, observations, using both *in situ* and remote sensing  
32 techniques.

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1 **Table 1:** Estimates of the Global Warming Potential for three time horizons for  
 2 aviation emissions, relative to CO<sub>2</sub> for the present-day aviation fleet for each kg of  
 3 fuel burnt. The bottom 4 rows show how much the CO<sub>2</sub> effect, for each kg of fuel  
 4 burnt, should be multiplied to account for the non-CO<sub>2</sub> effects.  
 5

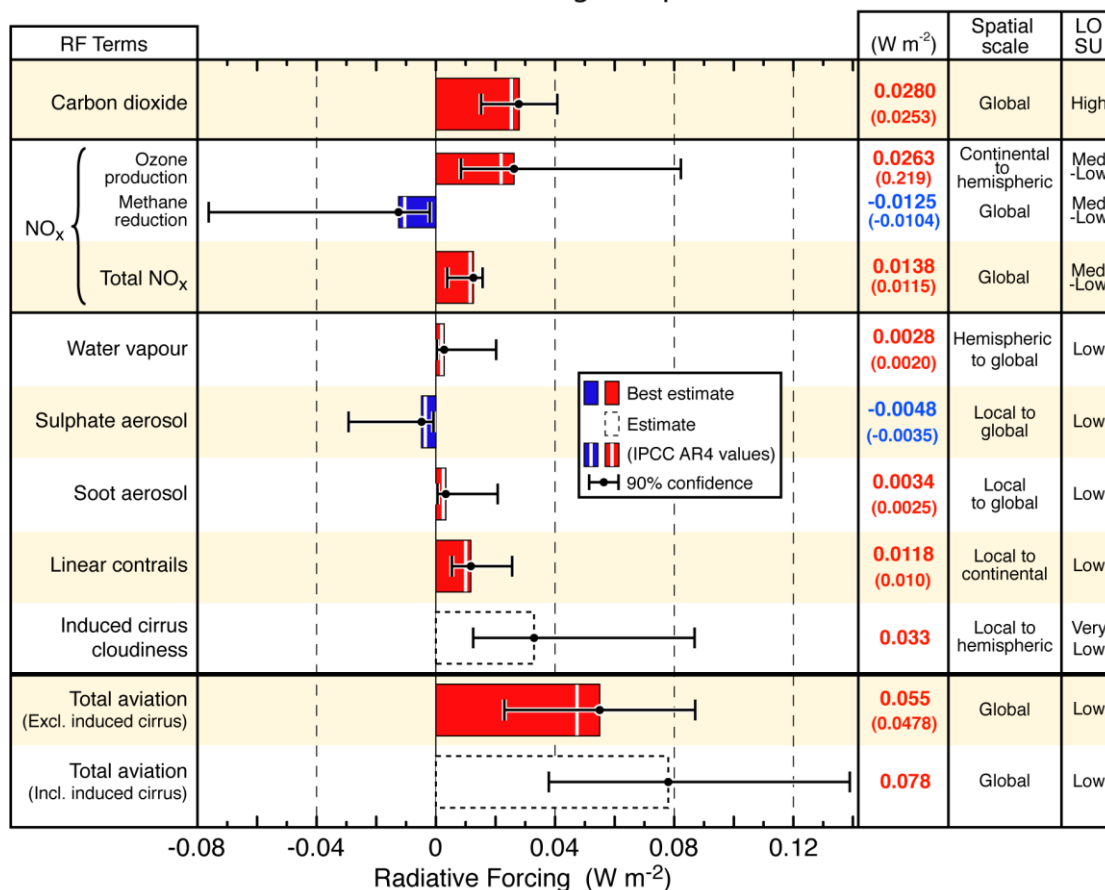
	<b>Time Horizon (years)</b>		
	<b>20</b>	<b>100</b>	<b>500</b>
<b>NO<sub>x</sub> (high estimates)</b>	0.68	0.10	0.03
<b>NO<sub>x</sub> (low estimates)</b>	0.17	-0.003	-0.001
<b>Contrails</b>	0.74	0.21	0.064
<b>Aviation-induced cloud (AIC)</b>	2.2	0.63	0.19
<b>Water vapour</b>	0.27	0.078	0.023
<b>CO<sub>2</sub>-multiplier (NO<sub>x</sub> high, no AIC)</b>	2.7	1.4	1.1
<b>CO<sub>2</sub>-multiplier (NO<sub>x</sub> high, including AIC)</b>	4.9	2.0	1.3
<b>CO<sub>2</sub>-multiplier (NO<sub>x</sub> low, no AIC)</b>	2.2	1.3	1.1
<b>CO<sub>2</sub>-multiplier (NO<sub>x</sub> low, including AIC)</b>	4.4	1.9	1.3

6  
 7 **Table 2:** Estimates of the Global Temperature-change Potential for three time  
 8 horizons for aviation emissions, relative to CO<sub>2</sub> for the present-day aviation fleet for  
 9 each kg of fuel burnt. The bottom 4 rows show how much the CO<sub>2</sub> effect, for each kg  
 10 of fuel burnt, should be multiplied to account for the non-CO<sub>2</sub> effects.  
 11

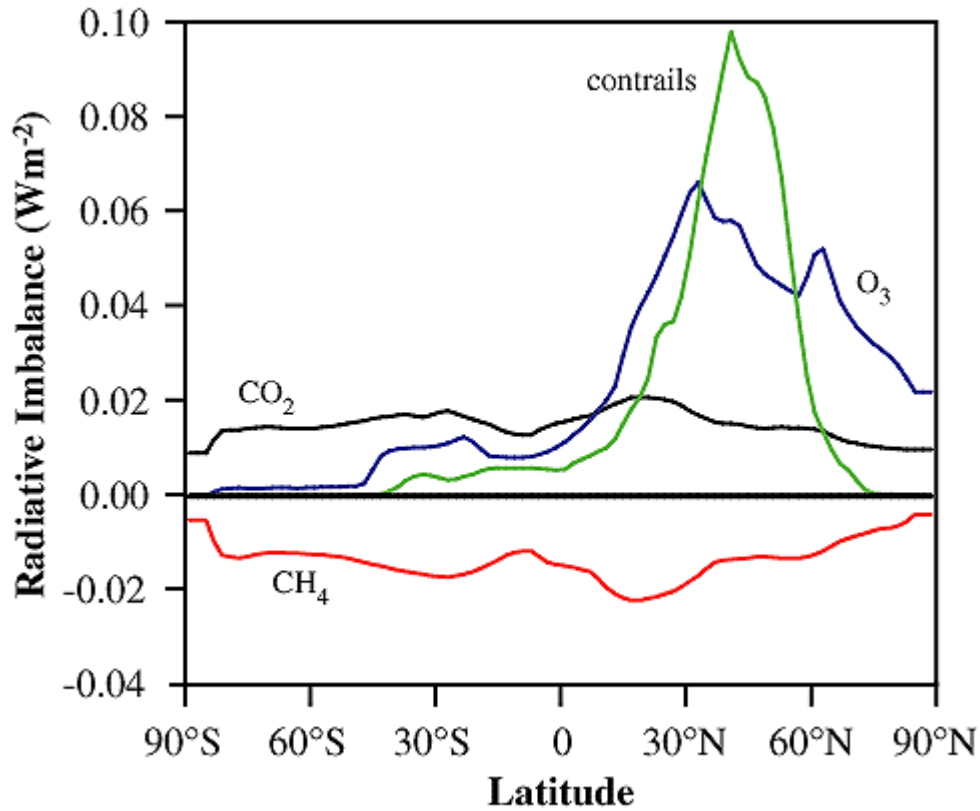
	<b>Time Horizon (years)</b>		
	<b>20</b>	<b>50</b>	<b>100</b>
<b>NO<sub>x</sub> (high estimates)</b>	-0.29	-0.09	0.01
<b>NO<sub>x</sub> (low estimates)</b>	-0.85	-0.30	-0.01
<b>Contrails</b>	0.21	0.04	0.03
<b>Aviation-induced cloud (AIC)</b>	0.64	0.11	0.09
<b>Water vapour</b>	0.08	0.01	0.01
<b>CO<sub>2</sub>-multiplier (NO<sub>x</sub> high, no AIC)</b>	1.0	1.0	1.1
<b>CO<sub>2</sub>-multiplier (NO<sub>x</sub> high, including AIC)</b>	1.6	1.1	1.1
<b>CO<sub>2</sub>-multiplier (NO<sub>x</sub> low, no AIC)</b>	0.4	0.7	1.0
<b>CO<sub>2</sub>-multiplier (NO<sub>x</sub> low, including AIC)</b>	1.1	0.9	1.1

12  
 13  
 14

### Aviation Radiative Forcing Components in 2005



1  
2 **Figure 1.** Global-mean radiative forcing components due to aviation for 2005, relative  
3 to preindustrial times. Coloured bars represent best estimates (except for the case of  
4 aviation-induced cloud changes (AIC) where a best-estimate cannot be given). Values  
5 indicated by the white lines within the bars are from Forster *et al.* (2007). The induced  
6 cloudiness (AIC) estimate includes linear contrails. Numerical values are given on the  
7 right for both Forster *et al.* (2007) (in parentheses) and for Lee *et al.* (2009). Error  
8 bars represent the 90% likelihood range for each estimate. The best estimate value of  
9 total radiative forcing from aviation is shown with and without AIC. The spatial scale  
10 of each radiative forcing and its level of scientific understanding (LOSU) are shown  
11 in the columns on the right. Reproduced from Lee *et al.* (2009) © Elsevier.  
12



1  
 2 **Figure 2:** Radiative forcing as a function of latitude for global aviation in 1992,  
 3 relative to pre-industrial times, for a number of aviation-induced forcings. Note that  
 4 the global-mean of these values will not correspond to those in Figure 1, as they are  
 5 for a different period and because of improvements in understanding. Reproduced  
 6 from IPCC (1999) © Cambridge University Press.  
 7  
 8