Aviation and Climate Change

Olivier Dessens[1], Marcus O. Köhler [2], Helen L. Rogers[3] , Rod L. Jones[3], John A. Pyle[3,4]

[1] Energy Institute, University College London, London, U.K.
[2] Department of Geography, University of Birmingham, Birmingham, U.K.
[3] Centre for Atmospheric Science, Cambridge University, Cambridge U.K.
[4] NCAS Climate-Composition, Cambridge University, Cambridge U.K.

Abstract

We describe the current status of knowledge regarding the contribution of aviation to anthropogenic climate forcing. The emissions and associated radiative forcings from aviation are compared to those from other modes of transport. The different analytical metrics used to quantify climate forcing are presented showing their relevancies and their uncertainties. The discussion then focuses on the use of radiative forcing, one of the most commonly used metric, in accounting for the climate change contribution from aviation with a particular look at how the contribution from CO_2 and non-CO_2 greenhouse gases can be compared.

1. Introduction

Emissions from aircraft engines affect the radiative balance of the atmosphere, and therefore the climate system, through various mechanisms. These include direct emissions of the greenhouse gases carbon dioxide, CO_2 (Sausen & Schumann, 2000; Sausen *et al.*, 2005), and emissions of nitrogen oxides, NO_x (Stevenson *et al.*, 2004, Köhler *et al.*, 2008, 2013, Gilmore *et al.*, 2013), which influence atmospheric chemistry and result in changes of the abundance of ozone (O_3) and methane (CH_4). Water vapor from aviation transported or directly emitted within the stratosphere is assumed to have a negligible effect on climate (Wilcox *et al.*, 2012). Fuel sulphur is converted to gaseous H_2SO_4, an important aerosol precursor in the atmosphere. In the case of aviation, emissions of particulates (Gettelman *et al.*, 2013) can both directly scatter and absorb incoming solar radiation and indirectly affect the microphysical and thus the optical properties of clouds. The larger influence on clouds is thought to be the formation of contrails and contrail-induced cloudiness (Schumann, 2002). All these processes however exert their respective influence over different spatial and temporal scales (IPCC, 1999; Lee *et al.*, 2009b).

In 1999 an assessment of the effects of aviation on the global atmosphere was undertaken within the IPCC in a special report "Aviation and the Global Atmosphere" (IPCC 1999). To date aviation is the only transportation subsector that has been separately assessed for its climate forcing contribution by the IPCC. Since then, however, the science has

improved and a new comprehensive assessment was recently conducted within the European Project ATTICA (Lee *et al.*, 2009a).

Government and industry have increasingly attempted to account for the 'non-CO_2 effects' of aviation through the use of a multiplication factor, where the net climate contribution of present and future aviation emissions is assumed to be a multiple of the climate forcing contribution associated with its respective CO_2 emissions. Within the EU Emissions Trading System (ETS) [EU Directive 2008/101/EC] this multiplication factor is referred to as an uplift factor. The use of a multiplier began with the IPCC, which defined the Radiative Forcing Index (RFI) as the ratio of radiative forcing from all past aviation emissions to that from past CO_2 emissions alone (IPCC 1999). For the remainder of this paper we have adopted the term uplift factor to refer to these respective multipliers but we shall distinguish whether we are considering past, present, or future emissions. The appeal of an uplift factor is in part due to its simplicity of use, since aviation's emissions of CO_2 are directly proportional to fuel burn, a well-known quantity for any aircraft operator. This approach is however scientifically flawed since it incorrectly assumes that all climate effects due to aviation are proportional to the amount of CO_2 emitted. If the example of aviation-induced cloudiness is taken, it is the distance flown rather than the amount of fuel burned that is of particular importance, and in the case of emissions of nitrogen oxides, it is the geographical location and altitude of the aircraft during flight that influences the magnitude of the climate forcing.

This paper will first examine the impact of aviation emissions on the atmosphere relative to road, shipping and rail. We will then discuss the variety of analytical metrics available for quantifying the change on the climate system due to these activities and assess the contribution of these transport modes using the radiative forcing metric. Finally, we will present the shortfalls in the usage of the radiative forcing metric.

2. Aviation emissions within the context of the transport sector

Petroleum products are the dominant fuel source for transportation with road transport accounting for 75% of total energy use by the transport sector (IEA, 2009a; 2009b). This dependence on fossil fuels makes transport a major contributor of greenhouse gases. Because of structural shifts in the economy, from agriculture to industry to services (a sector that includes transportation), transportation related CO_2 emissions are growing in both absolute and relative terms (Schäfer, 2005). Burning fuel in engines produces gaseous and aerosol products, some of which are unavoidable products of combustion such as CO_2 and water vapour. NO_x, volatile hydrocarbons (VOC) and carbon monoxide (CO) emissions depend on combustion characteristics whilst others such as sulfur dioxide, SO_2, are dependent on the fuel

composition. Here we will focus mainly on emissions of CO_2, NO_x and SO_2 which produce the largest changes in atmospheric composition and climate due to the transportation sector. The impact on the atmosphere differs however between these species. CO_2 is a well-known greenhouse gas with a long atmospheric lifetime (~100-1000 years), whereas NO_x has a much shorter lifetime in the atmosphere (hours to a day, depending on location, Jaeglé *et al.*,1998). Under typical tropospheric conditions, NO_x emissions increase the production rate of O_3 and enhance the removal mechanism of CH_4, both strong greenhouse gases. Sulphur contained in the fuel is rapidly oxidized to SO_2 and then SO_4^{--}, the result forming sulphuric acid aerosols. These particles have a strong direct effect on radiative forcing by enhanced scattering of the incoming solar radiation (cooling) and they also alter ozone chemistry in the stratosphere through heterogeneous processes. There is a further impact from aerosols, the indirect effect, whereby aerosols modify the lifetime of clouds together with their microphysical properties. The increase in cloud condensation nuclei and ice nuclei concentrations may lead to aviation-induced cirrus (warming) but large uncertainties remain in the level of scientific understanding associated with this process.

For the purpose of comparison, the magnitude of road, rail, shipping and aviation emissions for the year 2000 are presented in Table 1 (Hoor *et al.*, 2009). The non-transport sources represent bio and fossil fuel combustion, fossil fuel production, industrial processes and waste. Shipping sources represent both maritime and inland shipping. Rail includes both direct and indirect emissions (where indirect emissions occur as a result of electricity production for electrified rail transport). Within the transport sector the largest contribution to CO_2 emissions originates from road transport with 4.2 billion tonnes. Emissions of CO_2 from aviation are similar in magnitude to those from shipping, with these sectors accounting for an additional 663 million tonnes (shipping) and 675 million tonnes (aviation), which represents ~30% of the CO_2 emissions from roads. The NO_x emissions from aviation (2.8 million tonnes (NO_2)) represent ~10% of the NO_x emissions from roads (29.2 million tonnes (NO_2)) and ~20% of those from shipping (15.5 million tonnes (NO_2)). Emissions of sulphur are dominated by the shipping sector (8.72 million tonnes) due to the use of low grade fuel with high sulphur content. The contribution to sulphur emissions from road travel (1.9 million tonnes) is ~25% of that due to shipping, whilst aircraft SO_2 emissions are almost negligible in comparison (0.09 million tonnes).

Table 1 Global CO_2, NO_x (expressed as NO_2), and SO_2 anthropogenic emissions in million tonnes for the year 2000 by source (emissions data base from the QUANTIFY project; Hoor *et al.*, 2009).

	Non Transport	Aviation	Road	Shipping	Rail
CO_2	20,689	675	4,200	663.	124
NO_x	56.4	2.8	29.2	15.5	1.5
SO_2	132.5	0.09	1.9	8.7	0.6

Transport sector emissions also differ by geographical region (Figure 1). Road transport emissions have a geographical distribution similar to non-transport related anthropogenic emissions (industry, household, agriculture) and are released often in already significantly polluted air over continental regions. In contrast, shipping emissions are often located within the relatively unpolluted maritime boundary layer. A small fraction of the aviation emissions occur in the vicinity of airports (13% for CO_2 and 11.6% for NO_x, Kim *et al.*, 2007) and, as with road emissions, they become rapidly mixed with other continental anthropogenic emissions. The majority of aviation emissions are however located at cruise levels between 8 and 12 km in altitude. With an increased lifetime at high altitudes, NO_x emissions from aviation can potentially have a significant impact on the distribution of ozone and methane at these altitudes (Stevenson *et al.*, 2004; Köhler *et al.*, 2008).

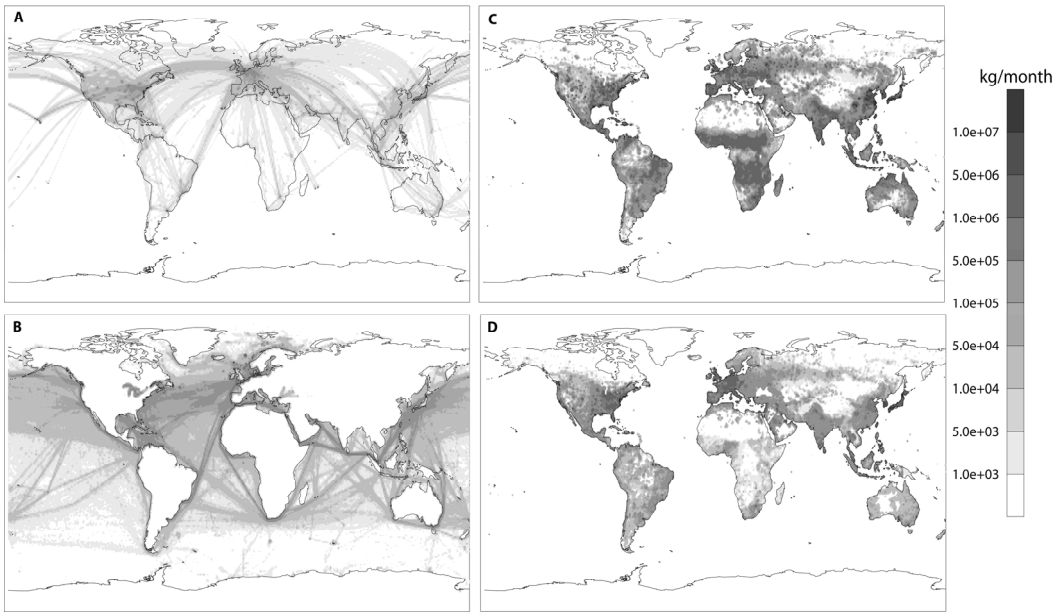

Figure 1: Geographical distribution of NO_x fluxes for the year 2000 in kg/month for: A) aviation, B) international shipping, C) anthropogenic non-transport emissions and D) road transport (Emissions database from the QUANTIFY project; Hoor *et al.*, 2009).

3. Quantifying the climate change contribution of the transport sector

To quantify the extent of climate change due to a variety of source emissions, analytical tools, or metrics, are used. They further enable informed decisions on mitigation policies to be made based on quantifying the climate impact of specific anthropogenic activities such as air travel. Overall, a metric should be simple to understand and well-grounded scientifically, allowing for a comparison between differing emissions and providing a guide to decisions concerning future activities, such as the design and operation of a new aircraft fleet. It is important when choosing a metric that it is closely related to the impact of concern (i.e., if climate stabilization below a given temperature change is of concern then the metric chosen should provide information on the temperature change). Unfortunately, metrics with increasing relevance to climate change impacts and damages inherently increase in uncertainty (Figure 2) thereby reducing confidence in their applicability.

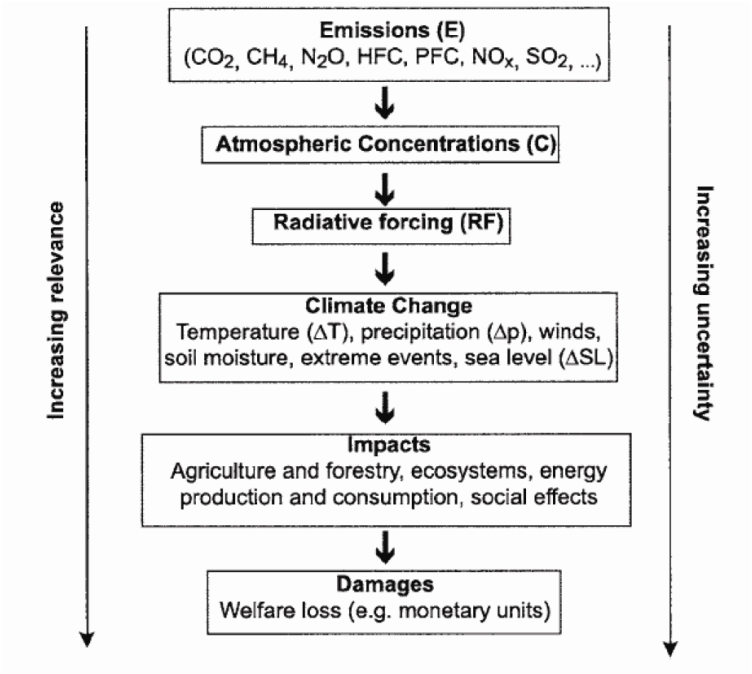

Figure 2: Cause and effect chain of the potential climate effect of emissions (from Fuglestvedt *et al.*, 2003)

Three metrics commonly used to determine the effects of the transportation sector on the environment are Radiative Forcing (RF); Global Warming Potential (GWP); and Global Temperature Potential (GTP). RF is an expression of the radiative imbalance resulting from changes in atmospheric composition, land albedo or cloudiness due to human activities. GWP is the integrated RF for either pulse or sustained emissions above the current background levels over a specific time interval compared to the forcing from an equal mass emission of CO_2. Finally GTP combines the GWP (for either pulse or sustained emissions) with an analytical climate model to give the ratio of the surface temperature change that will

occur at a certain point in time to the temperature change for an equal mass emission of CO_2. RF, which we will focus on here, has been widely used as a climate change metric for long-lived gases, but its suitability has been questioned for the other GHGs as some of their RFs are spatially inhomogeneous and seasonally varying (Shine *et al.*, 2005a). RF used as backward looking metric is a measure of the change in the Earth's energy balance at the top of the atmosphere dependent on integrated past emissions and the lifetime and radiative efficiency of their products in the atmosphere. In the future, changes in aviation operations will likely alter the relative magnitude of aviation effects between the short and the long lived radiative agents.

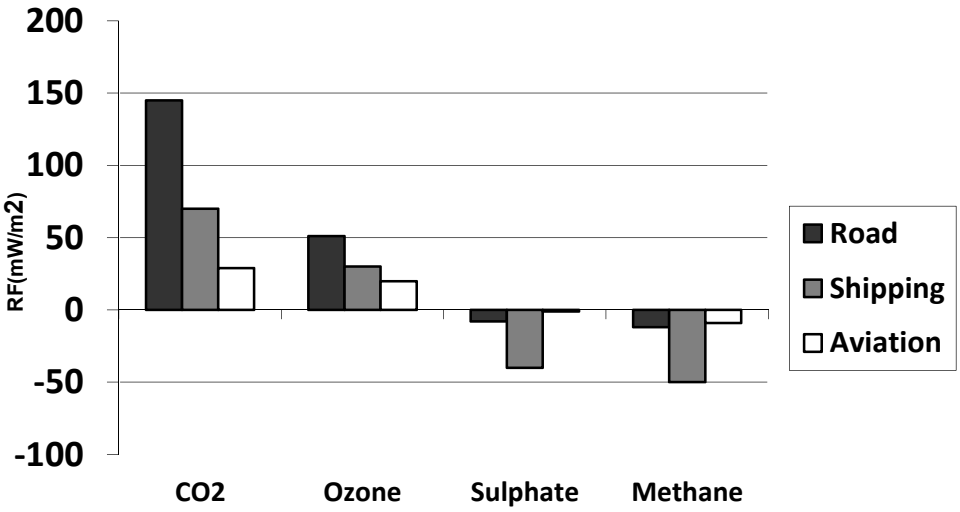

Figure 3: Global mean radiative forcing values for 2000 due to the emissions from the different modes of transport (road/shipping/aviation) in mW/m ^{2} relative to preindustrial times (data from Fuglestvedt *et al*., 2008).

The climate forcing contribution from the transportation sector can be calculated for each mode of transport and for each emission type (Fuglestvedt *et al.*, 2008). For comparison, Figure 3 shows the radiative forcing from atmospheric perturbations in CO_2, ozone and methane (due to NO_x emissions) and sulphuric acid aerosol. The CO_2 results are the radiative forcings due to the cumulative CO_2 emissions since 1900, whilst the ozone, aerosol and methane radiative forcing calculations are due to the year 2000 emissions. This difference in the integration periods is appropriate because of the much shorter atmospheric lifetime of radiative forcing associated with the non-CO_2 constituents. It should be noted that the change in methane, due to NO_x emissions, occurs on a longer timescale than ozone and sulphur aerosol perturbations: a decade for methane compared to days/weeks for ozone and aerosol (Stevenson *et al.*, 2004; 2009). The change in lifetime and steady-state methane concentration is calculated offline from a two-years integration following the technique described in

Fuglestvedt *et al.* (1999) using the instantaneous change to OH concentration. The RF is then calculated from the steady-state methane concentration for the year 2000. Due to the long atmospheric lifetime of CO_2 the radiative forcing of CO_2 emissions is dependent not only on present-day emissions but also on the accumulation of the CO_2 emitted in the past. Road transport has been the major contributor to CO_2 radiative forcing until 2000 with 145 mW/m^2, shipping (65 mW/m^2) representing ~50% that of road travel, and aviation (25 mW/m^2) representing ~15%. The integrated radiative forcing values in Figure 3 are not linearly related to the CO_2 emissions in 2000 as shown in Table 1 because of significant differences between the transport sectors in the historical time line of their emissions. This is particularly evident for shipping and aviation CO_2 emissions, which are nearly equivalent in 2000 in Table 1, yet the RF from shipping is more than double the aviation values in Figure 3. The difference in integrated RF between these two sectors derives from different historical start dates for significant CO_2 emissions: ~1870 for shipping and ~1950 for aviation. The equal ratios of 15% between aviation and road sources in terms of CO_2 emissions and RF due to CO_2 can be explained by the fact that road CO_2 emission increased at a rate of 12 million tonnes per year before 1950 and 72 million tonnes per year afterwards, following the pattern of aviation growth.

The magnitude of NO_x emissions from aviation is significantly less than those from road or shipping (see Table 1), but with the majority of these emissions occurring at cruise altitude (8-12 km) with increased ozone production efficiency (Stevenson *et al.*, 2004; Köhler *et al.*, 2008) and higher ozone radiative efficiency (IPCC 1999, Figure 6-10), aviation leads to the largest ozone radiative forcing increase per unit of NO_x emitted (global RF / global emissions: 1.7, 2.0 and 7.2 mW/m^2/million tonnes(NO_2) for road, shipping, and aviation, respectively) in the transport sector. As road emissions are released within the already polluted continental regions near the ground, where also the lifetime of NO_x is short their relative contribution to ozone radiative forcing is smaller (Hoor et al., 2009). With a lifetime of weeks to months for ozone, the radiative forcing calculated for the ozone perturbation is not dependent on the accumulation of ozone in the atmosphere (such as CO_2) but is strongly related to the magnitude and location of the NO_x emissions that drove the ozone production. For aviation, the radiative forcing due to increased atmospheric ozone is quantitatively similar to the radiative forcing due to CO_2 (18 mW/m^2 from O_3 and 24 mW/m^2 from CO_2 perturbations in terms of global means). However, the spatial distributions of these two contributions differ significantly as shown in IPCC 1999 (Figure 6-9).

Shipping has the largest negative radiative forcing contribution from methane concentration changes within the transport sectors. This is the result of the high NO_x/CO and NO_x/VOC ratios in the emissions and the unpolluted environment (low NO_x) in which the

emissions are released (Fuglestvedt, 2008). These higher NO_x/CO and NO_x/VOC ratios increase the OH production and thus the loss of methane (cooling effect) from shipping emissions. The absolute amount of emissions from present day aviation fleet results in a relatively low radiative forcing contribution from methane concentration change due to aviation sources.

As the largest contribution to transport sulphur emissions, shipping sulphur emissions have a significant negative contribution to radiative forcing (a cooling effect) of -40 mW/m^2. The contributions from road and aviation sulphur emissions are negligible as the concentrations in sulphur of the fuels used in these transport modes are extremely low and regulated.

Focusing on aviation, the total radiative forcing from aviation in 2000 was calculated at 48 mW/m^2 in Sausen et al (2005). Within this calculation the effect on cirrus clouds has not been accounted for due to poor scientific knowledge and high uncertainty in its estimate. More recently the effects of aviation on climate change have been re-assessed for the year 2005 (Lee *et al.*, 2009 a). The updated value for the aviation contribution to radiative forcing from preindustrial times until 2005 is 55 mW/m^2 excluding the induced cirrus effect. The radiative forcing components, listed below, produced by the different aviation emissions are quantitatively represented in Figure 4 in a format consistent with the IPCC (2007) results for all anthropogenic forcings (adapted from Lee *et al.*, 2009a). The change in radiative forcing can be summarized in the following way:

- *positively* (warming) by emissions of CO_2: 28 mW/m^2;
- *positively* by tropospheric O_3 increase (via atmospheric chemistry from emissions of NO_x): 26 mW/m^2;
- *negatively* (cooling) by the reduction of ambient CH_4 (via atmospheric chemistry from emissions of NO_x): -12 mW/m^2;
- *negatively* by sulphate particles arising from sulphur in the fuel: -5 mW/m^2;
- *positively* by emissions of soot particles: 3 mW/m^2;
- *positively* by linear persistent contrails (condensation trails) formed in the wake of the aircraft: 11 mW/m^2;
- *positively* by enhanced cirrus cloud coverage formed from spreading contrails. Additional cloud condensation nuclei (particles) introduced into the upper troposphere by aircraft exhaust emissions could also influence natural cirrus clouds,

probably causing a positive forcing (however these results have presently large uncertainties): 33 mW/m^2.

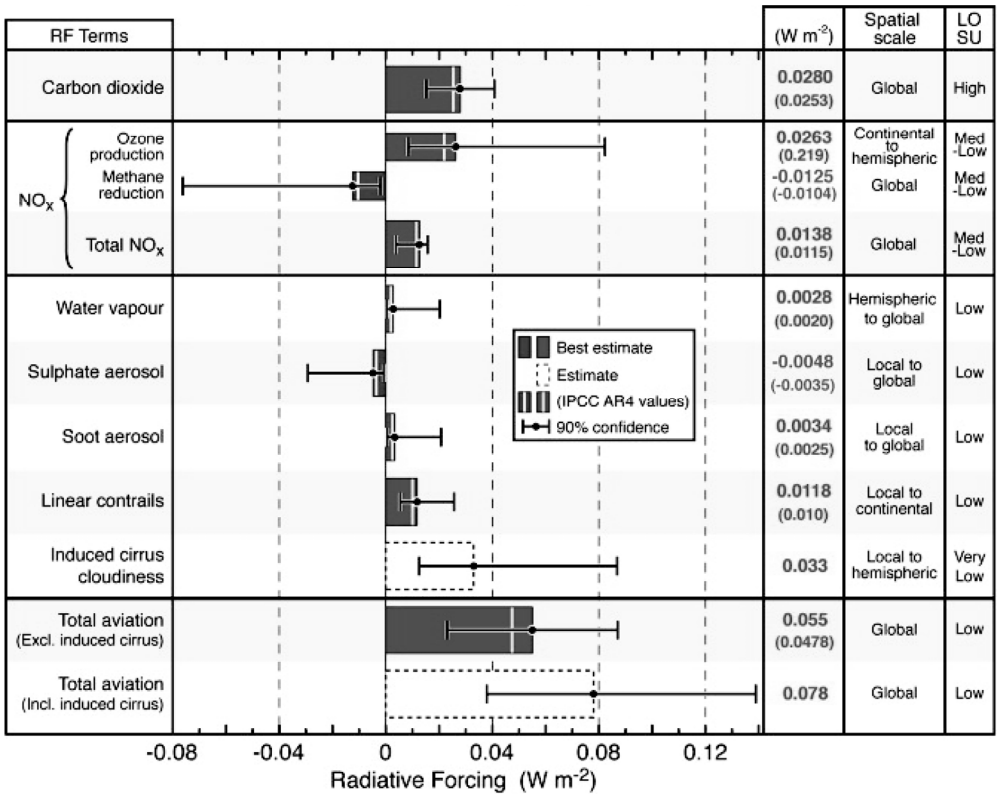

Figure 4 Radiative forcing components from global aviation as evaluated from preindustrial times until 2005. Bars represent updated best estimates or an estimate in the case of aviation-induced cloudiness (AIC) as listed in Table 2. IPCC AR4 values are indicated by the white lines in the bars as reported in IPCC 2007. The induced cloudiness (AIC) estimate includes linear contrails. Numerical values are given on the right for both IPCC AR4 (in parentheses) and updated values. Error bars represent the 90% likelihood range for each estimate. The median value of total radiative forcing from aviation is shown with and without AIC. The median values and uncertainties for the total NO_x RF and the two total aviation RFs are calculated using a Monte Carlo simulation. The Total NOx RF is the combination of the CH_4 and O_3 RF terms, which are also shown here. The AR4 value noted for the Total NOx term is the sum of the AR4 CH_4 and O_3 best estimates. Note that the confidence interval for 'Total NO_x' is due to the assumption that the RFs from O_3 and CH_4 are 100% correlated; however, in reality, the correlation is likely to be less than 100% but to an unknown degree. The geographic spatial scale of the radiative forcing from each component and the level of scientific understanding (LOSU) are also shown on the right (adapted from Lee *et al.*, 2009a).

4. Shortfalls In The Usage of Radiative Forcing

Radiative forcing has a long-standing usage in climate assessments but it is important to note that it is not designed to fully account for differences in the climate response between forcing agents or species (otherwise referred to as the efficacy), and it is not expected to directly inform the user of the final climate change impacts related to the radiative forcing

modifications (e.g. 'damages' as shown in Figure 2). The Global Warming Potential provides the integrated radiative forcing, over a chosen time interval, compared with the equivalent integrated forcing from an equal mass emission of CO_2. The simple analytical calculation for GWP is well established for emission regulatory purposes but as with radiative forcing is not necessarily proportional to the final climate change impact. As with RF, GWP does not account for differences in the climate response between forcing agents. For example, two greenhouse gases may have the same GWP but one may have high radiative forcing and short lifetime while the second has low radiative forcing and long lifetime. The change in temperature due to these two gases, with equal GWPs, will be different (Shine *et al*., 2005b). When used as a global metric, GWP unlike radiative forcing, is unable to provide information on regional variations or to account for possible changes to the background atmosphere. Global Temperature Potential (GTP) uses GWP combined with an analytical climate model to give the ratio of the change in surface temperature at a chosen time, to the temperature change due to the emission of an equal mass of CO_2. As with GWP it uses a simple analytical calculation, although there are extra uncertainties due to unknown climate responses (climate feedbacks such as change in albedo or extra release of greenhouse gases). Unlike both RF and GWP, GTP is more relevant for determining the climate response to human activities through changes in surface temperature, which consequently drive the changes in other meteorological phenomena (wind, precipitation). This is in comparison to RF and GWP, which consider the radiative climate response (W/m^2).

As a backward looking metric, radiative forcing, due to its consideration of historical emissions, accounts for the concentration changes of greenhouse gases that have occurred due to short-lived aviation emissions, but does not represent the long-term future impact of CO_2. Radiative forcing from the aviation fleet will not be a constant in the future if aviation operations remain constant. Therefore, it is incorrect to use radiative forcing for the present aviation fleet as the future radiative forcing value of the fleet. This is simply because of the long lifetime of CO_2 (100-1000 years) which causes the CO_2 radiative forcing of a stable operating fleet to increase with time indefinitely. In the case of the radiative forcing approach originally suggested for use in determining the climate change contribution due to aviation by the European Parliament (13 November, 2007), the magnitude of the individual contributions from different radiative agents to climate change is heavily dependent on the choice of the time horizon. In addition, it would not have been applied consistently across the different transport mode sectors (road, rail or shipping, for example).

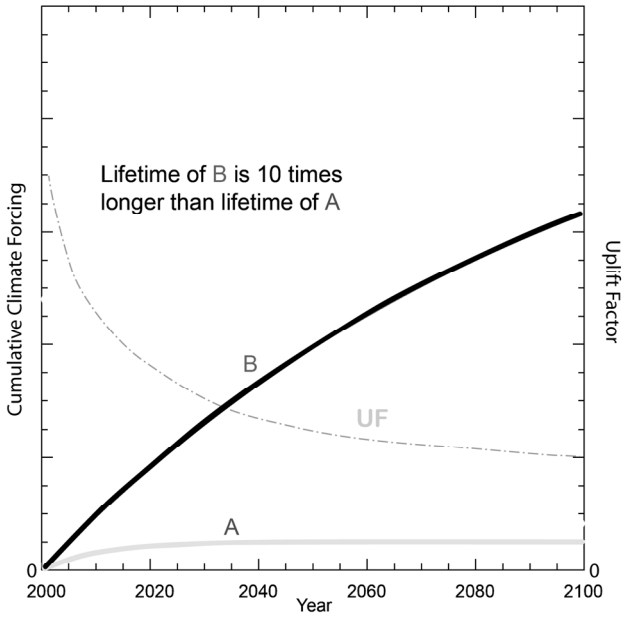

Figure 5 Conceptual graphic representation of total climate forcing over 100 years for two example species - 'A' (shown in grey) and 'B' (shown in black). The uplift factor (UF, shown in grey dot-dashed) is the total climate forcing of A+B divided by the climate forcing of B. The lifetime of the species B is 10 times longer than the lifetime of species A. The time series of the forcing from species A and B are indicative of a constant release of aviation emissions.

If the impact of aviation on the future climate is assumed to be a multiple of its CO_2 emissions (i.e., an *uplift factor* is adopted which is often assumed to be equal to the RFI as calculated using historical emissions with a backward calculated RF), using the 100-year time horizon adopted in the Kyoto Protocol, and applied systematically across all aviation radiative forcing contributions, its value would almost certainly be much less (1.5 calculated in Forster 2006) than the factor 2 originally suggested by the European Parliament. Furthermore this factor would vary within the timeframe considered. For example, in the scenario presented in Figure 5 the uplift factor varies between 2.7 and 1.5 during the 100 year timescale. This uplift factor is based on the RF changes over 100 years due to two example species, A and B, where the lifetime of species B is 10 times longer than the lifetime of species A, and both species have sustained constant emissions during the period.

A potentially significant contribution to climate change from aviation also results from the formation of condensation trails (line-shaped clouds otherwise referred to as contrails). Contrails form when conditions in the expending and cooling exhaust gas plume reach saturation with respect to liquid water, and persist if the environment remains saturated with respect to ice. This mechanism can be represented by the Schmidt-Appleman criterion (Schmidt, 1941; Appleman, 1953; Schumann, 2002), which predicts the threshold temperature for contrail formation based on ambient pressure and relative humidity, the

combustion temperature and overall efficiency, and the emission index of water vapour from aviation. As with cirrus clouds, contrails act to reduce the amount of both incoming short wave radiation (resulting in a cooling effect) and outgoing long-wave radiation (resulting in a warming effect). The overall potential climate effect of aviation from contrails depends on engine characteristics, the ambient background conditions and the distance flown (i.e., the contrail coverage) and their potential development into aviation-induced cirrus. It is this dependency on the traffic movements and atmospheric conditions (Gierens *et al.*, 2009) that further limit the usefulness of using an uplift factor or a multiple of the CO_2 emissions or fuel usage for aviation.

An uplift factor approach can be of value, provided it is understood that a single time horizon must be chosen and applied across all emissions (though not for contrails/cirrus as discussed above), and then only if the transportation sector's contribution to climate change is adequately understood. A choice of a specific uplift factor could lead to design and technology measures being applied within industry in order to modify the tradeoff between different engine emissions, which may result in future global increased radiative forcing contribution and climate response. For example, if the European Parliament were to adopt a similar methodology for calculating the uplift factor for shipping to that originally suggested for aviation, they would obtain a negative uplift factor since sulphur emissions from shipping lead to the formation of short-lived particles that cause a strong cooling (Figure 6). However, as for aviation, over long time horizons the role of CO_2 becomes dominant.

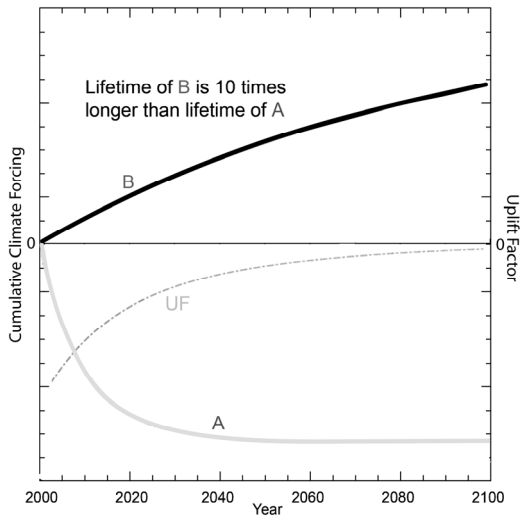

Figure 6 Conceptual graphic representation showing total climate forcing over 100 years of two example species - 'A' (shown in grey) and 'B' (shown in black). The uplift factor (UF, shown in grey dot-dashed) is the total climate forcing of A+B divided by the climate forcing of B. The lifetime of the species B is 10 times longer than the lifetime of species A. The time series of the forcing from species A and B are indicative of a constant release of shipping emissions.

5. Conclusions

There are large differences in the radiative forcing resulting from emissions produced by the transport sector (long-lived versus short-lived) as well as between the forcing due to the transport subsectors (in term of signs and magnitudes). In terms of present day radiative change due to historical aviation emissions, CO_2 dominates the warming contribution to the forcing, followed by the production of tropospheric O_3. Aerosols and reduction in CH_4 have a cooling effect at a lower magnitude. By subsector, again taking into account the historical emissions, road transport has a dominant warming effect followed by aviation at a lower strength. Shipping causes a net cooling due to the strong effects of aerosols and methane. The radiative forcing change from aviation for the year 2005 has been estimated at 48 to 55 mW/m^2, around 3 percent of the 1.6 W/m^2 radiative forcing change due to all anthropogenic activities as presented in IPCC (2007). Within the radiative forcing calculations due to aviation, the impact from cloud formation (contrails and cirrus) has the highest uncertainty (Lee *et al.*, 2009a).

Within the developed countries, the aviation sector has the largest growth rates for greenhouse gas emissions within the transportation sector (Schäfer *et al.*, 2009). Attempting to address climate change by an emissions trading scheme that includes the CO_2 emissions from aviation as in the EU-ETS is an important first step towards accounting for the aviation contribution to anthropogenic climate forcing. The absence of the non-CO_2 climate forcing agents from the scheme however needs to be addressed. There are a variety of metrics available for quantifying the climate change impact of anthropogenic emissions and activities. Of concern is the result that the relative importance of contributing climate species, or different transportation sectors, depends strongly upon the metric and the timeline chosen. The recognition that climate impacts extend beyond CO_2 alone is critically important. The key however is to ensure that a scientifically rigorous methodology is applied appropriate for the respective emissions effect on climate. Although not discussed in detail earlier it is obviously desirable that any metric adopted should be applicable across all sectors (e.g. transport, industry etc.) in order to provide an accurate comparison of the climate effects of the various sectors. Uplift factors for present day forcings are not suitable to represent and compare different atmospheric perturbations in term of future climate changes and instead we suggest that an appropriate range of analytical tools need to be developed to quantify the climate impact of the various emissions from aviation as well as the impact of aviation relative to other transportation and energy sectors.

Acknowledgements: O. Dessens acknowledge funding from QUANTIFY (European Union 6th Framework Program under contract number 003893). We are very grateful for the comments from two reviewers for constructive input to the paper.

References

Appleman, H. (1953) The formation of exhaust contrails by jet aircraft, Bull. Am. Meteorol. Soc., **34**, 14-20.

Directive 2008/101/EC of the European Parliament and of the Council of November 2008 amending Directive 2003/87/EC so as to include aviation activities in the scheme for green house gas emission allowance trading within the community. Official Journal of the European Union L8, 13 January 2009, pp. 3-21.

Forster, P.M. de F., K.P. Shine, and N. Stuber (2006). It is premature to include non-CO_2 effects of aviation in emission trading schemes, *Atmos. Env.* **40**, 1117–1121.

Forster, P.M. de F., K.P. Shine, and N. Stuber (2007). Corrigendum to "It is premature to include non-CO_2 effects of aviation in emission trading schemes", *Atmos. Env.* **41**, 3941.

Fuglestvedt, J., Berntsen, T., Isaksen, I., Mao, H., Liang, X., and Wang, W. (1999). Climatic forcing of nitrogen oxides through changes in tropospheric ozone and methane: global 3D model studies, Atmos. Environ., 33, 961–977.

Fuglestvedt, J.S., T. Berntsen, O. Godal, R. Sausen, K. P. Shine and T. Skodvin (2003). Metrics of Climate Change: Assessing radiative forcing and emission indices, Clim. Change **58**, 267–331.

Fuglestvedt, J.S., T. Berntsen, G. Myhre, K. Rypdal, R.B. Skeie (2008). Climate forcing from the transport sectors, *PNAS* **105**(2), 454-458.

Gettelman, A. and C. Chen (2013). "The climate impact of aviation aerosols." Geophysical Research Letters 40(11): 2785-2789.

Gierens, K., B. Kärcher, H. Mannstein, B. Mayer (2009). Aerodynamic contrails: Phenomenology and flow physics. J. Atmos. Sci., 66, 217-226.

Gilmore C.K, S.R.H. Barrett, J. Koo and Q. Wang (2013). Temporal and spatial variability in the aviation NOx-related O3 impact Environ. Res. Lett. 8 034027 doi:10.1088/1748-9326/8/3/034027

Hoor, P., J. Borken-Kleefeld, D. Caro, O. Dessens, O. Endresen, M. Gauss, V. Grewe, D. Hauglustaine, I. S. A. Isaksen, P. Jöckel, J. Lelieveld, G. Myhre, E. Meijer, D. Olivie, M. Prather, C. Schnadt Poberaj, K. P. Shine, J. Staehelin, Q. Tang, J. van Aardenne, P. van Velthoven, and R. Sausen (2009). The impact of traffic emissions on atmospheric ozone and OH: results from QUANTIFY, Atmos. Chem. Phys., 9, 3113-3136.

IEA, 2009a, International Energy Agency, Energy Balances of OECD Countries, IEA Paris, 354 pages, ISBN 978-92-64-06120-0.

IEA, 2009b, International Energy Agency, Energy Balances of non-OECD Countries, IEA Paris, 498 pages, ISBN 978-92-64-06126-2.

IPCC, 1999: Aviation and the Global Atmosphere - Prepared in collaboration with the Scientific Assessment Panel to the Montreal Protocol on Substances that Deplete the Ozone Layer J.E.Penner, D.H.Lister, D.J.Griggs, D.J.Dokken, M.McFarland (Eds.), Cambridge University Press, UK, 373 pp.

IPCC, 2007: Climate Change 2007: The Physical Science Bases – Contribution of the Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (Eds.) Cambridge University Press, Cambridge, UK , 996 pp.

Jaeglé, L., D. J. Jacob, Y. Wang, A. J. Weinheimer, B. A. Ridley, T. L. Campos, G. W. Sachse, and D. E. Hagen (1998), Sources and chemistry of NOx in the upper troposphere over the United States, Geophys. Res. Lett., 25(10), 1705-1708.

Kim, B.Y., G. Fleming, J. Lee, I.A. Waitz, J. Clarke, S. Balasubramanian, A. Malwitz, K. Klima, M. Locke, C.A. Holsclaw, L.Q. Maurice, M.L. Gupta (2007). System for assessing Aviation's Global Emissions (SAGE), Part 1: Model description and inventory results, Transportation Research, Part D, Vol 12, 325-346.

Köhler, M.O., G. Rädel, O. Dessens, K. P. Shine, H.L. Rogers, O. Wild, J.A. Pyle (2008). Impact of perturbations to nitrogen oxide emissions from global aviation, *J. Geophys. Res.* **113**, D11305, doi:10.1029/2007JD009140.

Köhler, M.O., G. Rädel, K.P. Shine, H.L. Rogers, J.A. Pyle (2013). Latitudinal variation of the effect of aviation NOx emissions on atmospheric ozone and methane and related climate metrics, *Atmos. Environ.* **64**, 1–9, doi:10.1016/j.atmosenv.2012.09.013.

Lee, D.S., D.W. Fahey, P.M. Foster, P.J. Newton, R.C.N. Wit, L.L. Lim, B. Owen, and R. Sausen, Aviation and global climate change in the 21st century, Atmos. Environ. (2009a), doi:10.1016/j.atmosenv.2009.04.024.

Lee, D.S., G. Pitari, V. Grewe, K. Gierens, J.E. Penner, A. Petzold, M.J. Prather, U. Schumann, A. Bais, T. Berntsen, D. Iachetti, L.L. Lim, R. Sausen, Transport impacts on atmosphere and climate: Aviation, Atmospheric Environment (2009b), doi:10.1016/j.atmosenv.2009.06.005

Sausen *et al.* (2005). Aviation radiative forcing in 2000: An update to IPCC (1999), Meteorol. Z. **14** (4), 555-561.

Sausen R. and U. Schumann (2000). Estimates of the climate response to aircraft CO_2 and NO_x emissions scenarios, *Clim. Change* **44**, 27-58.

Schäfer A. (2005) "Structural Change in Energy Use", Energy Policy, 33(4): 429-437.

Schäfer A., Heywood J.B., Jacoby H.D., Waitz I.A. (2009). Transportation in a Climate-Constrained World, MIT Press.

Schmidt, E. (1941) Die Entstehung von Eisnebel aus den Auspuffgasen von Flugmotoren. Schriften der Dt. Akad. der Luftfahrtforschung, **44**, 1-15.

Schumann, U. (2002) Contrail Cirrus, IN: Cirrus, Eds. D. Lynch *et al.*, Oxford University Press, 231-255.

Shine, K.P., Bernsten, T.K., Fuglestvedt, J.S., Sausen, R., (2005a). Scientific issues in the design of metrics for inclusion of NO_x in global climate agreements. *PNAS* **102**, 15,768–15,773.

Shine, K.P., Fuglestvedt, J.S., Hailemariam, K., Stuber, N., (2005b). Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases, *Clim. Change* **68**, 281–302. Stevenson, D.S., Doherty, R.M., Sanderson, M.G., Collins, W.J., Johnson, C.E., Derwent, R.G. (2004). Radiative forcing from aircraft NO_x emissions: mechanisms and seasonal dependence. *J. Geophys. Res.* **109**, D17307.

Stevenson, D.S. and R.G. Derwent (2009). How does the location of aircraft nitrogen oxide emissions affect their climate impact?, *Geophys. Res. Lett.*, 36, L17810, doi:10.1029/2009GL039422.

Wilcox, L.J., K.P. Shine, B.J. Hoskins (2012). Radiative forcing due to aviation water vapour emissions, Atmospheric Environment, Volume 63, Pages 1-13, ISSN 1352-2310