Contents lists available at ScienceDirect

Transport Policy

journal homepage: www.elsevier.com/locate/tranpol

Aviation and climate change

Olivier Dessens [a,*], Marcus O. Köhler [b], Helen L. Rogers [c], Rod L. Jones [c], John A. Pyle [c,d]

[a] Energy Institute, University College London, London, UK
[b] School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK
[c] Centre for Atmospheric Science, Department of Chemistry, University of Cambridge, Cambridge, UK
[d] NCAS Climate-Composition, University of Cambridge, Cambridge, UK

ARTICLE INFO

Keywords:
Aviation
Climate change
Radiative forcing

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 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 and 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 vapour 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 and Chen, 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 (2009)] 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

* Corresponding author.
E-mail address: o.dessens@ucl.ac.uk (O. Dessens).

http://dx.doi.org/10.1016/j.tranpol.2014.02.014
0967-070X

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 sulphur 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 oxidised 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).

	Nontransport	Aviation	Road	Shipping	Rail
CO_2	20,689	675	4200	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 (Fig. 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).

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 stabilisation 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 (Fig. 2) thereby reducing confidence in their applicability.

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

Please cite this article as: Dessens, O., et al., Aviation and climate change. Transport Policy (2014), http://dx.doi.org/10.1016/j.tranpol.2014.02.014