Aviation and Climate Change: Best practice for calculation of the global warming potential

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Abstract

Purpose

There are specific effects of emissions in high altitude, which lead to a higher contribution of aviation to the problem of climate change than just the emission of CO_2 from burning fuels. The exact relevance is subject to scientific debate, but there is a consensus that aircrafts have an impact that is higher than just their contribution due to the direct CO_2. The gap between this scientific knowledge on the one side and the missing of applicable GWP (global warming potential) factors on the other side is an important shortcoming for life cycle assessment or carbon footprint studies which aim to cover all relevant environmental impacts of the services or products investigated.

Methods

In this paper the state of the art concerning the accounting for the specific effects of aircraft emissions has been identified. Therefore, the relevant literature was evaluated and practitioners were asked for the approaches used by them.

Results

Four major approaches are used ranging from an RFI (radiative forcing index) factor of 1 (no factor at all) to a factor 2.7 for the total aircraft CO_2 emissions. If only emissions in the higher atmosphere are taken into account, RFI factors between 1 and 8.5 are used in practice.

Conclusions

For the time being an RFI of 2 on total aircraft CO_2 (or 5.2 for the CO_2 emissions in the higher atmosphere) is considered to be the best-practice approach because it is based on recent scientific publications, this basic literature cannot be misinterpreted. Furthermore it is also recommend by some political institutions. These factors can be multiplied by the direct CO_2 emissions of the aircraft in order to estimate the total global warming potential.

Keywords: global warming potential, aviation, radiative forcing index, climate change, aircraft, transport services

1 Introduction

Climate change is one of the environmental impacts addressed in nearly every life cycle assessment (LCA) and it is in the focus of carbon footprinting. The metrics used for the assessment is the global warming potential (GWP). This is expressed in most cases in the unit of kilogram of carbon dioxide equivalents per functional unit (kg CO_2-eq). Most LCA studies use the most recent characterisation factors published by the Intergovernmental Panel on Climate Change (IPCC) with the reference year 2006 (Solomon et al. 2007) or sometimes the older version with the reference year 2001 (Albritton & Meira-Filho 2001). The characterisation factors allow assessing the relative impact of different greenhouse gases to the problem of climate change. Different greenhouse gases such as such as methane (CH_4) or dinitrogen monoxide (N_2O) are expressed as carbon dioxide (CO_2), equivalents. There is not much discussion within the LCA community about the application of this indicator (e.g. Guinée et al. 2001; Hauschild et al. 2011).

But, there is one specific issue in this context, for which so far no standardized methodology is available. There are several specific effects of emissions by aircrafts in the higher atmosphere, which lead to a comparable higher contribution of aviation to the problem of climate change than just the emission of CO_2 from burning the aviation fuels. The following pathways are discussed (Penner et al. 2000; UBA 2012):

- Nitrogen oxide (NOx) emissions leading to ozone (O_3) formation and methane (CH_4) degradation
- Stratospheric water
- Contrails
- Sulphate aerosols reflecting sunlight
- Soot aerosols absorbing sunlight

Nevertheless, it is difficult to estimate global warming potential (GWP) characterisation factors for the different emissions that contribute to the problem and Penner et al. (2000) states:

“GWP has provided a convenient measure for policymakers to compare the relative climate impacts of two different emissions. However, the basic definition of GWP has flaws that make its use questionable, in particular, for aircraft emissions. For example, impacts such as contrails may not be directly related to emissions of a particular greenhouse gas. Also, indirect RF (radiative forcing) from ozone produced by NO_x *emissions is not linearly proportional to the amount of NOx emitted but depends also on location and season. Essentially, the build-up and radiative impact of short-lived gases and aerosols will depend on the location and even the timing of their emissions. Furthermore, the GWP does not account for an evolving atmosphere wherein the RF from a 1-ppm increase in* CO_2 *is larger today than in 2050 and the efficiency of NOx at producing tropospheric* O_3 *depends on concurrent pollution of the troposphere. In summary, GWPs were meant to compare emissions of long-lived, well-mixed gases such as* CO_2*,* CH_4*,* N_2O*, and hydrofluorocarbons (HFC) for the current atmosphere; they are not adequate to describe the climate impacts of aviation. In view of all these problems, we will not attempt to derive GWP indices for aircraft emissions in this study. The history of radiative forcing (Figure 1), calculated for the changing atmosphere, is a far better index of anthropogenic climate change from different gases and aerosols than is GWP.”*

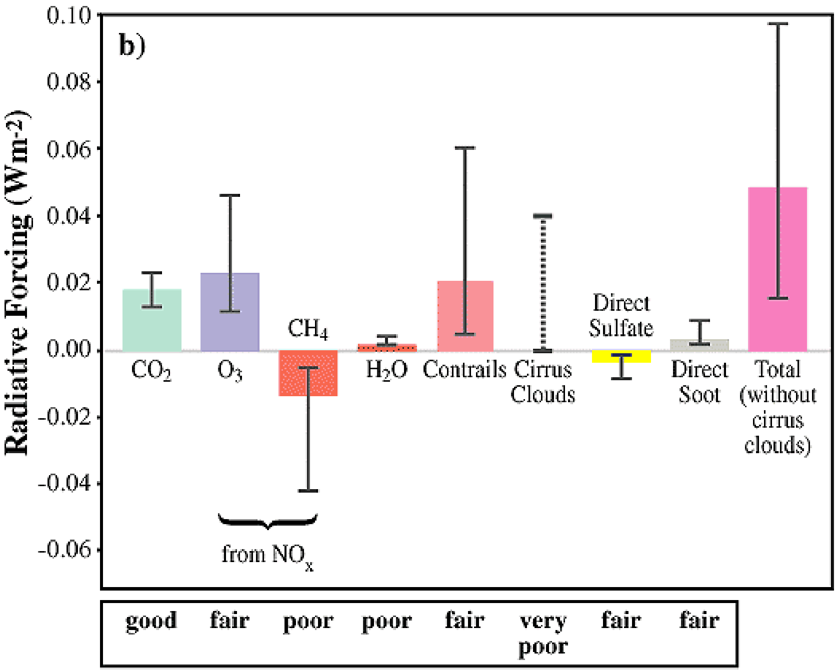

Figure 1 Radiative forcing from aircraft movements in 1992 (Penner et al. 2000) and quality of assessments

The exact relevance of the emissions from aviation is still the subject of scientific debate. Some of the relevant emissions have a very short life time. Thus the concept of GWP, which has been developed for long-lived emissions, is not applicable. Calculations for the contribution of NO_x to these effects show a high variation. The effect of aircraft emissions depends also considerably on the exact location and timing of the emission due to the nonlinear chemistry, which is an important difference compared to the effects caused by “normal” greenhouse gases (see Solomon et al. 2007, chapter 2, paragraph 2.10.3.4 for further references). Several studies have addressed the direct impact of contrails, but the indirect effect of contrails has not yet been investigated in detail (Penner et al. 2000:3.6).

On the other side there is not much doubt that aircrafts have an impact on climate change that is higher than just its direct contribution due to the CO_2 emissions from burning the aviation fuels (e.g. UBA 2012). The gap between this scientific knowledge on the one side and the missing of applicable GWP factors on the other side is an important shortcoming for life cycle assessment (LCA) or carbon footprint (CF) studies which aim to compare all relevant environmental impacts of transport services. The application of only the GWP for greenhouse gases leads to an underestimation of radiative forcing effects caused by aircrafts.

Publications by the IPCC speak about a radiative forcing index (RFI) factor of 3 to 5 that should be multiplied by the direct CO_2 emissions from burning aviation fuels in order to account for all climate change effects of aviation, but so far there is no clear recommendation on a specific factor to be used (Grassl & Brockhagen 2007; IPCC 2001, 2007; Penner et al. 2000). The RFI factor is based on the observation of the present impacts that can be attributed to the total aircraft emissions within one reference year. It is assumed that the amount of emissions will be more or less in a steady state in order to estimate their contribution to climate change. So far it is not related to a specific time frame of observation while GWP can be calculated for 20, 100 or 500 year time horizons. It is also not possible to calculate characterisation factors for the emissions caused by aircrafts which lead to this specific problem and thus the concept of GWP cannot be applied directly.

So far there are many approaches used by different calculators and practitioners in order to deal with this issue. These approaches are discussed in this article. For understanding the different calculations practices some key questions have to be answered:

- Which RFI factor is used by the practitioners in the calculation?
- Is the RFI factor multiplied by the total CO_2 emissions during the operation of the aircraft or just with the part of emissions in the higher atmosphere?
- If the latter approach is used: how has the share of emissions in the higher atmosphere been calculated?

In this paper the state of the art and the best practice of accounting for the specific effects of aircraft emissions is evaluated. Therefore, LCA and CF experts were asked directly and via different email discussions lists. Furthermore, relevant literature and internet investigation have been used to find further examples on this issue.

2 Overview on approaches used in life cycle assessment and carbon footprinting

Four major approaches for the interpretation of available literature, which are used in practice, have been identified. All found approaches are shown in Table 1. They range from an RFI factor of 1 (no factor at all) to an RFI factor 2.7 applied on all aircraft CO_2 emissions.
In life cycle inventory analysis (LCI), information about the specific amount of aircraft CO_2 emissions is difficult to extract (e.g. ecoinvent Centre 2010; European Commission 2010; Hischier et al. 2001). But, in some databases such as ecoinvent CO_2 emissions in the stratosphere are accounted for as an emission in a specific subcompartment (Frischknecht et al. 2007a; Spielmann et al. 2007). In ecoinvent data for average passenger transports by aircraft, the share of CO_2 emissions in the lower stratosphere and upper troposphere is about 24% of the total aircraft CO_2 emissions (corrected data[1] from Spielmann et al. 2007). Thus it is possible to recalculate the RFI factor for this specific share of emissions in the higher atmosphere. The above mentioned RFI factor of 1 to 2.7 corresponds than to an RFI factor of 1 to 8.5 that can be applied on the CO_2 emissions in the lower stratosphere and upper troposphere. The column showing these figures is labelled as “RFI, fully on CO2, stratosphere” in Table 1.

The first group of approaches does not apply a specific RFI factor to aircraft CO_2 emissions. Thus these approaches take a conservative interpretation of the available literature and only account for the GWP of greenhouse gases (IPCC 2007). The interpretation that aircrafts emissions do not have a specific higher impact is mainly made by database developers such as ecoinvent (Frischknecht et al. 2007b; Hauschild et al. 2011), software providers such as SimaPro (PRé Consultants 2012), life cycle impact assessment methods (Frischknecht et al. 2009; Goedkoop & Sprinsma 2000; Goedkoop et al. 2009) and in several international standards related to LCA and carbon footprinting (e.g. Carbon Trust & DEFRA 2011; International Organization for Standardization (ISO) 2011; WBCSD & WRI 2011). Considering the broad range of literature confirming the surplus impacts of aircrafts concerning climate change these approaches are not considered to be appropriate to be used in assessment.

The second group of approaches applies a RFI factor of 2.7-3 only to the CO_2 emissions in the higher atmosphere (Grießhammer and Hochfeld 2009; Knörr 2008atmosfair 2008). It seems as if it is not clear how the older IPCC publications have to be interpreted and if the factor provided in these publications has to be applied to the total CO_2 of the aircraft or just the part in the higher atmosphere (IPCC 2007; Penner et al. 2000Grassl & Brockhagen 2007). This approach was mainly found to be used in the German language area. It seems to be based on a report and interpretation published by the German federal environmental agency (Mäder 2008). It is used by some companies for calculations necessary to provide carbon offsetting for passenger flights (e.g. atmosfair 2008). As these approaches are based on partly outdated literature that is not easy to interpret they are not considered for determining the best-practice in this article.

The third group of approaches applies a factor of 1.7 to 2 to all CO_2 emissions from aircrafts, which corresponds to a factor of about 3.9 to 5.2 for emissions in the higher atmosphere. This approach is based on recent papers

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[1] An error in ecoinvent data have been discovered while elaborating this article and have been corrected. The calculation of average contributions by Spielmann (2007:Table 7-7) was erroneous and has been corrected with the shares of mode of operation provided by Spielmann (2007:Table 7-10).

published in scientific journals (Lee et al. 2009; Lee et al. 2010; Peters et al. 2011). These papers provide clear recommendations how they applied and used the RFI factor. The Stockholm Environment Institute and the German Umweltbundesamt came also to these RFI figures based on a more political discussion of different literature sources (Kollmuss & Crimmins 2009; UBA 2012). This RFI factor is used by at least one company providing carbon offsetting services (myclimate 2009). A new but in the range similar calculation has been made by Azar & Johansson 2012). They calculated emission weighting factors (EWFs) for the CO_2 from aircrafts with 5 different metrics (GWP, GTP, SGTP, and two economic metrics, relative damage cost (RDC) and a cost-effective trade-off (CE-TO)). The range found for the EWF was 1.3 to 2.9. They named 1.7 to be the best estimate using the GWP metric. This group of approaches seems to be based on the most recent literature. The range of results is confirmed by different independent researchers. Thus, this group of approaches is considered to be the most appropriate one.

The fourth group of approaches is based on the same original literature as the second one (IPCC 2007), but interprets the factors 2.7 to 2.8 in a way that it has to be applied to the total CO_2 released by aircrafts (Frischknecht et al. 2007b; Gössling & Upham 2009). This would correspond to an RFI factor of about 8.1 to 8.5 on the CO_2 emissions in the higher atmosphere. This approach is used by some companies providing carbon offsetting services such as Primaklima[2] and greenmiles[3]. As this seems to a misinterpretation this group of approaches is not taken into account for the recommendations in this article.

The scenarios calculated by two groups of authors (Frischknecht et al. 2007b; Peters et al. 2011) consider also the share of different types of emissions to the total. This would allow calculating specific GWP factors for the contribution of single air emissions as described in the beginning of this article. But, these GWP factors depend on the actual total amount of emissions contributing to these pathways and thus it would be more complicated to be updated. Such an approach is thus not further discussed in this article.

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[2] www.prima-klima-weltweit.de

[3] www.greenmiles.de

Table 1 Overview on approaches used for the calculation of greenhouse gas emissions related to aviation. If not provided in the publication, the “RFI, fully on CO_2, stratosphere” has been calculated based on the share of this type of emissions in corrected ecoinvent data v2.2.

Group	Application	RFI, CO2 stratosphere	RFI, other aircraft CO_2	*RFI, fully on CO_2, stratosphere*	calculated GWP per pkm	Interpretation	Scientific background paper
1	ecoinvent v2.2	1	1	1.0	0.127	Frischknecht et al. 2007b	IPCC 2007
	SimaPro	1	1	1.0	0.127	PRé Consultants 2012	IPCC 2007
	PAS 2050:2011	1	1	1.0	0.127	Separate reporting of aircraft CO_2 is necessary.	Carbon Trust & DEFRA 2011
	ISO/CD 14067.3:2011	1	1	1.0	0.127	CO_2 from aircrafts should be reported separately, no recommendation for assessment.	International Organization for Standardization (ISO) 2011
	Product Accounting & Reporting Standard	?	?			For air travel emission factors, multipliers or other corrections to account for radiative forcing may be applied to the GWP of emissions arising from aircraft transport. If applied companies should disclose the specific factor used.	WBCSD & WRI 2011
	ILCD Handbook	1	1	1.0	0.127	Not mentioned as a specific issue	Hauschild et al. 2011
-	Forster et al. 2006, 2007, without cirrus	1.2	1.2	1.8	0.148	Gössling & Upham 2009	Cited as Forster et al. (2006, 2007)[4]
2	PCF - Germany	2.7	1	2.7	0.171	Grießhammer & Hochfeld 2009	IPCC 2007; Penner et al. 2000
	atmosfair	3	1	3.0	0.178	atmosfair 2008	Grassl & Brockhagen 2007 based on IPCC 2007
	EcoPassenger	3	1	3.0	0.178	Based on (atmosfair 2008), calculated range of total RFI of 1.27 to 2.5 based on travel distances.	Knörr 2008
	CO2OL, www.co2ol.de	1.27-2.7	1.27-2.7	3.0	0.178	Depending on travel distance. Own assumption based on (Grießhammer & Hochfeld 2009; Knörr 2008).	Knörr 2008

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[4] http://www.sciencedirect.com/science/article/pii/S1352231005010587$

Group	Application	RFI, CO2 stratosphere	RFI, other aircraft CO_2	*RFI, fully on CO_2, strato-sphere*	calculated GWP per pkm	Interpretation	Scientific background paper
	ESU-services, scenario, 2010	2.99	1	3.0	0.178	Geometric mean of RFI 1.9 to 4.7, atmosfair concerning application only to CO_2, stratosphere	Grassl & Brockhagen 2007 based on IPCC 2007
3	Stockholm Environment Institute	2	2	5.2	0.235	Kollmuss & Crimmins 2009	IPCC 2007
	Umweltbundesamt	2	2	5.2	0.235	UBA 2012	Lee et al. 2009 and other literature
	myclimate	2	2	5.2	0.235	myclimate 2009	Kollmuss & Crimmins 2009
	Lee et al. 2009	2	2	5.2	0.235	N. Jungbluth	Lee et al. 2009; Lee et al. 2010
	Peters et al. 2011	1.8	1.8	4.6	0.219	N. Jungbluth[5], calculation in the paper shows the contribution of different emissions and the influence of time frames	Peters et al. 2011
	Azar & Johansson 2012	1.7 (1.3-2.9)	1.7 (1.3-2.9)	3.9	0.202	Calculation of emissions weighting factors (EWFs) with 5 different metrics (GWP, GTP, SGTP, and two economic metrics, relative damage cost (RDC) and a cost-effective trade-off (CETO)). The range found for the EWF was 1.3 to 2.9. Using the GWP metric 1.7 is provided as best estimate.	Azar & Johansson 2012
4	Forster et al. 2006, 2007, with max. cirrus	2.8	2.8	8.5	0.321	Gössling & Upham 2009	Cited as Forster et al. (2006, 2007)
	ecoinvent, scenario	2.72	2.72	8.2	0.312	Frischknecht et al. 2007b, GWP also calculated for single emissions	IPCC 2007
	Primaklima	2.7	2.7	8.1	0.310	Primaklima[6]	IPCC 2007
	greenmiles	2.7	2.7	8.1	0.310	Personal communication with Dr. Sven Bode (Greenmiles GmbH)	IPCC 2007

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[5] According to a personal communication with C. Soli in April 2012.

[6] http://www.prima-klima-weltweit.de/co2/kompens-berechnen.php

3. Recommendations for best practice

This paper cannot solve the scientific issues and difficulties behind calculating RFI or GWP of aircraft emissions. Nevertheless it seems to be necessary to better harmonize the approaches used in LCA and CF calculations. In the moment different approaches come to quite different results and thus have a large influence on the outcome of studies where emissions from aircrafts play an important role.

At this time the factor of 2 on total aircraft CO_2 (or 5.2 for the emissions in the higher atmosphere) is considered to be the most convincing approach for the following reasons. It is based on the recent scientific publications (Azar & Johansson 2012; Lee et al. 2009; Lee et al. 2010; Peters et al. 2011). This basic scientific literature cannot be misinterpreted (as it is the case for the second and fourth group of approaches). Furthermore it is also recommended by some political institutions (Kollmuss & Crimmins 2009; UBA 2012). It is recommended to apply the factor if possible only on the emissions in the higher atmosphere because this allows for a better differentiation between short and long distance flights. Based on the evaluations of the state of the art in this article, it is recommended using this factor as a best practice approach for the time being.

4. Results

Figure 2 shows the implications of this recommendation for the calculation of the GWP with a 100 year time horizon according to Solomon et al. (2007) and expressed in carbon dioxide equivalents (CO_2-eq). Without applying an RFI factor, long and short-distance flights show a carbon footprint between 108 and 213 grams of CO_2-eq per passenger-kilometre, respectively. Including additional impacts in the higher atmosphere rises this to 220 to 320 grams of CO_2-eq. Taking the RFI factor into account, flying is clearly worse from a global warming point of view than other means of passenger transportation compared in Figure 2. Without the application of an RFI factor short distance flights would have about the same emissions as average passenger cars.

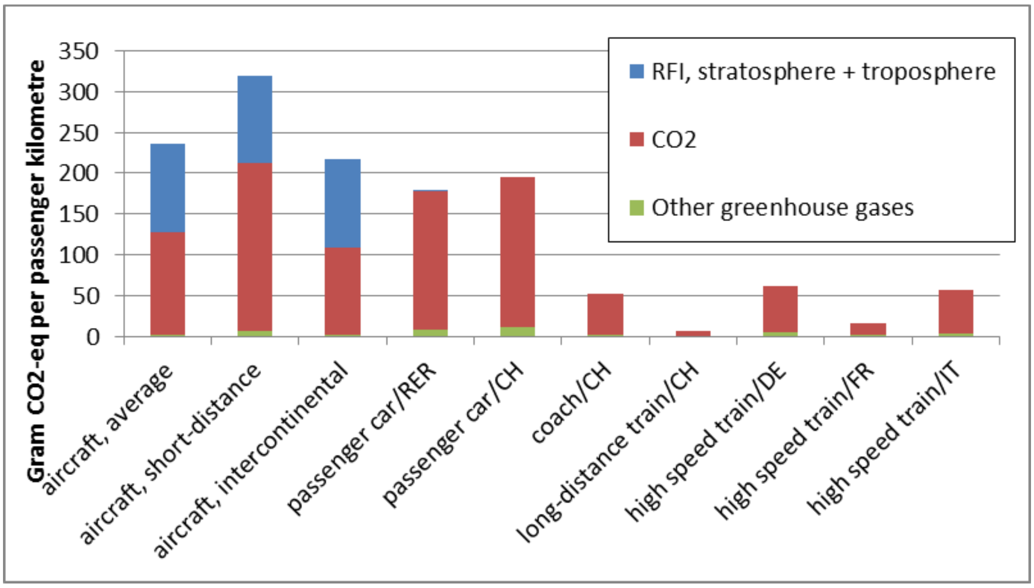

Figure 2 Global warming potential of different means of passenger transports based on corrected ecoinvent v2.2 data (LC-inventories 2013; Spielmann et al. 2007) considering the recommended RFI factor of 5.2 for emissions in the higher atmosphere. RER – European average, CH – Switzerland, DE – Germany, FR – France, IT - Italy

5. Outlook

This recommendation should be revised as soon as the IPCC provides clear recommendations on this issue or if new scientific results are published leading to different conclusions.

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