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Recommendations for calculation of the global warming potential of aviation including the radiative forcing index

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Recommendations for calculation of the global warming potential of aviation including the radiative forcing index

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Contents

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Abstract

Aircrafts contribute more to global warming than can be expected from their CO_2 emissions alone. The relevant scientific evidence is available. However, suitable GWP factors (Global Warming Potential) for relevant emissions are lacking. This is a shortcoming in the calculation of the CO_2 footprint (CF). In an article accepted by the Int J LCA, the state-of-the-art for accounting for such impacts is presented. Approaches found for the so-called RFI (radiative-forcing-index) factor are ranging from 1 to 2.7. This RFI factor can be multiplied with the direct CO_2 emissions of aircrafts to calculate the total global warming potential of aviation services.

An RFI factor of 2 on total aircraft CO_2 emissions is recommended in this article because it is based on the correct interpretation of the most recent scientific publications. If detailed data on the share of emissions in the higher atmosphere are available, calculations will be more accurate if the CO_2 emissions in the higher atmosphere are multiplied by a factor of 5.2. In this way, in typical assessments, this leads to a relevant increase in the GWP impacts due to aviation services.

The proposed method can be applied in carbon footprint and life cycle assessment studies. It is recommended to use this factor at least in a sensitivity analysis if impacts of aviation transport play a relevant role in a life cycle. The factor also needs to be considered for aircrafts using biofuels.

Kurzfassung

Flugzeuge tragen mehr zur globalen Erwärmung, als allein auf Grund ihrer direkten CO_2-Emissionen zu erwarten ist. Die entsprechenden wissenschaftlichen Erkenntnisse liegen vor. Es fehlen jedoch geeignete GWP-Faktoren (Global Warming Potential) für die für diesen Effekt relevante Emissionen. Dies ist ein Mangel bei der Berechnung des CO_2-Fußabdrucks (CF). In einem Artikel, der vom Int J LCA zur Publikation angenommen wurde, wird der Stand der Wissenschaft zur Berücksichtigung solcher Auswirkungen in Ökobilanzen aufgezeigt. Die Ansätze für RFI-Faktoren (radiative Forcing-Index) reichen von 1 bis 2.7. Dieser RFI Faktor wird dann mit den direkten CO_2-Emissionen von Flugzeugen multipliziert, um das gesamte Treibhauspotenzial von Flugverkehrsdiensten zu berechnen.

Gemäss der Analyse im Artikel wird ein RFI-Faktor von 2 für die gesamten CO_2-Emissionen von Flugzeugen empfohlen, da er auf der richtigen Interpretation der neuesten wissenschaftlichen Veröffentlichungen basiert. Wenn detaillierte Daten über den Anteil der Emissionen in der höheren Atmosphäre vorliegen, sind die Berechnungen genauer, wenn ein Faktor von 5.2 direkt mit der Menge der CO_2-Emissionen in der höheren Atmosphäre multipliziert wird. Auf diese Weise führt dies in der Bewertung zu einer relevanten Erhöhung des Treibhauspotenzials durch Luftverkehrsdienstleistungen.

Der vorgeschlagene Ansatz und Faktor kann für die Berechnung von CO2-Fussabdrücken und Ökobilanzen verwendet werden. Es wird empfohlen diesen Faktor in alle Studien, zumindest in einer Sensitivitätsanalyse, einzusetzen, in denen ein relevanter Beitrag von CO_2 Emissionen aus dem Flugverkehr gegeben ist. Der Faktor muss auch dann berücksichtigt werden, wenn Biotreibstoffe für Flugzeuge eingesetzt werden.

Résumé

La contribution des avions au réchauffement de la planète est supérieure à ce que l'on peut attendre seul de leurs émissions de CO_2. Les preuves scientifiques pertinentes sont disponibles. Toutefois, les facteurs de PRP (potentiel de réchauffement de la planète) appropriés pour les émissions pertinentes font défaut. Il s'agit d'une lacune dans le calcul de l'empreinte CO_2 (FC). Dans ce article accepté par l'Int J LCA, l'état de l'art en matière de comptabilisation de ces impacts est présenté. Les approches vont de facteurs RFI (radiatif-forcing-index) de 1 à 2,7 qui peuvent être multipliés par les émissions directes de CO2 des avions pour calculer le potentiel de réchauffement global total des services aériens.

Un facteur de RFI de 2 sur les émissions totales de CO_2 des avions est recommandé dans cet article car il est basé sur l'interprétation correcte des publications scientifiques les plus récentes. Si des données détaillées sur la part des émissions dans la haute atmosphère sont disponibles, les calculs seront plus précis si un facteur RFI de 5,2 est multiplié par ces émissions de CO_2 dans la haute atmosphère. De cette façon, dans des évaluations typiques, cela conduit à une augmentation significative des impacts du PRG dus aux services aériens.

La méthode proposée peut être appliquée dans les études d'empreinte carbone et d'analyse du cycle de vie. Il est recommandé de l'utiliser au moins comme analyse de sensibilité si les incidences du transport aérien jouent un rôle important dans un cycle de vie. Ce facteur doit également être pris en compte pour les avions utilisant des biocarburants.

Keywords

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

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Summary

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 emissions. The gap between this scientific knowledge on the one side and the missing of applicable GWP (global warming potential) factors for relevant emissions on the other side is an important shortcoming for life cycle assessment (LCA) or carbon footprint (CF) studies which aim to cover all relevant environmental impacts of the transport services investigated.

Methods

In this paper, the state of the art concerning the accounting for the specific effects of aircraft emissions in LCA and CF studies is discussed. Therefore, the relevant literature was evaluated, and practitioners were asked for the approaches used by them.

Results

Five major approaches are identified 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 considered, RFI factors between 1 and 8.5 are used or proposed 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 if using present models in ecoinvent) is recommended to be used in LCA and CF studies because it is based on the latest scientific publications; this basic literature cannot be misinterpreted. Furthermore, it is also recommended by some political institutions. These factors can be multiplied by the direct CO_2 emissions of the aircraft to estimate the total global warming potential.

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 (CF). The metrics commonly 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). The characterization factors allow assessing the relative impact of different greenhouse gases to the problem of climate change. Different greenhouse gases such as methane (CH_4) or dinitrogen monoxide (N_2O) are expressed as carbon dioxide (CO_2), equivalents. Most LCA studies use the most recent characterization factors published by the Intergovernmental Panel on Climate Change (IPCC) with the reference year 2013 (IPCC 2013) or sometimes the older version with the reference year 2006 (Solomon et al. 2007).

These characterization factors did not change much in the past, based on more recent measurements. The impact of such updates on calculated results was typically in the range of ± 5%.[1] Between 2013 and 2018 no indications on more relevant changes in these characterization factors were found within the LCA community.

However, 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 (and other greenhouse gases) 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
- Sulfate aerosols reflecting sunlight
- Soot aerosols absorbing sunlight

Nevertheless, it is difficult or impossible to provide global warming potential (GWP) characterization 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."*

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[1] https://www.pre-sustainability.com/news/updated-carbon-footprint-calculation-factors, 15.08.2018

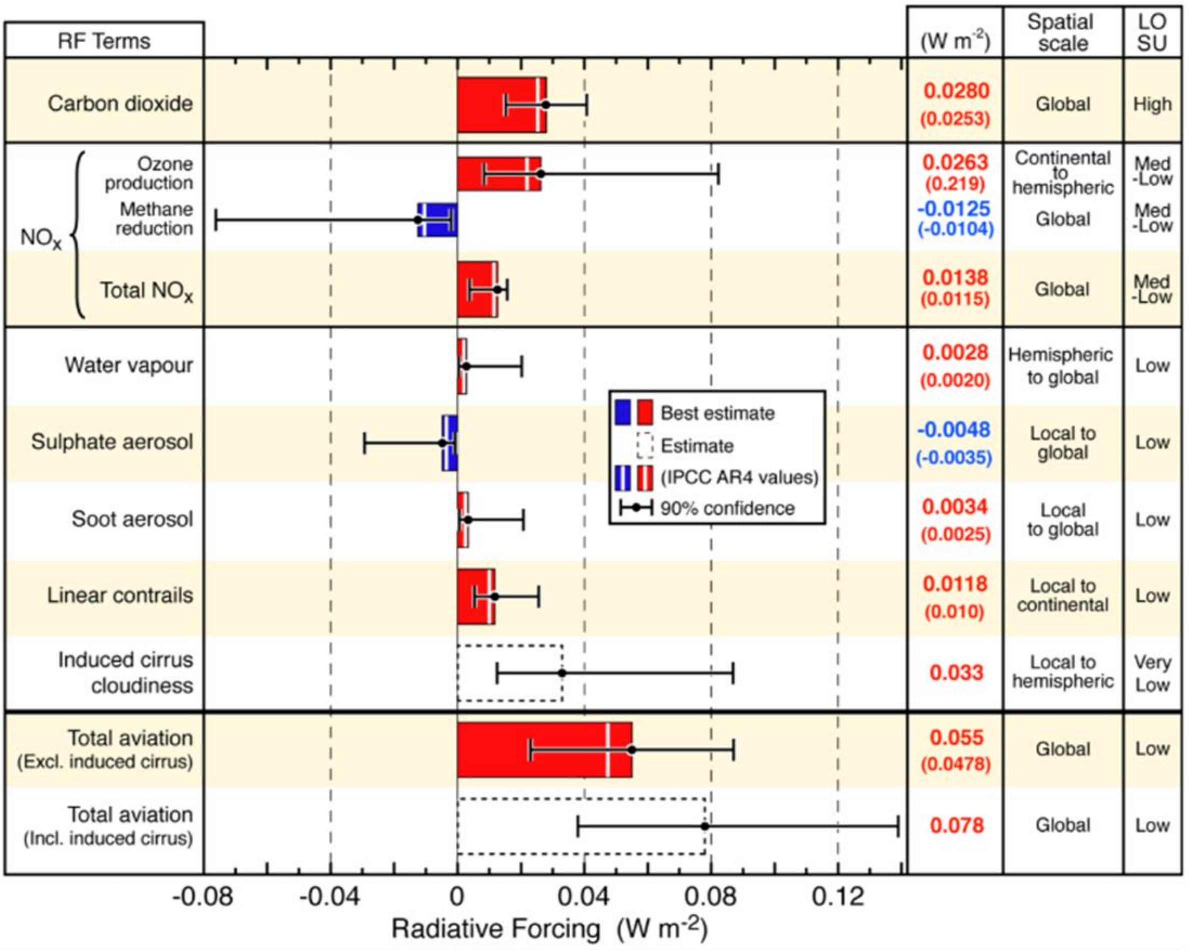

Figure 1 Radiative forcing from aircraft movements in 2005 and quality of assessments (Lee et al. 2009)[2]

The newer publications of the IPCC do not provide as much details for the contribution of aviation anymore as shown in Figure 2.

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[2] https://www.icao.int/Meetings/EGAP/Presentations/E-GAP_Session%20I_David%20Fahey.Aviation%20Climate.final.pdf

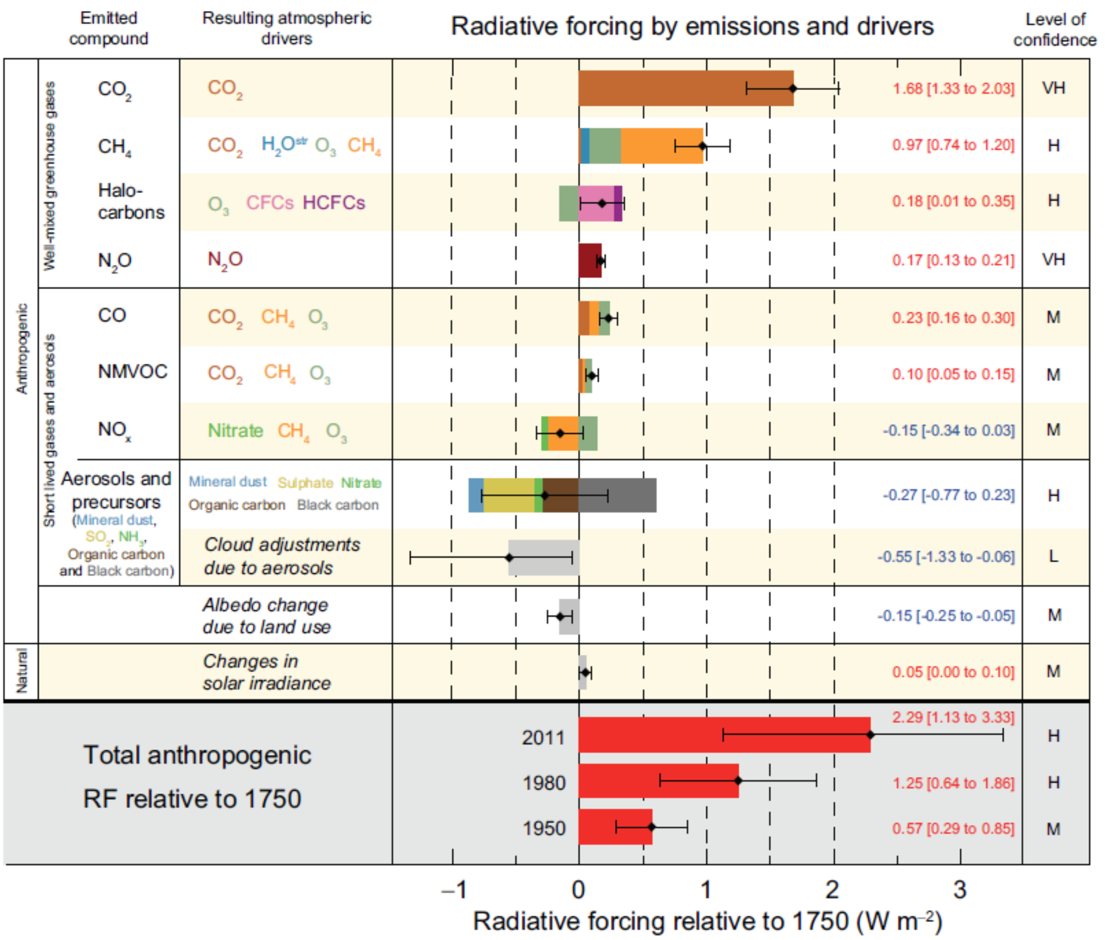

Figure SPM.5 | Radiative forcing estimates in 2011 relative to 1750 and aggregated uncertainties for the main drivers of climate change. Values are global average radiative forcing (RF[14]), partitioned according to the emitted compounds or processes that result in a combination of drivers. The best estimates of the net radiative forcing are shown as black diamonds with corresponding uncertainty intervals; the numerical values are provided on the right of the figure, together with the confidence level in the net forcing (VH – *very high*, H – *high*, M – *medium*, L – *low*, VL – *very low*). Albedo forcing due to black carbon on snow and ice is included in the black carbon aerosol bar. Small forcings due to contrails (0.05 W m^{-2}, including contrail induced cirrus), and HFCs, PFCs and SF_6 (total 0.03 W m^{-2}) are not shown. Concentration-based RFs for gases can be obtained by summing the like-coloured bars. Volcanic forcing is not included as its episodic nature makes is difficult to compare to other forcing mechanisms. Total anthropogenic radiative forcing is provided for three different years relative to 1750. For further technical details, including uncertainty ranges associated with individual components and processes, see the Technical Summary Supplementary Material. {8.5; Figures 8.14–8.18; Figures TS.6 and TS.7}

Figure 2 Radiative forcing estimates in 2011 (IPCC 2013:30)

The exact relevance of the emissions from aviation is still the subject of scientific debate. Some of the relevant emissions have a 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).

Another study shows that contrail cirrus gives the largest warming contribution in the short term but remains important at about 15% of the CO_2 impact in several regions even after 100-years. Results in this paper also illustrate both the short- and long-term impacts of CO_2: while CO_2 becomes dominant on longer timescales, it also gives a notable warming contribution already 20-years after the emission (Lund et al. 2017).

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). Even if the effects of aviation have a short-time effect and would diminish soon after stopping this technology, this does not seem to be a realistic scenario for the time frame of decisions made today with LCA and CF studies. Furthermore, one should consider the exponential growing importance of aviation today (Bows-Larkin et al. 2016).[3] The authors of one article investigating these developments summarize this with the headline conclusion "*the aviation industry's current projections of the sector's growth are incompatible with the international community's commitment to avoiding the 2 ◦C characterization of dangerous climate change*" (Bows-Larkin et al. 2016).

The application of only the GWP for greenhouse gases thus leads to an underestimation of radiative forcing effects caused by aircrafts. 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 LCA or CF studies which aim to compare all relevant environmental impacts of transport services.

Different publications calculate so-called radiative forcing index (RFI) factor that can be multiplied by the direct CO_2 emissions from burning aviation fuels in order to account for all climate change effects of aviation. Estimations for the RFI factor are ranging from 1.9 to 5 (e.g., Grassl & Brockhagen 2007; IPCC 2001, 2007; Penner et al. 2000). But, so far, there is no clear recommendation, e.g., by the IPCC on a specific RFI factor to be used as customary practice.

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 in a steady state 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.

The total RF of aviation is estimated with $0.078 Wm^2$ in 2005 and represents approximately 4.9% of total RF from all human activities (Fahey & Lee 2016).

Based on different publications, IPCC 2013 assesses the combined contrail and contrail-induced cirrus effective radiative forcing for 2011 to be + 0.05 (+ 0.02 to + 0.15) W/m^2 take into account uncertainties on spreading rate, optical depth, ice particle shape, and radiative transfer and the ongoing increase in air traffic (IPCC 2013:610). A low confidence is attached to this estimate.

Since the assessment of the IPCC for 2005, not much new insights have been gained concerning the relevance of aviation (Fahey & Lee 2016). Thus, some researchers recommend neglecting these effects in global assessments (e.g., Brasseur 2008:38).

It is not possible to calculate easily characterization factors for the emissions caused by aircrafts which lead to this specific problem and thus the concept of GWP cannot be applied directly. There is a lively debate within the scientific community if it makes sense to develop some type of metrics for the emissions due to aviation that is comparable to the GWP used for other greenhouse gases (e.g., Fuglestvedt et al. 2010). This article presents also a literature review for GWP developed for all types of transport-related emissions.

The variability of approaches can also be found in practical applications. So far, there are many approaches used by different carbon footprint calculators and LCA practitioners to deal with this issue. A discussion of the approaches used in practice is the focus of this article. For understanding the different calculation practices, some key questions must 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?

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[3] http://data.worldbank.org and ICAO sustainability report 2016 (https://www.icao.int/environmental-protection/Documents/ICAO%20Environmental%20Report%202016.pdf), online 11.06.2018.

- If the latter approach is used, how has the share of emissions in the higher atmosphere been calculated?

The focus of this paper is to evaluate the state of the art of accounting for the specific effects of aircraft emissions in LCA and CF studies. Therefore, LCA and CF experts were asked directly and via different email discussion lists. Furthermore, relevant literature and internet investigation have been used to find further examples on this issue. It is not an aim of this article to provide further knowledge or insights in the complicated matter as such. But the article should help practitioners to interpret and understand the different approaches correctly and apply them according to the goal and scope of their studies. Therefore, recommendations are provided how to tackle this issue in practice. A first version as a working paper has been published in 2013 (Jungbluth 2013)and was then updated and extended in view of presentations at conferences in 2018.

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

Five major approaches for the interpretation of available literature, which are used in practice, have been identified during the intensive literature research over the last seven years. All approaches identified in this research 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 (LCI) analysis, 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 sub-compartment (Frischknecht et al. 2007a; Spielmann et al. 2007). This does allow to assign a specific GWP characterization factor for this sub-category of CO_2 emissions in the life cycle impact assessment.

In ecoinvent data v2.2 for average passenger transports by aircraft, the share of CO_2 emissions in the lower stratosphere and upper troposphere is 23.9% of the total aircraft CO_2 emissions (corrected data[4] from Spielmann et al. 2007). Thus, it is possible to recalculate the RFI factor for this specific share of emissions in the higher atmosphere according to the following equitation (1):

$$CF\ CO2, stratosphere = \frac{RFI\ all - (1 - Share\ CO2,\ stratosphere)}{Share\ CO2, stratosphere} \qquad (1)$$

where,

CF CO2,stratosphere = characterization factor for emissions of CO2 in the stratosphere

RFI all = RFI proposed for the total CO2 emissions of aircrafts

Share CO2,stratosphere = share of CO2 emissions in the stratosphere according to LCI data

The above mentioned RFI factor of 1 to 2.7 corresponds then to a characterization factor of 1 to 8.5 that can be applied on the CO_2 emissions in the lower stratosphere and upper troposphere. The column in Table 1 showing these figures is labeled as “RFI, fully on CO2, stratosphere” in Table 1. These basic assumptions are also still valid for ecoinvent data v3.4 (ecoinvent Centre 2017):

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[4] An error in ecoinvent data has been discovered while elaborating this working paper and has 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).

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, 2013). The interpretation that aircraft emissions do not have a specific higher impact is mainly made by database developers (e.g. European Commission et al. 2011; Frischknecht et al. 2007b), by software providers such as SimaPro (SimaPro 8.5.3), within life cycle impact assessment methods (European Commission et al. 2011; Frischknecht et al. 2009; Goedkoop & Spriensma 2000; Goedkoop et al. 2009; Huijbregts et al. 2017), 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.

2. The second group of approaches includes the GWP caused by contrails, water vapor, and aviation-induced cirrus clouds. But, the contribution of clouds is neglected as the estimate is considered to be too uncertain. Thus, this approach can be categorized as minimum estimate of the possible effects (e.g., Ecoplan / Infras 2014:307; Frischknecht et al. 2016). The approach can be used if generally a cautious perspective is taken on uncertain environmental effects.

3. The third group of approaches applies a RFI factor of 2.7-3 only to the CO_2 emissions in the higher atmosphere (e.g., atmosfair 2008; Grießhammer & Hochfeld 2009; Knörr 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 (Grassl & Brockhagen 2007; IPCC 2007; Penner et al. 2000). 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 providing recommendations in this article.

4. The fourth 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 also used in more recent papers 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 (Azar & Johansson 2012). They calculated emission weighting factors (EWFs) for the CO_2 from aircrafts with five 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 seems to be the most appropriate one for an estimation of the effects.

5. The last group of approaches is based on the same original literature as the third 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[5] and greenmiles.[6] As this seems a misinterpretation and overestimation of the effects, this group of approaches is not considered 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. Nevertheless, 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.

Another approach to tackle this problem is the characterization of emissions like water, NMVOCs, particulates, NOx, and SOx with single characterization factors for each type of emission. Two publications have been found that suggest such factors (Fuglestvedt et al. 2010; Lund et al. 2017). We tried to apply these factors in our LCA software SimaPro, but different difficulties occurred in the interpretation of the published factors (e.g., they are not provided per kg of emission or information concerning the share of emissions in higher and lower atmosphere were missing). Both approaches also still applied an additional RFI factor on the CO2. Results of this calculation seem to be lower than the RFI factor recommended by us by a factor of 5, but due to the uncertainty of the interpretation we refrain from publishing these results here.

Due to these uncertainties, an approach to apply characterization factors on different single emissions is thus not further followed up in this article because of the high uncertainties while interpreting the available literature.

3 Recommendations for calculating the global warming potential of aviation in LCA

This paper cannot solve all 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 and to provide better guidance on this issue. In the moment, different approaches come to quite different results and thus have an enormous influence on the outcome of studies where emissions from aircrafts play a significant role.

Different approaches have been evaluated in depth in the previous chapter. The influence on the results has been highlighted in Table 1 (supplementary material). Currently, a characterization factor (CF) of 2 kg CO2-eq per total direct aircraft CO_2 emissions (or 5.2 for the emissions in the higher atmosphere if using ecoinvent v2.2, ecoinvent v3.4, or ESU 2018 data) is seen as the most convincing approach for the following reasons. It is based on the different approaches used in 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 third and fifth group of approaches). The proposal does not neglect the proofed additional effects of aviation. It is based on a reasonable guess of the average effects in contrast to the second approach which only makes a minimum assumption. Furthermore, it is also recommended by some political institutions (Kollmuss & Crimmins 2009; UBA 2012).

It is recommended to apply the factor if possible in the LCA calculation tool 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 for the time being.

While using other databases, the average share of emissions in higher atmosphere must be considered in the calculations and the characterization factor for CO_2 emission in the higher

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

[6] www.greenmiles.de

atmosphere can be calculated accordingly according to equation (1). For the applications with ecoinvent data a characterisation factor of 5.2 is calculated in equation (2):

$$5.2 = \frac{2 - (1 - 23.9\%)}{23.9\%} \quad (2)$$

A CSV file with an LCIA method for SimaPro is provided as supplementary material for this article.

Depending on the goal and scope of their study, LCA practitioners might also apply other approaches as described in the previous chapter. This article can then help to provide arguments in view of such a choice.

4 Results

Figure 3 shows the implications of this recommendation for the calculation of the GWP with a 100-year time horizon according to IPCC (2013) and expressed in carbon dioxide equivalents (CO_2-eq). Without applying an RFI factor, long- and short-distance flights show a carbon footprint between 118 and 230 g of CO_2-eq per passenger-kilometer, respectively. Including additional impacts in the higher atmosphere rises this to 230 to 340 g 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 3. Without the application of an RFI factor, short-distance flights would have about the same emissions as average passenger cars.

It must be noted that for a full environmental picture and comparison of different means of transport, also other environmental indicators must be considered in an LCA. Thus, this figure should only be read as an example regarding the influence of the impact assessment for the global warming indicator, but not as a general statement regarding the pros and cons of different transport devices.

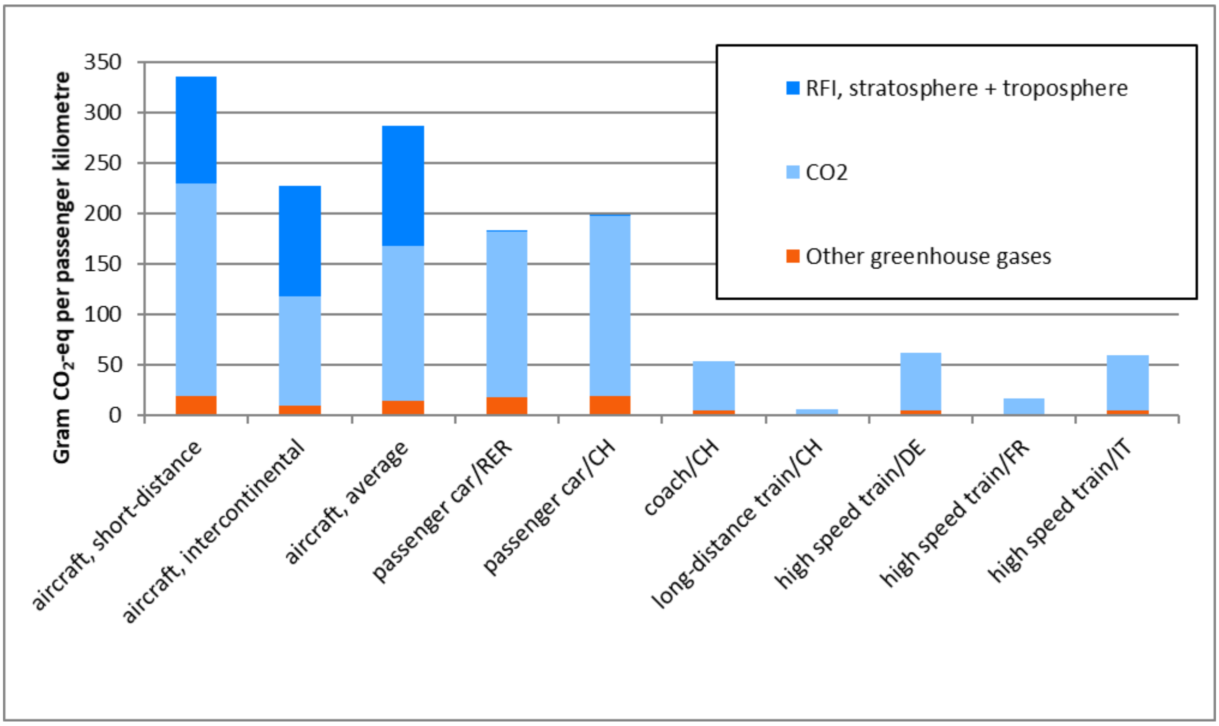

Figure 3 Global warming potential 2013 of different means of passenger transports based on ESU database 2018 (ESU 2018; LC-inventories 2018; Spielmann et al. 2007) considering the recommended RFI factor of 5.2 for emissions in the higher atmosphere. RER – European average, CH – Switzerland, DE – Germany, FR – France, IT - Italy

The results presented in this figure can also be directly compared with the results for an average airplane calculated with all approaches investigated in this paper as shown in Table 1.

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.

This is an ongoing debate. Thus, comments by the LCA and CF community to this paper and its usefulness are highly welcome.

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7 Annexe

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 ESU database 2018.

Group	Application	RFI, CO2 stratosphere	RFI, other airplane CO2	***RFI, fully on CO2, stratosphere***	calculated GWP per pkm	Interpretation	Scientific background paper
1	Ecoinvent	1	1	*1.0*	0.168	Frischknecht et al. 2007b	IPCC 2007
	SimaPro	1	1	*1.0*	0.168	SimaPro 8.5.3	IPCC 2007
	PAS 2050:2011	1	1	*1.0*	0.168	Separate reporting of aircraft CO2 is necessary	Carbon Trust & DEFRA 2011
	ISO/CD 14067.3:2011	1	1	*1.0*	0.168	CO2 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*	0.168	Not mentioned as a specific issue	Hauschild et al. 2011
2	Frischknecht et al. 2016 http://www.lcaforum.ch/portals/0/df66/DF66-02_Frischknecht.pdf	1.35	1.35	*1.50*	0.210	Additional GWP caused by contrails, water vapor and aviation induced cirrus clouds. Contribution of clouds neglected as to uncertain, 70% of CO2 in stratosphere	Ecoplan / Infras 2014:307, Lee et al. 2010
	Forster et al. 2006, 2007, without cirrus	1.2	1.2	*1.8*	0.192	Gössling & Upham 2009	Cited as Forster et al. (2006, 2007), http://www.sciencedirect.com/science/article/pii/S1352231005010587$
3	PCF - Germany	2.7	1	*2.7*	0.216	Grießhammer & Hochfeld 2009	IPCC 2007; Penner et al. 2000
	Atmosfair	3	1	*3.0*	0.225	atmosfair 2008	Grassl & Brockhagen 2007 based on IPCC 2007
	EcoPassenger	3	1	*3.0*	0.225	Based on (atmosfair 2008), calculated range of total RFI of 1.27 to 2.5 based on travel distances.	Knörr 2008

Group	Application	RFI, CO2 stratosphere	RFI, other airplane CO2	***RFI, fully on CO2, stratosphere***	calculated GWP per pkm	Interpretation	Scientific background paper
	CO2OL, www.co2ol.de	1.27-2.7	1.27-2.7	*3.0*	0.225	Depending on travel distance. Own assumption based on (Grießhammer & Hochfeld 2009; Knörr 2008).	Knörr 2008
	ESU-services, scenario, 2010	2.99	1	*3.0*	0.224	geometric mean of RFI 1.9 to 4.7, atmosfair concerning application only to CO2, stratosphere	Grassl & Brockhagen 2007 based on IPCC 2007
4	Stockholm Environment Institute	2	2	*5.2*	0.286	Kollmuss & Crimmins 2009	IPCC 2007
	myclimate	2	2	*5.2*	0.286	myclimate 2009	Kollmuss & Crimmins 2009
	Lee et al. 2009	2	2	*5.2*	0.286	N. Jungbluth	Lee et al. 2009; Lee et al. 2010
	Klima-Allianz Schweiz	2	2	*5.2*	0.286	Klima-Allianz Schweiz 2016	Lee et al. 2009; Lee et al. 2010
	Peters et al. 2011	1.9	1.9	*4.9*	0.280	N. Jungbluth, Soli: I think, but don't remember 100% sure, that the share of air emissions occurring in higher altitudes were adapted by the cicero people to reflect the aviation industry average, but that the fuel use data from the air process given in the report, were used.	Peters et al. 2011
	Azar 2012	1.7	1.7	*3.9*	0.251		
	This study	**2**	**2**	***5.2***	**0.287**	**Recommendation for best-practice**	**This paper**
5	Forster et al. 2006, 2007, with max. cirrus	2.8	2.8	*8.5*	0.381	Gössling & Upham 2009	Cited as Forster et al. (2006, 2007)
	ecoinvent, scenario	2.72	2.72	*8.2*	0.372	Frischknecht et al. 2007b	IPCC 2007
	Primaklima	2.7	2.7	*8.1*	0.369	http://www.prima-klima-welt-weit.de/co2/kompens-berechnen.php	IPCC 2007
	greenmiles	2.7	2.7	*8.1*	0.369	Personal communication with Dr. Sven Bode (Greenmiles GmbH)	IPCC 2007