

2018

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



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

Working paper version 31 August 2018.

Authors

Niels Jungbluth; Christoph Meili

ESU-services Ltd.

Vorstadt 14

CH-8200 Schaffhausen

jungbluth@esu-services.ch

www.esu-services.ch

Tel. +41 44 940 61 32

Contents

ABSTRACT	IV
KEYWORDS	IV
SUMMARY	V
1 INTRODUCTION	1
2 OVERVIEW ON APPROACHES USED IN LIFE CYCLE ASSESSMENT AND CARBON FOOTPRINTING	5
3 RECOMMENDATIONS FOR BEST PRACTICE	11
4 RESULTS	11
5 OUTLOOK	12
6 REFERENCES	12

Imprint

Citation	Niels Jungbluth;Christoph Meili (2018) Aviation and Climate Change: Best practice for calculation of the global warming potential. ESU-services Ltd. commissioned by ESU-services Ltd., Schaffhausen, Switzerland, www.esu-services.ch/de/publications/
The company	ESU-services Ltd., fair consulting in sustainability Vorstadt 14, CH-8200 Schaffhausen www.esu-services.ch Phone 0041 44 940 61 32, Fax +41 44 940 67 94 jungbluth@esu-services.ch
About us	ESU-services Ltd. has been founded in 1998. Its core objectives are consulting, coaching, training and research in the fields of life cycle assessment (LCA), greenhouse gas footprints, water footprint in the sectors energy, civil engineering, basic minerals, chemicals, packaging, telecommunication, food and lifestyles. Fairness, independence and transparency are substantial characteristics of our consulting philosophy. We work issue-related and accomplish our analyses without prejudice. We document our studies and work transparency and comprehensibly. We offer a fair and competent consultation, which makes it for the clients possible to control and continuously improve their environmental performance. The company worked and works for various national and international companies, associations and authorities. In some areas, team members of ESU-services performed pioneering work such as development and operation of web based LCA databases or quantifying environmental impacts of food and lifestyles.
Liability Statement	Information contained herein have been compiled or arrived from sources believed to be reliable. Nevertheless, the authors or their organizations do not accept liability for any loss or damage arising from the use thereof. Using the given information is strictly your own responsibility.
Version	31.08.18 07:35 https://esuserVICES-my.sharepoint.com/personal/mitarbeiter1_esuserVICES_onmicrosoft_com/Documents/310 RFI best practice/Bericht/jungbluth-2018-RFI-best-practice-3.0.docx

Abstract

Aircrafts have a contribution to global warming that is higher than their CO₂-emissions alone. The gap between science on the one side and the missing of applicable GWP (global-warming-potential) factors for relevant emissions on the other is a shortcoming for carbon footprint (CF) calculations. Here we present the state-of-the-art for accounting. Approaches are ranging from RFI (radiative-forcing-index) factors of 1 to 2.7 that can be multiplied with the direct CO₂ emissions in order to calculate the total global warming potential of aviation services.

An RFI of 2 on total aircraft CO₂ (or 5.2 for the CO₂ in higher atmosphere) is identified as best-practice because it is based on the correct interpretation of the most recent scientific publications. This factor can be multiplied with the CO₂ emissions in the higher atmosphere for calculating the GWP of transport services provided by aircrafts.

Keywords

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

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 CO₂ 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 CO₂-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 has been identified. 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 CO₂ 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 CO₂ (or 5.2 for the CO₂ emissions in the higher atmosphere) is the best-practice approach 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 CO₂ 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 CO₂-eq). Most LCA studies use the most recent characterisation 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). The characterisation factors allow assessing the relative impact of different greenhouse gases to the problem of climate change. Different greenhouse gases such as methane (CH₄) or dinitrogen monoxide (N₂O) are expressed as carbon dioxide (CO₂), equivalents.

These characterisation 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 characterisation factors were found within the LCA community².

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 CO₂ (and other greenhouse gases) from burning the aviation fuels. The following pathways are discussed (Penner et al. 2000; UBA 2012):

- Nitrogen oxide (NO_x) emissions leading to ozone (O₃) formation and methane (CH₄) 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 NO_x 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 CO₂ is larger today than in 2050 and the efficiency of NO_x at producing tropospheric O₃ depends on concurrent pollution of the troposphere. In summary, GWPs were meant to compare emissions of long-lived, well-mixed gases such as CO₂, CH₄, N₂O, 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.”

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

² <https://support.simapro.com/articles/Article/LCA-Discussion-List/>, 15.08.2018

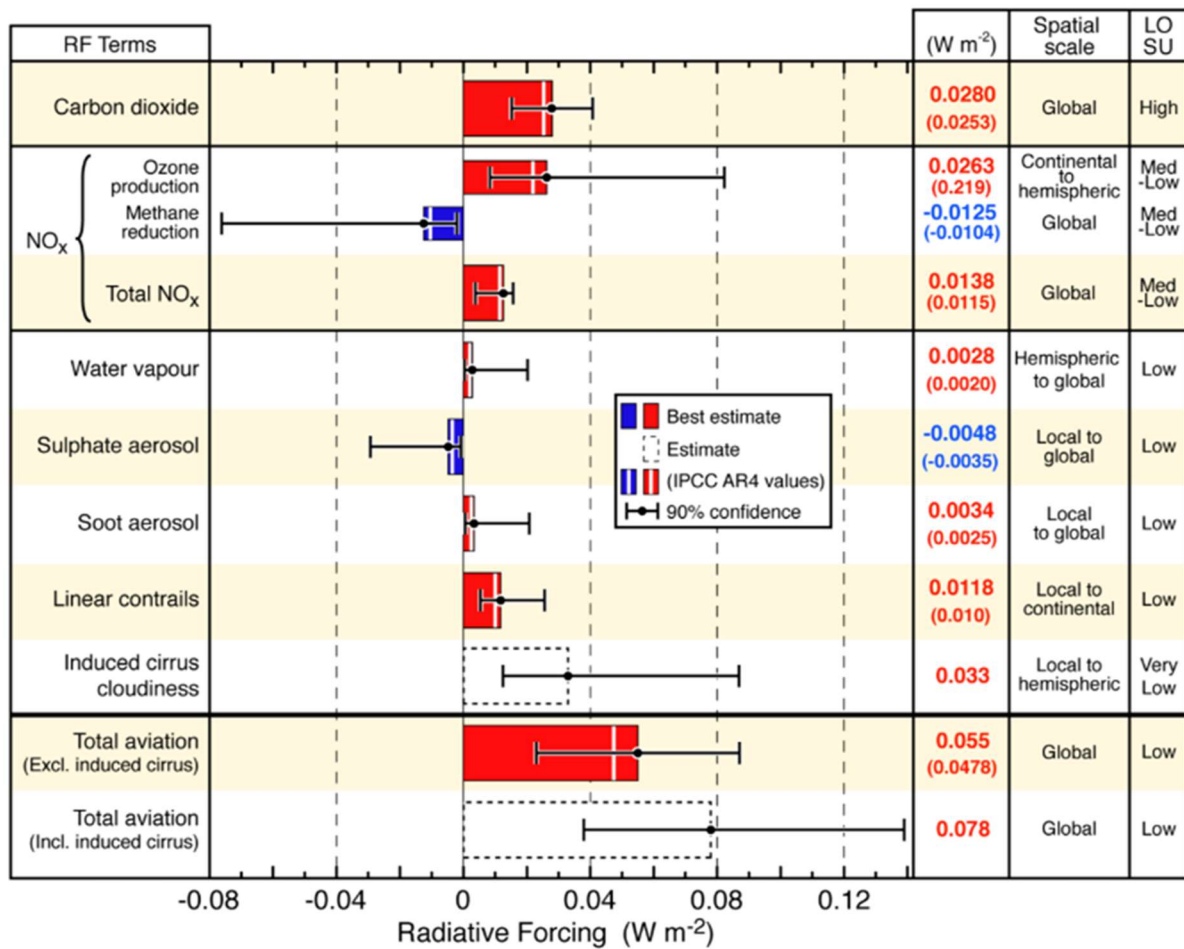


Figure 1 Radiative forcing from aircraft movements in 2005 and quality of assessments (Lee et al. 2009)³

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

³ https://www.icao.int/Meetings/EGAP/Presentations/E-GAP_Session%20I_David%20Fahey_Aviation%20Climate.final.pdf

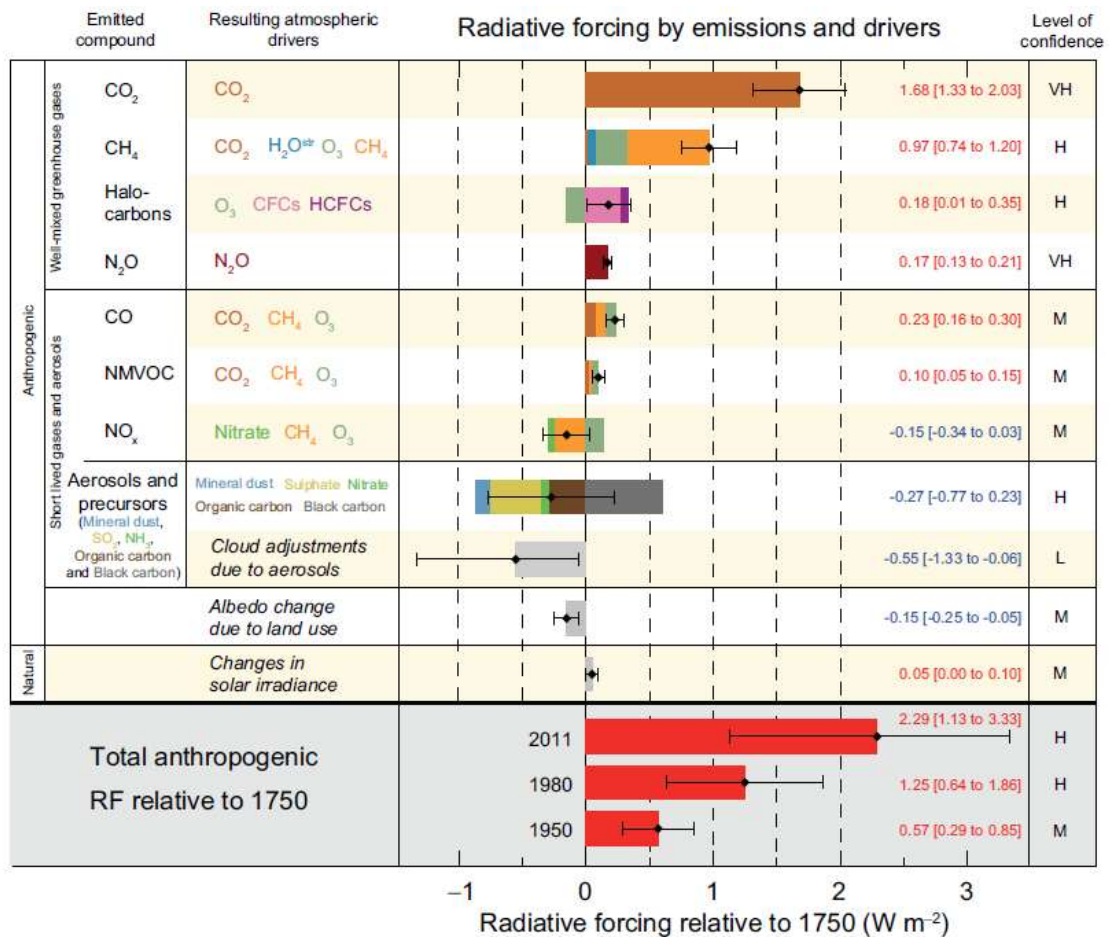


Figure SPM.5 | Radiative forcing estimates in 2011 relative to 1750 and aggregated uncertainties for the main drivers of climate change. Values are global average radiative forcing (RF¹⁴), partitioned according to the emitted compounds or processes that result in a combination of drivers. The best estimates 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 SF₆ (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 it 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 remain important at about 15% of the CO₂ impact in several regions even after 100 years. Results in this paper also illustrate both the short- and long-term impacts of CO₂: while CO₂ 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 CO₂ 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 and when considering the exponential growing importance of aviation today.⁴

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 thus leads to an underestimation of radiative forcing effects caused by aircrafts.

Different publications calculate so-called radiative forcing index (RFI) factor ranging from 1.9 to 5 that should be multiplied by the direct CO₂ emissions from burning aviation fuels in order to account for all climate change effects of aviation (e.g. Grassl & Brockhagen 2007; IPCC 2001, 2007; Penner et al. 2000). But, so far there is no clear recommendation on a specific factor to be used.

This 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.

The total RF of aviation is estimated with 0.078 W m⁻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/m² 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 characterisation 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 (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 calculations 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 CO₂ 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?

⁴ <http://data.worldbank.org> and [ICAO sustainability report 2016 \(https://www.icao.int/environmental-protection/Documents/ICAO%20Environmental%20Report%202016.pdf\)](https://www.icao.int/environmental-protection/Documents/ICAO%20Environmental%20Report%202016.pdf), online 11.06.2018.

The focus of this paper is to evaluate the state of the art and the best practice of accounting for the specific effects of aircraft emissions. 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. 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. A first version as a working paper has been published in 2012 on www.esu-services.ch/ourservices/pcf/ 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 five years. 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 CO₂ emissions.

In life cycle inventory analysis (LCI), information about the specific amount of aircraft CO₂ emissions is difficult to extract (e.g. ecoinvent Centre 2010; European Commission 2010; Hirschier et al. 2001). But, in some databases such as ecoinvent CO₂ 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 characterisation factor for this sub-category of CO₂ emissions in the life cycle impact assessment.

In ecoinvent data v2.2 for average passenger transports by aircraft, the share of CO₂ emissions in the lower stratosphere and upper troposphere is 23.9% of the total aircraft CO₂ emissions (corrected data⁵ 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 then to an RFI factor of 1 to 8.5 that can be applied on the CO₂ emissions in the lower stratosphere and upper troposphere. The column showing these figures is labelled as “RFI, fully on CO₂, stratosphere” in Table 1. These basic assumptions are also still valid for ecoinvent data v3.4 (ecoinvent Centre 2017).

1. The first group of approaches does not apply a specific RFI factor to aircraft CO₂ 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 aircrafts 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), software providers such as SimaPro (SimaPro 8.5.3), 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

⁵ 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).

minimum estimate of the possible effects (e.g. Ecoplan / Infrac 2014:307; Frischknecht et al. 2016).

3. The third group of approaches applies a RFI factor of 2.7-3 only to the CO₂ emissions in the higher atmosphere (e.g. atmosfair 2008; Griebhammer & 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 CO₂ 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 CO₂ 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 CO₂ 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 seems to be the most appropriate one for a best-guess 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 CO₂ 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 CO₂ emissions in the higher atmosphere. This approach is used by some companies providing carbon offsetting services such as Primaklima⁶ and greenmiles⁷. As this seems to 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 characterisation of emissions like water, NMVOCs, particulates, NO_x, SO_x etc. with characterisation factors. 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

⁶ www.prima-klima-weltweit.de

⁷ www.greenmiles.de

approaches also still applied an additional factor on the CO₂. Results of this calculation seem to be lower than the RFI factor recommend by us by a factor of five, but due to the uncertainty of the interpretation we refrain from publishing these results here.

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

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 CO₂, stratosphere” has been calculated based on the share of this type of emissions in ESU database 2018.

Group	Application	RFI, CO ₂ stratosphere	RFI, other airplane CO ₂	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	Seperate reporting of aircraft CO ₂ is necessary	Carbon Trust & DEFRA 2011
	ISO/CD 14067.3:2011	1	1	1.0	0.168	CO ₂ from aircrafts should be reported seperatly, 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 CO ₂ in stratosphere	Ecoplan / Infrac 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

Overview on approaches used in life cycle assessment and carbon footprinting

Group	Application	RFI, CO2 stratosphere	RFI, other airplane CO2	RFI, fully on CO2, stratosphere	calculated GWP per pkm	Interpretation	Scientific background paper
	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
	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	Recomendation 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-weltweit.de/co2/kompens-berechnen.php	IPCC 2007

Overview on approaches used in life cycle assessment and carbon footprinting

Group	Application	RFI, CO2 stratosphere	RFI, other airplane CO2	<i>RFI, fully on CO2, stratosphere</i>	calculated GWP per pkm	Interpretation	Scientific background paper
	greenmiles	2.7	2.7	8.1	0.369	Personal communication with Dr. Sven Bode (Greenmiles GmbH)	IPCC 2007

3 Recommendations for best practice

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. Currently a characterisation factor (CF) of 2 on total aircraft CO₂ (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). 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.

While using other databases the average share of emissions in higher atmosphere must be considered in the calculations and the characterisation factor for CO₂ emission in the higher atmosphere can be calculated accordingly according to the following formula:

$$CF_{CO_2, stratosphere} = \frac{RFI_{all} - (1 - Share_{CO_2, stratosphere})}{Share_{CO_2, stratosphere}}$$

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

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 (CO₂-eq). Without applying an RFI factor, long and short-distance flights show a carbon footprint between 118 and 230 grams of CO₂-eq per passenger-kilometre, respectively. Including additional impacts in the higher atmosphere rises this to 230 to 340 grams of CO₂-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.

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.

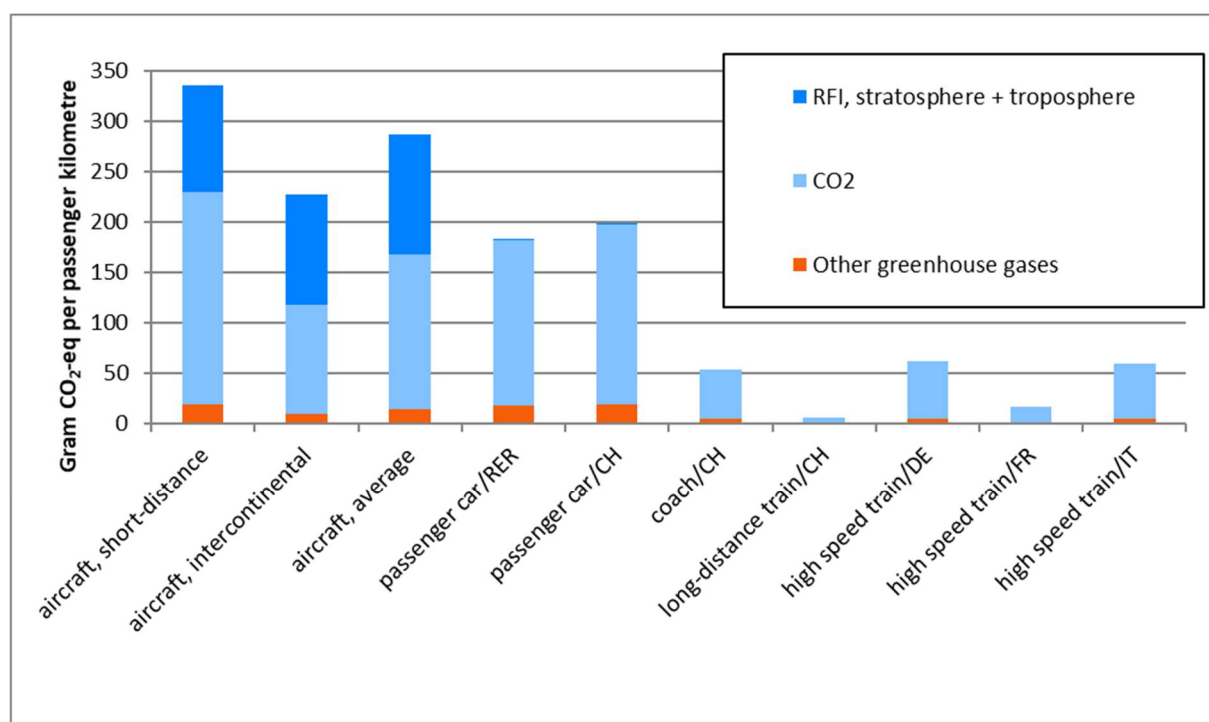


Figure 3 Global warming potential 2013 of different means of passenger transports based on ESU database 2018 (ESU 2018; LC-inventories 2018; Spielmann et al. 2007) considering the recommended RFI factor of 5.2 for emissions in the higher atmosphere. RER – European average, CH – Switzerland, DE – Germany,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

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 to this paper and its usefulness are highly welcome.

6 References

atmosfair 2008 atmosfair (2008) Der Emissionsrechner. atmosfair, retrieved from: <https://www.atmosfair.de/index.php?id=60&L=0>.

Azar & Johansson 2012 Azar C. and Johansson J. A. (2012) Valuing the non-CO₂ climate impacts of aviation. *In: Climatic Change*, **2012**(111), pp. 559–579, DOI 10.1007/s10584-011-0168-8.

Brasseur 2008 Brasseur G. P. (2008) A Report on the Way Forward - Based on the Review of Research Gaps and Priorities Sponsored by the Environmental Working Group of the U.S. NextGen Joint Planning and Development Office, retrieved from: https://www.researchgate.net/publication/224999220_ACCRI_-_A_Report_on_the_Way_Forward_based_on_the_Review_of_Research_Gaps_and_Priorities.

Carbon Trust & DEFRA 2011 Carbon Trust and DEFRA (2011) PAS 2050:2011: Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. British Standard, BSi, London, retrieved from: www.bsigroup.com/upload/Standards%20&%20Publications/Energy/PAS2050.pdf.

ecoinvent Centre 2010 ecoinvent Centre (2010) ecoinvent data v2.2, ecoinvent reports No. 1-25. Swiss Centre for Life Cycle Inventories, Duebendorf, Switzerland, retrieved from: www.ecoinvent.org.

ecoinvent Centre 2017 ecoinvent Centre (2017) ecoinvent data v3.4, ecoinvent reports No. 1-25. Swiss Centre for Life Cycle Inventories, Zurich, Switzerland, retrieved from: www.ecoinvent.org.

Ecoplan / Infras 2014 Ecoplan / Infras (2014) Externe Effekte des Verkehrs 2010: Monetarisierung von Umwelt-, Unfall- und Gesundheitseffekten. Bundesamt für Raumentwicklung, Bern, Zürich und Altdorf, retrieved from: www.ecoplan.ch.

ESU 2018 ESU (2018) The ESU database 2018. ESU-services Ltd., Schaffhausen, retrieved from: www.esu-services.ch/data/database/.

References

- European Commission 2010 European Commission (2010) ILCD Handbook (International Reference Life Cycle Data System), Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment. European Commission, DG-JRC, retrieved from: lct.jrc.ec.europa.eu/eplca/deliverables/consultation-on-international-reference-life-cycle-data-system-ilcd-handbook.
- European Commission et al. 2011 European Commission, Joint Research Centre and Institute for Environment and Sustainability (2011) International Reference Life Cycle Data System (ILCD) Handbook - Recommendations for Life Cycle Impact Assessment in the European context - based on existing environmental impact assessment models and factors. EUR 24571 EN, Luxembourg, retrieved from: lct.jrc.ec.europa.eu/assessment/projects.
- Fahey & Lee 2016 Fahey D. W. and Lee D. S. (2016) Aviation and Climate Change: A Scientific Perspective, retrieved from: <http://e-space.mmu.ac.uk/618290/1/Fahey%20and%20Lee%20CCLR%202016.pdf>.
- Frischknecht et al. 2007a Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Heck T., Hellweg S., Hirschier R., Nemecek T., Rebitzer G. and Spielmann M. (2007a) Overview and Methodology. ecoinvent report No. 1, v2.0. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.
- Frischknecht et al. 2007b Frischknecht R., Jungbluth N., Althaus H.-J., Bauer C., Doka G., Dones R., Hellweg S., Hirschier R., Humbert S., Margni M. and Nemecek T. (2007b) Implementation of Life Cycle Impact Assessment Methods. ecoinvent report No. 3, v2.0. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.esu-services.ch/data/ecoinvent/.
- Frischknecht et al. 2009 Frischknecht R., Steiner R. and Jungbluth N. (2009) The Ecological Scarcity Method - Eco-Factors 2006: A method for impact assessment in LCA. Federal Office for the Environment FOEN, Zürich und Bern, retrieved from: www.bafu.admin.ch/publikationen/publikation/01031/index.html?lang=en.
- Frischknecht et al. 2016 Frischknecht R., Messmer A., Stolz P. and Tuchschnid M. (2016) mobitool – Grundlagenbericht Hintergrund, Methodik & Emissionsfaktoren, retrieved from: https://www.mobitool.ch/admin/data/files/marginal_download/file_de/21/544-mobitool-hintergrundbericht-v2.0.pdf?lm=1479747138.
- Fuglestvedt et al. 2010 Fuglestvedt J. S., Shine K. P., Berntsen T., Cook J., Lee D. S., Stenke A., Skeie R. B., Velders G. J. M. and I.A. Waitz (2010) Transport impacts on atmosphere and climate: Metrics. In: *Atmospheric Environment*, **44**(37), pp. 4648-4677, <https://doi.org/10.1016/j.atmosenv.2009.04.044>.
- Goedkoop & Spriensma 2000 Goedkoop M. and Spriensma R. (2000) The Eco-indicator 99: A damage oriented method for life cycle impact assessment. PRé Consultants, Amersfoort, The Netherlands, retrieved from: www.pre.nl/eco-indicator99/.
- Goedkoop et al. 2009 Goedkoop M., Heijungs R., Huijbregts M. A. J., De Schryver A., Struijs J. and van Zelm R. (2009) ReCiPe 2008 - A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. First edition. Report I: Characterisation, NL, retrieved from: lca-recipe.net/.
- Gössling & Upham 2009 Gössling S. and Upham P. (2009) Climate Change and Aviation. Earthscan, retrieved from: books.google.ch/books?id=LIVeZkURpcMC&pg=PA77&lpg=PA77&dq=gwp+and+aviation&source=bl&ots=VDdSFS9kG_&sig=R0xoInfgcbJpzLpKhFb_JcV-BbM&hl=de&sa=X&ei=TV4T7W8H-n64QSCkCsDw&ved=0CFYQ6AEwBg#v=onepage&q=gwp%20and%20aviation&f=false.
- Grassl & Brockhagen 2007 Grassl H. and Brockhagen D. (2007) Climate forcing of aviation emissions in high altitudes and comparison of metrics: An update according to the Fourth Assessment Report, IPCC 2007. IPCC, retrieved from: www.mpimet.mpg.de/fileadmin/download/Grassl_Brockhagen.pdf.
- Grießhammer & Hochfeld 2009 Grießhammer R. and Hochfeld C. (2009) Memorandum Product Carbon Footprint. Öko-Institut, Berlin, retrieved from: www.bmu.de/files/pdfs/allgemein/application/pdf/memorandum_pcf_lang_bf.pdf.
- Hirschier et al. 2001 Hirschier R., Baitz M., Bretz R., Frischknecht R., Jungbluth N., Marheineke T., McKeown P., Oele M., Osset P., Renner I., Skone T., Wessman H. and de Beaufort A. S. H. (2001) Guidelines for Consistent Reporting of Exchanges from/to Nature within Life Cycle Inventories (LCI). In: *Int J LCA*, **6**(4), pp. 192-198, retrieved from: www.scientificjournals.com/sj/lca/.
- Huijbregts et al. 2017 Huijbregts M. A. J., Steinmann Z. J. N., Elshout P. M. F., Stam G., Verones F., Vieira M., Zijp M., Hollander A. and van Zelm R. (2017) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. In: *The International Journal of Life Cycle Assessment*, **22**(2), pp. 138-147, 10.1007/s11367-016-1246-y, retrieved from: <http://dx.doi.org/10.1007/s11367-016-1246-y>.
- International Organization for Standardization (ISO) 2011 International Organization for Standardization (ISO) (2011) Carbon Footprint of products. ISO/CD 14067: committee draft.

References

- IPCC 2001 IPCC (2001) Climate Change 2001: The Scientific Basis. In: *Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)* (ed. Houghton J. T., Ding Y., Griggs D. J., Noguer M., van der Linden P. J. and Xiaosu D.). IPCC, Intergovernmental Panel on Climate Change, Cambridge University Press, The Edinburgh Building Shaftesbury Road, Cambridge, UK, retrieved from: www.grida.no/climate/ipcc_tar/wg1/.
- IPCC 2007 IPCC (2007) The IPCC fourth Assessment Report. Cambridge University Press., Cambridge.
- IPCC 2013 IPCC (2013) Climate Change 2013: The Physical Science Basis, Cambridge, United Kingdom and New York, NY, USA, retrieved from: <http://www.ipcc.ch/report/ar5/wg1/>.
- Klima-Allianz Schweiz 2016 Klima-Allianz Schweiz (2016) Klima-Masterplan Schweiz: Umsetzung des Paris Abkommen - Teilbericht zur Reduktion von Treibhausgasen und Auswirkungen des Klimawandels im Ausland, retrieved from: www.klima-allianz.ch.
- Knörr 2008 Knörr W. (2008) EcoPassenger: Environmental Methodology and Data. ifeu - Institut für Energie- und Umweltforschung Heidelberg GmbH, Heidelberg, retrieved from: info.rejseplanen.dk/files/Diverse/Ecopassenger_Methodology_Report.pdf.
- Kollmuss & Crimmins 2009 Kollmuss A. and Crimmins A. M. (2009) Carbon Offsetting & Air Travel, Part 2: Non-CO2 Emissions Calculations. Stockholm Environment Institute, Stockholm, retrieved from: www.co2offsetresearch.org/PDF/SEI_Air_Travel_Emissions_Paper2_June_09.pdf.
- LC-inventories 2018 LC-inventories (2018) Corrections, updates and extensions of ecoinvent data v2.2. BAFU, retrieved from: www.lc-inventories.ch.
- Lee et al. 2009 Lee D. S., Fahey D. W., Forster P. M., Newton P. J., Wit R. C. N., Lim L. L., Owen B. and Sausen R. (2009) Aviation and global climate change in the 21st century. In: *J Atmosenv*, **in press**, pp. 1-18, retrieved from: www.tiaca.org/images/tiaca/PDF/IndustryAffairs/2009%20IPCC%20authors%20update.pdf.
- Lee et al. 2010 Lee D. S., Pitari G., Grewec V., Gierens K., Penner J. E., Petzold A., Prather M. J., Schumann U., Bais A., Bernsten T., Iachetti D., Lim L. L. and Sausen R. (2010) Transport impacts on atmosphere and climate: Aviation. In: *J Atmosenv*, **2010**(44), pp. 4678–4734, 10.1016/j.atmosenv.2009.06.005, retrieved from: ac.els-cdn.com/S1352231009004956/1-s2.0-S1352231009004956-main.pdf?_tid=2127a67595d8edf6c516e912c49c4240&acdnat=1333532417_ad6f8409ad87089beac3d618cce3f283.
- Lund et al. 2017 Lund M. T., B. Aamaas, Berntsen T., Bock L., Burkhardt U., Fuglestedt J. S. and Shine K. P. (2017) Emission metrics for quantifying regional climate impacts of aviation. In: *Earth System Dynamics*, **8**, pp. 547-563, <https://doi.org/10.5194/esd-8-547-2017>.
- Mäder 2008 Mäder C. (2008) Klimawirksamkeit des Flugverkehrs: Aktueller wissenschaftlicher Kenntnisstand über die Effekte des Flugverkehrs. Umweltbundesamt, FG I 2.1 Klimaschutz, Dessau, DE, retrieved from: www.atmosfair.de/fileadmin/user_upload/Medienecke/Downloadmaterial/Wissenschaftliche_Berichte/Umweltbundesamt_Flugverkehr0308.pdf.
- myclimate 2009 myclimate (2009) The myclimate Flight Emission Calculator. myclimate, retrieved from: www.myclimate.org/fileadmin/documents/cms/E_flight_calculator.pdf.
- Penner et al. 2000 Penner J. E., Lister D. H., Griggs D. J., Dokken D. J. and McFarland M. (2000) IPCC Special report aviation and the global atmosphere: Summary for Policymakers. In: *A Special Report of IPCC Working Groups I and III*. IPCC, Intergovernmental Panel on Climate Change, Cambridge University Press, The Edinburgh Building Shaftesbury Road, Cambridge, UK, retrieved from: www.ipcc.ch/pub/reports.htm.
- Peters et al. 2011 Peters G. P., Aamaas B., Lund M. T., Solli C. and Fuglestedt J. S. (2011) Alternative “Global Warming” Metrics in Life Cycle Assessment: A Case Study with Existing Transportation Data. In: *Environ. Sci. Technol.*, **2011**(45), pp. 8633–8641, [dx.doi.org/10.1021/es200627s](https://doi.org/10.1021/es200627s), retrieved from: pubs.acs.org/doi/abs/10.1021/es200627s.
- SimaPro 8.5.3 SimaPro (8.5.3) SimaPro 8.5.3 (2018) LCA software package. PRé Consultants, Amersfoort, NL, retrieved from: www.simapro.ch.
- Solomon et al. 2007 Solomon S., Qin D., Manning M., Alley R. B., Bernsten T., Bindoff N. L., Chen Z., Chidthaisong A., Gregory J. M., Hegerl G. C., Heimann M., Hewitson B., Hoskins B. J., Joos F., Jouzel J., Kattsov V., Lohmann U., Matsuno T., Molina M., Nicholls N., Overpeck J., Raga G., Ramaswamy V., Ren J., Rusticucci M., Somerville R., Stocker T. F., Whetton P., Wood R. A. and Wratt D. (2007) Technical Summary. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Spielmann et al. 2007 Spielmann M., Roberto Dones, Bauer C. and Tuchschnid M. (2007) Life Cycle Inventories of Transport Services. ecoinvent report No. 14, v2.0. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.
- UBA 2012 UBA (2012) Klimawirksamkeit des Flugverkehrs: Aktueller wissenschaftlicher Kenntnisstand über die Effekte des Flugverkehrs. Umweltbundesamt, FG I 2.1 Klimaschutz, Dessau, DE, retrieved from: www.umweltbundesamt.de/klimaschutz/publikationen/klimawirksamkeit_des_flugverkehrs.pdf.

References

WBCSD & WRI 2011 WBCSD and WRI (2011) Product Life Cycle Accounting and Reporting Standard. World Business Council for Sustainable Development, World Resources Institute, The Greenhouse Gas Protocol Initiative.