

On behalf of the Mobility Platform of ETH Zurich

How to include non-CO₂ climate change contributions of air travel at ETH Zurich

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Editorial Information

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1. Introduction

In addition to emitting carbon dioxide, aircraft operation in the upper troposphere and lower stratosphere alter the atmospheric concentration of greenhouse gases such as ozone and methane, trigger the formation of condensation trails (contrails) and increase cirrus cloudiness (IPCC 1999). This leads aircraft to have higher climate change contributions than what would be expected when considering only their fuel consumption or CO₂ emissions (IPCC 1999). Despite the high uncertainties related to actual global warming attributable to some of these atmospheric processes, the concept of a CO₂ emissions weighting factor (EWF) can be used to approximate these non-CO₂ climate change contributions and relate them to the more easily computable CO₂ emissions (Forster et al. 2006).

Radiative forcing

Radiative forcing (RF) is a measure of a change to the earth-atmosphere energy budget compared to the year 1750 (IPCC convention). This results from changing atmospheric concentrations of greenhouse gases and other effects such as albedo. It is measured in W/m² at the top of the atmosphere (Lee et al. 2009). Although RF has been used in the past to calculate EWFs for aircraft, it is not ideal for this purpose because it does not consider different lifetimes of the gases (Fuglestedt et al. 2010).

Global warming potential

Global warming potential (GWP) is the integral of the radiative forcing caused by a pulse emission of a greenhouse gas over a certain time compared to the radiative forcing of a 1 kg emission of carbon dioxide integrated over the same time (Fuglestedt et al. 2010). The GWP is used to transfer emissions of different greenhouse gases to a common scale in which they are comparable and can be added to a measure for their combined effect. The result is measured in kg CO₂-equivalents (CO₂_{eq}). This method can account for the different atmospheric lifetimes of different greenhouse gases. However, the time horizon over which to integrate is arbitrary. A shorter time horizon (e.g. 20 years) gives a higher relative weight to short lived climate gases, while a longer time horizon (e.g. 500 years) downplays the importance of these short-lived gases. The Kyoto protocol used a time horizon of 100 years. Thus, GWP100 has become the de facto standard. We base our EWF calculation on the GWP100.

The use of EWFs has become popular in recent years and it has become common procedure in carbon accounting methods to apply an EWF to aircraft CO₂ emissions. However, there seems to be a lack of consensus regarding the correct EWF to use, with factors ranging from 1 to 3 depending on the methodology used (Jungbluth 2018). The goal of this short paper is to review

the relevant scientific literature and determine the most appropriate EWF to be used by the ETH Zurich air travel monitoring system.

Two sets of information are needed to calculate the EWFs from aircraft operation. In section 2 we provide the GWP100 value for all the relevant aircraft emissions and in section 3 we provide the relative amounts of each of these substances emitted by aircraft. With these two pieces of information we calculate EWF values in section 4. In section 5 we examine the sensitivity of this metric to flight distance and in section 6 we provide a CO₂ EWF that considers the entire life cycle climate change contributions of air travel.

2. Non-CO₂ climate change impacts from aircraft cruise phase

In this section we discuss all relevant aircraft climate impacts and relate their global warming potential to that of CO₂ using the GWP100 metric. All GWP100 values are given in kg CO₂ eq per kg emission¹.

Water vapor

The radiative forcing and lifetime of aircraft water vapour emissions depend strongly on flight altitude and latitude. Water vapour emissions at higher altitudes have drastically higher RF than at lower altitudes, and RF values are also higher over the tropics than over the poles. Fuglestad et al. (2010) state that although there is not yet an estimate for the global air travel fleet as a whole, Grewe and Stenke's (2008) RF and lifetime values for 30-90° N and 198 hPa (roughly 12 km altitude) can be used as an approximate basis to estimate the global average. Based on these inputs, Fuglestad et al. compute a GWP100 value of 0.2 for aircraft cruise phase water vapour emissions. According to Fuglestad et al., uncertainty for this value is likely on the order of several tens of percent.

Lee et al. (2010) also cite Grewe and Stenke (2008) as a basis but present a water vapour GWP100 value of 0.14. As Lee et al. refer to Fuglestad et al. for more detail, we choose to use the value from Fuglestad et al. as base value here.

Contrails and Aviation Induced Cirrus (AIC)

Contrails are line shaped condensation trails created by the mixture of aircraft exhaust with cold atmospheric air (Lee et al. 2010). Aviation induced cirrus (AIC) are cirrus clouds caused by spreading contrails via shear and uplift processes as well as other mechanisms such as cloud formation due to the presence of additional nucleation sites due to aircraft emissions (Lee et al., 2010)².

Contrails and AIC have a net positive radiative forcing because they trap outgoing terrestrial radiation more than they reflect incoming solar radiation. There is however, significant uncertainty in the radiative forcing values of contrails and AIC, due to regional and temporal variability.

Both Lee et al. (2010) and Fuglestad et al. report a GWP100 value of 0.21 for contrails and 0.63 for AIC which is taken from the 2007 IPCC report (IPCC 2007). Fuglestad et al. state that the uncertainty for contrails is a factor of 1.5 to 2 and roughly 3 for AIC.

¹ For contrails and AIC per kg of CO₂ emission, see footnote 2

² Contrails and AIC cannot be directly linked to the emission of any one aircraft emission specimen. While they are triggered by the emission of water vapour from the aircraft engine, they are so highly dependent on the atmospheric state that it does not make sense to link them to the water vapour emission. Despite this fact it is common to quantify contrails per kg of CO₂ emitted in the cruise phase to be consistent with other emissions.

Lund et al. (2017) report a GWP100 value for contrail cirrus, consisting of contrails and AIC, of 0.84, which is the same as the sum of the values reported above, but is apparently calculated using a different methodology as in the 2007 IPCC report.

NO_x

Climate impacts from aircraft cruise phase NO_x emissions are due to a combination of NO_x induced ozone formation and methane degradation. These two processes have positive and negative radiative forcing respectively, and roughly cancel each other out. However, the degree to which they cancel each other out depends strongly on regional and environmental factors (Fuglestvedt et al. 2010, Lund et al. 2017). This leads to significant variability in the literature regarding the overall climate impact of aircraft NO_x emissions. The GWP100 factor for aircraft NO_x emissions ranges from -2.1 to 71 (Fuglestvedt et al. 2010), -21 to 67 (Myhre et al. 2011) and 4 to 60 (Skowron et al. (2013). Lund et al. (2017) seems to be the most advanced publication on the topic, so we use their global average GWP100 value of 77 as the basis for this calculation and include the range of results from the literature in the uncertainty analysis.

PM/ BC/ Soot

Particulate matter (PM) emissions contribute to aviation climate change via absorption of short-wave radiation and also alter cloud structure (Fuglestvedt et al. 2010). Lee et al. (2010) and Fuglestvedt et al. (2010) both report a GWP100 value for BC (black carbon) of 460, while Lund et al. (2017) report a GWP100 value of 1060, claiming that this value is specific to aircraft emissions and should be preferred to that of Fuglestvedt et al. We use the value from Lund et al. (2017) as the most likely value.

SO_x and Organic Carbon

SO_x and organic carbon (OC) both have negative contributions to climate change due to formation of particles which reflect solar radiation and change cloud properties (Fuglestvedt et al. 2010). These substances are comparatively less important when calculating aircraft cruise phase climate impacts (Lee et al. 2010). According to values reported by Lund et al. (2017), we use a GWP100 value of -77 for organic carbon and a GWP100 value of -152 for SO_x.

Regional variability

Lund et al. (2017) provide GWP100 factors for 6 global regions for most of the substances discussed above. Despite this, we use global average factors in our calculation as there is little difference between the global averages and the regionally averaged values for the most common destinations for ETH students and employees. A more detailed analysis is outside of the scope of this project.

3. Aircraft cruise phase emissions

In order to calculate the CO₂ emissions weighting factor, information is also needed regarding the relative emissions of each substance in the aircraft cruise phase. We take these emissions data from Cox et al. (2018), which are based upon the EEA's air pollutant inventory guidebook (2013). Cox et al. use the EEA data to calculate the average emissions of the Swiss aircraft fleet and their development over time. These figures also agree well with the global average values from the year 2000 presented by Lee et al. (2010).

4. CO₂ emissions weighting factor

Emission weighting factors are calculated by a multiplication of the emission of the substance relative to the emission of CO₂ (first line in Table 1) with the GWP100 factor of the substance. The resulting CO₂ EWF are presented in Table 1 below. We find a most likely total value of 2.0 and a likely range given the current level of scientific uncertainty of 1.3 to 3.6. These values are in good agreement with Lee et al. (2010) who report an EWF of 1.9 – 2.

Table 1: Summary of aircraft cruise phase emissions, GWP100 factors and CO₂ emissions weighting factor (EWF).

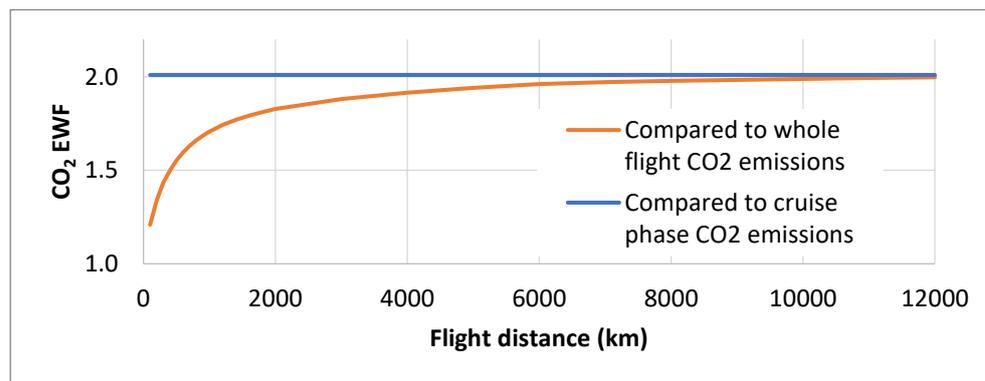
		CO ₂	H ₂ O	NO _x (as N)	PM/ BC	SO _x	OC	Contrails & AIC	Total EWF
Emissions relative to CO ₂		1	0.39	1.2E-03	3.7E-05	2.7E-04	3.1E-05	1	
GWP100 factor (kg CO ₂ eq/ kg)	Most likely	1	0.20	77	1060	-152	-77	0.84	
	Lowest likely	1	0.10	-2.10	460	-152	-77	0.30	
	Highest likely	1	0.40	77	1060	-140	0	2.31	
CO ₂ EWF	Most likely	1	0.08	0.094	0.039	-0.041	-0.0023	0.84	2.01
	Lowest likely	1	0.04	-0.003	0.017	-0.041	-0.0023	0.30	1.31
	Highest likely	1	0.16	0.094	0.039	-0.037	0	2.31	3.56

Table INFRAS.

5. Sensitivity to flight distance

The above CO₂ EWF values are calculated based on aircraft cruise phase CO₂ emissions only and therefore are independent of the total flight distance. This EWF can be used to calculate ETH Zurich's CO₂-eq emissions since the methodology to calculate CO₂ emissions distinguishes emissions from taxi, take-off, ascent, descent and landing from cruise phase emissions. However, since less sophisticated models only calculate the total CO₂ emission of a flight, it is also common to define CO₂ equivalence factors based on total flight CO₂ emissions. This factor has to be lower than the factor for cruise phase only and, of course, depends on flight distance. We show an approximation of this relationship in Figure 1 below. Thus, if only the total CO₂ emission of a 2000 km long flight were known, a CO₂ EWF of 1.83 would have to be applied to calculate CO₂-eq emissions comparable to those reported by ETH Zurich.

Figure 1: Approximation of EWF of total CO₂ emissions and cruise phase emissions only as a function of distance.



Graphics INFRAS.

6. Life cycle climate change impacts

In addition to non-CO₂ climate impacts from cruise phase emissions, it is also possible to include the life cycle climate change impacts due to the production of the jet fuel and the production, maintenance and end-of-life of the aircraft and airport. The infrastructure (airports, planes) production generally contributes less than 3% to the overall climate change impact of air travel (Cox et al 2018). This value depends on many factors such as flight distance, start and end point of the flight, load factor of the plane, type of aircraft and life time mileage of aircraft. Since most of these factors are flight specific, the calculation of the infrastructure's contribution to climate change impacts would have to be done for each flight separately. In view of the rather low relevance of these stages of the life cycle, this seems not justified and therefore, ETH Zurich decided to exclude the production, maintenance and disposal of airports and airplanes from its calculation.

However, greenhouse gas emissions from jet fuel production are more relevant (15.2% of CO₂ emission from operation) and directly related to the airplane's total CO₂ emissions (Cox et al. 2018). ETH Zurich decided to include them in their reporting to comply with the EN standard on calculation of energy consumption and GHG emission of transport services (EN 2013) and the ISO standard on LCA (ISO 2006).

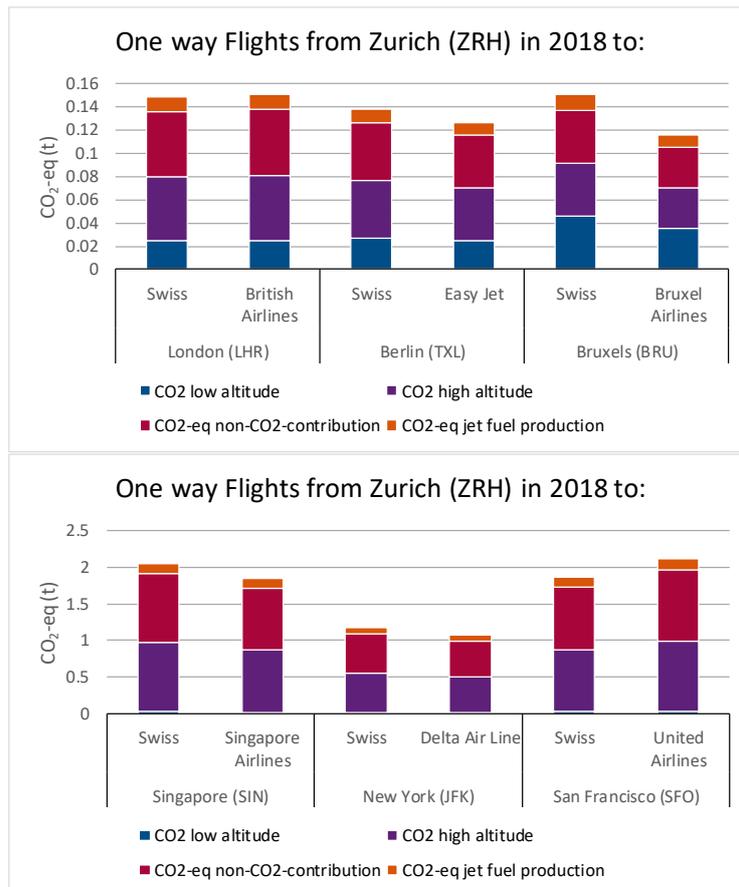
7. Recommendation

We recommend multiplying cruise phase (i.e. above 9000 m altitude) CO₂ emissions of aircraft operation by a factor of 2 and add this to the CO₂ emission of the other flight phases to estimate the total GWP100 of aircraft operation.

Greenhouse gas emissions of jet fuel production shall be calculated by multiplication of the total CO₂ emission³ of the aircraft operation (i.e. including taxi, take-off, ascent, cruise phase, descent and landing) with a factor of 0.152.

Results are best presented in a way that distinguishes the contributions of CO₂ emissions in low and high altitude, the contribution of non-CO₂ emissions in high altitude and emissions from jet fuel production (see Figure 2 for an example).

Figure 2: Example for presentation of total climate change impacts of specific (one way) flights



Graphics INFRAS, Operation CO₂-emissions from Atmosfair

³ CO₂ emission only, **not** total GWP of operation!

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