Overview of the impact of aviation on climate change and how this should be considered for air travel at ZHAW

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1 Introduction

Travelling is an essential part of international cooperation and as air traffic constitutes the only means of travelling long distances within reasonable timeframe, corporate air travel remains indispensable. This becomes evident in the fast recovery of the corporate travel sector after the SARS-CoV-2 travel restrictions have been lifted (Daher et al., 2022)[1]. With air traffic being a relevant contributor to climate change, this poses a dilemma for organisations and institutions who are seeking for more sustainable business practices. Although the most effective way to reduce CO_2 emissions is to avoid producing them, carbon offset also offers a viable solution to this problem. In order to perform a proper life cycle analysis (LCA) and thus determine appropriate compensations for air travel, a multitude of complex processes and interdependent factors have to be considered. The following pages will give a brief overview and conclude with a recommendation for best practice.

First, the contribution of air traffic to climate change must be understood. 2.8% of global CO_2 emissions from fossil fuel combustion are emitted into the atmosphere by aircraft engines (IPCC, 2022; Lee et al., 2021). Overall, however, aviation is responsible for around 4% of the observed human-induced global warming to date, with number ranging between 3.5 to 4.9%, depending on the method used for quantification (Klöwer et al., 2021; Lee et al., 2009; Lee et al., 2021). CO_2 emissions only are therefore not sufficient to estimate the impact of aviation on climate change, as the so-called non-CO_2 effects, which are triggered by other substances emitted by aircraft, must also be taken into account (Frömming et al., 2021). The relevant non-CO_2 emissions and their respective ways of affecting radiation are briefly explained in section 2.
Quantifying the radiative forcing of non-CO_2 effects is much more difficult than for CO_2 and is still subject to scientific debate. One reason for this is the short atmospheric lifetime of non-CO_2 emissions. While CO_2 remains in the atmosphere up to centuries and is thus evenly distributed around the globe (Archer et al., 2009), non-CO_2 emissions such as H_2O or aerosol particles have a lifetime of hours to days and their effects on climate are, as a consequence, dependent on local conditions (Frömming et al., 2021; Kärcher, 2018; Klöwer et al., 2021; Lee et al., 2021; Matthes et al., 2021). Various approaches have been developed to quantify the impact of both natural and anthropogenic emissions on the Earth's climate with regard to their atmospheric lifetime (see box). The most commonly used approach for LCAs is GWP_{100}, which is a measure of the effective radiative forcing (ERF) of the emission of a given substance compared to the ERF of the same amount of emitted CO_2, integrated over 100 years. This leads to a systematic underestimation of short-lived climate pollutants (SLCPs), as their effect is artificially diluted when integrated over a period that exceeds their lifetime. To overcome this deficiency, the metric GWP* was introduced (Allen et al., 2018; Cain et al., 2019). Since SLCPs are responsible for a large share of the non-CO_2 effects, their underrepresentation results in a severe underestimation of the warming potential of aircraft emissions. GWP* is therefore chosen as representative metric in this report to describe the impact of aviation on climate change.

Second, it must be understood that for a given airport pair, CO_2 and non-CO_2 emissions can vary significantly from flight to flight. On one hand, these emissions depend on the fuel consumption, which itself depends on distance (e.g. routing), airplane type, total weight of passengers and freight, cruise speed and flight altitude. On the other hand, the emissions depend on

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[1] Also: ACI 2022, see https://aci.aero/2022/06/28/the-impact-of-covid-19-on-airportsand-the-path-to-recovery/, accessed July 10th, 2022

Instantaneous radiative forcing (IRF) [W/m^2]

In IPCC AR6 WG1 IRF is defined as the immediate change in radiative flux at the top of atmosphere (TOA) following a perturbation of climate forcing agents before accounting for adjustments. As for all radiative forcing (RF) metrics, the year 1750 is used as baseline and the result is given in W/m^2 (IPCC, 2021).

Stratospheric-temperature-adjusted radiative forcing (SARF) [W/m^2]

Same as IRF but including adjustments of the stratospheric temperature response. Note that SARF was used as the reference metric for RF in many older publications as well as in the IPCC reports prior to AR5 (IPCC, 2021).

Effective radiative forcing (ERF) [W/m^2]

The ERF includes adjustments of stratospheric and tropospheric temperatures, water vapor, clouds, atmospheric circulation and surface albedo that are uncoupled to any global mean surface air temperature (GSAT) change. No timescale is used for the definition of ERF but it is crucial that a clear distinction is made between included adjustments, which are independent of surface temperatures and occur on timescales of hours to several month, and not included feedbacks, which influence land and sea surface temperatures and have timescales of a year or more. This metric is also recommended by the IPCC AR5 and AR6 for RF because it best reflects the surface air temperature changes caused by the different climate forcing agents (IPCC, 2021).

Global warming potential (GWP) [Tg CO_2^{eq} yr^{-1}]

The global warming potential is defined as the ERF of an impulse emission of a given climate forcing agent compared to the ERF of a CO_2 impulse emission of the same mass integrated over a certain time period. Typical integration periods are 20, 50 and 100 years, yielding GWP_{20}, GWP_{50} and GWP_{100}. It should be noted that shorter integration periods (e.g. 20 years) give relatively more weight to short-lived climate pollutants (SLCP), such as black carbon, methane, tropospheric ozone and some hydrofluorocarbons, than longer integration periods (e.g. 100 years) (IPCC, 2021). The GWP and its following derivatives are given in CO_2-equivalent (Tg CO_2^{eq} yr^{-1}).

Global temperature change potential (GTP) [Tg CO_2^{eq} yr^{-1}]

Same as GWP except that here the actual GSAT response caused by the different climate forcing agents at the end of the integration period (e.g. 100 years for GTP_{100}) is given (IPCC, 2021).

GWP* [Tg CO_2^{eq} yr^{-1}]

A modified form of GWP, denoted GWP*, accounts for SLCPs by emitting the CO_2-equivalent of these substances in a one-time push at the end of the period under consideration. Allen et al. (2018) and Cain et al. (2019) have further improved the method by introducing a term for the short- and long-timescale climate responses of the SLCP to changes in RF.

environmental conditions, such as temperature, relative humidity or atmospheric pressure (see section 2). Consequently, the impact on climate change of a flight with the same airplane over the same distance, can differ significantly not only between seasons, but also from day to day. Proper consideration of these factors requires a sophisticated modelling approach, which is briefly discussed in section 3. Due to the disproportionate amount of computational power needed for such calculations and the still (too) large resulting uncertainties there are other approaches to find a more viable solution, which are discussed in section 4.

There are currently several developments in the aviation industry, that will change both future aircraft technology and flight operations, and with it the fuel consumption and non-CO_2 effects.

Any approach to quantify those effects today, must therefore be adjusted in the future. The major developments and their (likely) impact on the radiative forcing caused by air travel are briefly discussed in section 5.

2 Impact of aircraft engine emissions on climate change

This section describes relevant types of emissions and their impact on the climate system that result from the combustion of fuel in an aircraft engine.

2.1 Carbon dioxide (CO_2)

For every kg of aviation fuel burned, 3.16 kg of CO_2 are emitted into the atmosphere (ICAO, 2018). Since CO_2 is a long-lived and well-mixed GHG in the atmosphere, the location of the emissions plays only a minor role. The GWP* of aviation induced CO_2 for the year 2018 is 1034 Tg CO_2 yr^{-1} (Lee et al., 2021).

2.2 Water vapor (H_2O)

The combustion of aviation fuels produces another GHG, water vapor (1.24 kg per kg fuel) (Nojoumi et al., 2009). H_2O emissions in the troposphere hardly have any effect on the radiation balance due to the short lifetime and the already relatively high absolute humidity. The situation is different for the water vapor emitted into the much drier stratosphere. The absolute water vapor content in the stratosphere is significantly increased by water vapor emissions from aircraft engines, which changes the radiation balance. The effect is further enhanced by the longer lifetime of water vapor in the stratosphere (Solomon et al., 2010). Whether and how much water vapor is emitted into the stratosphere depends on the one hand on the flight altitude and on the other hand on the height of the tropopause, which itself varies with season, the latitude and current weather situation. Lee et al. (2021) estimated an GWP* for water vapor for the year 2018 of 42 Tg CO_2^{eq} yr^{-1}.

2.3 Nitrogen Oxides (NO_x)

Even though nitrogen oxides are not GHGs per se, these highly reactive molecules interact directly or indirectly with other substances to form, among others, ozone. They thus will have an impact on the radiation balance. While the short-term increase of ozone (O_3) has a positive ERF, the decrease in methane (CH_4) concentration as well as the long-term decrease in both O_3 and stratospheric water vapor has a negative ERF (Fuglestvedt, 1999). Due to the short lifetime of NO_x, the emission location plays an important role and because of the numerous processes involved, which can ultimately influence the radiation balance, the calculation is relatively complex and still associated with some uncertainties (Lee et al., 2021). The amount of NO_x emitted per kg of fuel also varies considerably depending on engine type and thrust setting (EASA, 2022). Lee et al. (2021) used an average value of 15.14 g NO_x per kg fuel for the ERF calculations of 2018, yielding a GWP* of 339 Tg CO_2^{eq} yr^{-1}.

2.4 Contrail cirrus

Linear contrails result from the emissions of water vapor and ice-nucleating particles (INP) into cold (well below the freezing point) atmospheric regions by aircraft engines at high altitudes. With the emitted H_2O, the air becomes (super-)saturated with respect to ice and the water freezes on to INPs and forms the typical linear contrails. If the surrounding air is dry, the ice crystals will sublimate, and the linear contrails vanish quickly. If, in contrast, the surrounding air is humid enough, the ice crystals can grow, multiply and spread via atmospheric motion. In this case, contrail cirrus, which usually are broader, more transparent, and longer-lived than linear contrails, will form (Kärcher, 2018). Both linear contrails and contrail cirrus have a net warming effect on surface air temperatures. It must be noted that the formation of contrail cirrus removes water vapor from the atmosphere in higher layers, which consequently leads to a reduction in the formation of natural cirrus clouds. This is the main reason why the ERF of contrail cirrus is much smaller than the SARF. Older studies that used SARF to quantify the effect of contrail cirrus on climate change generally overestimated this effect (Bickel et al., 2020). However, it must also be said that the uncertainties for this area are still very high. This is mainly because some mechanisms in the formation of contrail cirrus are not yet sufficiently understood. Lee et al. (2021) give a GWP* of 1834 Tg CO_2^{eq} yr^{-1} for contrail cirrus.

2.5 Aerosol-radiation interaction

Aerosol from aircraft engines emissions consist mainly of soot, and precursors of sulfate ($[SO_4]^{2-}$) and nitrate (NO_3^-) aerosols. Soot particles absorb the incoming shortwave radiation and thus contribute to a positive ERF, while sulfate and nitrate aerosols scatter the incoming shortwave radiation and thus contribute to a negative ERF (Righi et al., 2013). Since absorption and scattering depend on the incidence angle of the solar radiation, the latitude and the season influence the effect on the ERF. It should also be noted that the soot emissions from engines are not only dependent on fuel consumption and type, but also on turbine technology (similar to NO_x emissions) (EASA, 2022). Emissions of SO_2, the precursor of sulfate aerosols, are primarily dependent on the sulfur content of the fuel, which in turn depends on the origin of the crude oil and on the refinery process. Overall, the ERF values of soot, nitrate and sulfate aerosols are small, but their uncertainties are relatively large due to different parameterizations of the relevant processes in the models. Lee et al. (2021) give GWP* values of 20 Tg CO_2^{eq} yr^{-1} for soot and -158 Tg CO_2^{eq} yr^{-1} for sulfate aerosols. GWP* values for nitrate aerosols are not available. In another study, Prashanth et al. (2022) give an ERF value of -0.67 mW/m^2 for nitrate aerosol, which is approximately in the same absolute order of magnitude as the ERF of soot (only negative).

2.6 Aerosol-cloud interactions

Aerosols from engine emissions, mainly soot and sulfates, can act as both cloud condensation nuclei (CCN) and INPs, depending on their chemical composition and physical properties. They affect cloud formation and lifetime and thus also ERF. The effect of this aerosol-cloud interactions on the radiation budget is highly complex as it depends on formation conditions and aging of the aerosol particles, as well as environmental conditions (Lohmann et al., 2020). Despite current efforts in understanding the properties and mechanisms of these aerosols on cloud formation, the uncertainties do not allow a reasonable best estimation of the ERF and therefore also GWP* (Lee et al., 2021).

3 Calculation of the climate impact for single flights

Calculating the CO_2 emissions per passenger for a single flight is not trivial. The occupancy, the cargo volume and the seat configuration should be taken into account for each and every flight separately. Seat configuration can be determined relatively easily. Additionally, very recently, IATA published its recommended practices document 1746, which should serve as a generally accepted methodology for allocating emissions among seat classes (IATA, 2022). The occupancy and cargo volume of individual flights, however, varies greatly and can only be predicted approximately. In addition, there are different approaches as to how the additional emissions caused by the freight are distributed among the passengers (Iken and Aguessy, 2022). Fortunately, there are already some CO_2 calculators for air travel, the most sophisticated of which take into account aircraft type as well as seat class, occupancy and cargo (atmosfair, 2022). It should be noted that the results from these calculators, obtained for the same flight, can differ from each other, mirroring the uncertainties discussed in this document.

Calculating the non-CO_2 emissions of a single flight is even more challenging. As described in Chapter 2, the NO_x and particulate emissions depend on the combustion process of the engine

used, as well as on thrust, and can be described for a specific engine type by an emissions index (EI) multiplied by the mass of fuel used, the latter being proportional to CO_2 emissions of the flight. In addition, the climate impact of these non-CO_2 emissions depends on environmental conditions, such as relative humidity, altitude of the tropopause, etc. It is possible to model the environmental conditions along the flight trajectory (weather models) and the thrust settings (aircraft performance models with integrated emission modelling, e.g. Piano-X or OpenAP).
In summary, it can be said that although it is possible to model both the emission quantity and its distribution along the flight trajectory, it is complex, energy- and time-consuming, all while the uncertainties remain considerable.

4 (Non-)Sense of a singular factor to determine the climate impact for single flights

From the above explanations, it becomes clear that: a) CO_2 and non-CO_2 effects must be considered to estimate the impact of air traffic on climate, b) emissions and their climate effects (especially non-CO_2) vary from flight to flight, and c) calculating the total emissions of a single flight is subject to many uncertainties and, due to its complexity, not a feasible solution for daily business.

To take non-CO_2 effects into account, the radiative forcing index (RFI) was introduced in the life cycle assessment (LCA) of air travel. The RFI is the ratio of the total radiative forcing (due to CO_2 and non-CO_2 emissions) to the radiative forcing caused by CO_2 only. However, as described in the box, the RF concepts considers changes in the planetary radiation budgets back to the year 1750. For the aviation industry, this means that the entire cumulated effect of all CO_2 emissions from the aviation sector (since 1950) are taken into account together with the SLCP emitted shortly before and/or during the reference year (depending on their specific lifetime) (IPCC, 1999). The net aviation ERF for 2018 is 100.9 mW/m^2 and the ERF from aviation induced CO_2 emissions alone is 34.3 mW/m^2 resulting in an RFI of 2.9 (Lee et al., 2021). Although this value has been and still is used incorrectly by many as an emissions metric, it should not be directly related to annual CO_2 emissions for the reasons mentioned above (Azar and Johansson, 2012; Lee et al., 2010). Better suited for this purpose is a so-called emission weighting factor (EWF) (Eqn 1). This is calculated on the basis of the GWPs or GTPs and can thus be related to the annual CO_2 emissions of aviation of a specific year (t):

$$EWF(t) = \frac{GWP^*_{CO_2}(t) + GWP^*_{non-CO_2}(t)}{GWP^*_{CO_2}(t)} \tag{1}$$

4.1 Uniform EWF

Despite large variances and uncertainties, a uniform single value for the EWF has its appeal and is a feasible, user-friendly approach. If it is chosen as an average value for a large number of flights, it can be assumed that the total radiative forcing of some flights is overestimated, while others are underestimated, which makes for an approximately right estimation overall. To determine the average EWF, one can consult the total GWP* from air traffic emissions, as shown for the year 2018 in table 1. The summed GWP* of aviation is 3111 Tg CO_2^{eq} yr^{-1} and thus almost exactly three times higher than the CO_2 emissions of aviation in 2018. For this reason, based on the latest scientific findings, an EWF of 3 is proposed here.
As mentioned in the introduction, the commonly used metric for LCAs currently is GWP_{100}, which is why it is also listed here. Applying it to aviation yields a total CO_2-equivalent of 1797 Tg CO_2^{eq} yr^{-1}, which is much less than the GWP* and equals an EWF of 1.7. This is due to the systematic underestimation of long-term climate effects of short-lived pollutants (SCLPs), which are accounted for in the GWP*. Consequentially, the GWP_{100} and its resulting EWF are not recommended for use in this report.

Table 1 GWP* corresponding CO_2-equivalent (Tg CO_2^{eq}) emissions for the 2018 aviation emissions and aviation-induced cloudiness (Lee et al., 2021).

	CO_2	Contrail cirrus	Net NO_x	Aerosol-radiation		Water vapor emissions	Total CO_2-eq
				Soot emissions	SO_2 emissions		
GWP*	1034	1834	339	20	-158	42	3111
GWP_{100}	1034	652	136	11	-84	23	1797

4.2 Sensitivity to flight trajectory

In order to correctly quantify the influence of emissions on the radiation balance, the emission location is crucial. In general, it can be said that the higher in the atmosphere the emissions are emitted, the greater is their influence on the radiation balance (Fichter et al., 2005). Therefore, there are approaches to apply an EWF > 1 only for emissions at high altitude. This would give short-haul flights a smaller overall EWF than long-haul flights, as they usually cruise at lower altitudes than the latter (Jungbluth and Meili, 2019). However, the altitude at which the higher EWF is applied is not specified and it is far from trivial to allocate the emissions to different altitudes (see chapter 3). It is also less important at which altitude the emissions are emitted but rather in which air layer. If the air layer is supersaturated with respect to ice, contrail cirrus form (Kärcher, 2018), or if the emissions are injected into the stratosphere, the influence of water vapor on the radiation balance increases (Solomon et al., 2010; Wilcox et al., 2012). Thus, again, to calculate the EWF correctly, the environmental conditions along the flight path must be known in addition to the emissions.

4.3 Calculation of EWF for a single flight

As mentioned above, the calculation of the actual total CO_2 and non-CO_2 effects – and thus the actual EWF of a single flight – is theoretically possible by using modelling toolsets. However, this approach is extremely complex, time consuming and still subject to many uncertainties. A simplification of this process was suggested by Dahlmann et al. (2021), who developed a simple equation to calculate the CO_2-equivalents of NO_x, water vapor and contrail cirrus from the CO_2 emissions of a flight, taking into account only the flight distance and the mean latitude. Compared to a constant EWF, they were able to reduce the mean square error from 1.18 to 0.19. The application of the formula would be simple enough to use for everyday LCAs of flights, but, unfortunately, it has been developed for only one type of aircraft (A330-200), with no distinction made between the three different engine options. The application to other aircraft types is not admissible due to the different emission profiles of aircraft engines, and their significant impact on non-CO_2 emissions (see section 2). Therefore, the use of this method is not (yet) recommended here, until more parameters for the most widely used aircraft types and engines are available.

5 Expected future changes affecting the EWF

There currently exist numerous developments in the aviation sector which are supposed to have an impact on future climate impact of air traffic, and thus on the best practice to handle carbon offset. A selection of the most important trends and their possible impacts on the EWF are summarized in this section.

5.1 Sustainable aviation fuels

The aviation sector is working towards a more sustainable future. An important part of this are fuels from non-fossil sources. While biokerosene is already being used (in small quantities), other technologies like Power-to-Liquid, Sun-to-Liquid, or hydrogen used in fuel cells as well as in combustion engines are being developed and expected to be ready to be introduced in the next decade (ICAO, 2017). In addition to the reduction of CO_2 emissions, these new fuels are expected to have significantly less non-CO_2 effects, as they produce less particulate matter than fossil kerosene, which reduces the likelihood of contrail formation. Thus, with an increasing share of sustainable aviation fuels, the EWF is expected to decrease (Beyersdorf et al., 2014; Walls and Wittmer, 2022; Zhang et al., 2022).

5.2 Changes in fleet composition

In addition to the technological advances regarding sustainable fuels, changes in fleet composition such as aircraft with newer and more efficient engines and altered composition of non-CO_2 emissions, new propulsion technologies like battery or hydrogen power and other trends will have a lowering impact on EWF. A further significant potential effect is expected by the foreseen introduction of supersonic stratospheric flights. Increased traffic in the stratosphere will alter not only water vapor content in the stratosphere, but also its chemical composition and thus its radiative balance. While CO_2 emissions of supersonic aircraft will be higher than for subsonic ones due to their higher fuel burn, the net effect of non-CO_2 emissions however is highly uncertain and some estimates even expect it to be negative (Eastham et al., 2022; Matthes et al., 2022).

5.3 Changes in flight planning

Considering the significant dependence of non-CO_2 effects on the environmental conditions in a given air layer, some studies are suggesting how such vulnerable air layers could be avoided (Frömming et al., 2021; Niklaß et al., 2021). The increase in kerosene consumption by flying around these critical atmospheric layers is more than compensated for by the beneficial effects of avoided contrails and stratospheric emissions to the ERF. Once flight trajectories are adapted accordingly, the EWF is expected to decrease.

5.4 Changes in atmospheric structure and composition

The continuing increase in global mean temperature has various effects on the structure and composition of the atmosphere, which are suggested to affect non-CO_2 effects. As saturation water vapor pressure is temperature dependent, the absolute atmospheric H_2O content has been increasing in the past decades and is expected to continue to do so. The changes in relative humidity, however, remain unclear, and so do the implications for EWF (Borger et al., 2022; Hodnebrog et al., 2019).

Another consequence of global warming is a rise of the tropopause. With more heating from below, the troposphere stretches into higher altitudes. Assuming constant flight levels, this will lead to less air traffic near or even in the stratosphere (excl. supersonic stratospheric flights) and thus less radiative forcing from H_2O in the stratosphere (Meng et al., 2021).

The overall impact atmospheric changes on the EWF is subject to numerous uncertainties and difficult to predict at the moment.

6 Conclusion

Assessing the contribution of air travel to human induced global warming is characterized by large uncertainties, mostly due to non-CO_2 emissions of airplanes and direct and indirect impact on the radiative balance. Due to atmospheric conditions at high altitudes, non-CO_2 effects of air traffic can be significantly more substantial than the warming induced by the CO_2 emissions from fossil fuel combustion (Jungbluth and Meili, 2019; Lee et al., 2021). Consequentially, omitting them would potentially result in a severe underestimation of the climate impact of a flight. However, due to the complexity of (interdependent) processes and conditions which determine the non-CO_2 effects, explicitly calculating them for single flights is not applicable.

A user-friendly approach for integration of non-CO_2 effects is the EWF, with which the (much easier to calculate) CO_2 emissions of any given flight can be multiplied to estimate its total warming effect. We recommend using a uniform EWF of 3 for all flights, which reflects the impact of aviation on climate change for the year 2018, suggesting that over- and underestimation of single flights will even out. There are some suggestions to consider flight trajectories (altitude) to estimate individual EWFs for single flights, but they are based on assumptions and involve large uncertainties and thus, in our opinion, are not a significant improvement over using a uniform EWF.

Given the rapid current developments in research, regarding both aviation technology and climate impact assessment, as well as operational means to reduce non-CO_2 emissions impact, our recommendation must be understood as temporary best practice and must be reassessed in the upcoming years.

Lastly, and most importantly, when comparing aviation's impact on climate with other economic sectors, it is also important to ensure that the same metrics are used. As long as LCAs of other sectors use GWP_{100}, using GWP* for aviation results in a non-negligible overproportioned estimation of its relative contribution to global warming. Consequentially, when comparing with other sectors who use GWP_{100}, we recommend using the corresponding values for aviation (1797 Tg CO_2^{eq} yr^{-1} and an EWF of 1.7). However, even if the difference between GWP_{100} and GWP* is significantly smaller for many sectors as compared to aviation, due to the bigger impact of SCLPs at higher altitudes, using GWP_{100} still systematically underestimates the total warming potential of any given sector. An according adjustment of the LCA standard is therefore necessary but lies beyond the scope of this report.

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