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Climate assessment of single flights: Deduction of route specific equivalent CO_2 emissions

K. Dahlmann[a], V. Grewe[a,b], S. Matthes[a], and H. Yamashita[a]

[a]Institut für Physik der Atmosphäre, Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen, Germany; [b]Faculty of Aerospace Engineering, Section Aircraft Noise and Climate Effects, Delft University of Technology, Delft, The Netherlands

ABSTRACT
Climate impact of anthropogenic activities is more and more of public concern. But while CO_2 emissions are accounted in emissions trading and mitigation plans, emissions of non-CO_2 components contributing to climate change receive much less attention. One of the anthropogenic emission sectors, where non-CO_2 effects play an important part, is aviation. Hence, for a quantitative estimate of total aviation climate impact, assessments need to comprise both CO_2 and non-CO_2 effects (e.g., water vapor, nitrogen dioxide, and contrails), instead of calculating and providing only CO_2 impacts. However, while a calculation of CO_2 effects relies directly on fuel consumption, for non-CO_2 effects detailed information on aircraft trajectory, engine emissions, and ambient atmospheric conditions are required. As often such comprehensive information is not available for all aircraft movements, a simplified calculation method is required to calculate non-CO_2 impacts. In our study, we introduce a simple calculation method which allows quantifying climate assessment relying on mission parameters, involving distance and geographic flight region. We present a systematic analysis of simulated climate impact from more than 1000 city pairs with an Airbus A330-200 aircraft depending on the flight distance and flight region to derive simplified but still realistic representation of the non-CO_2 climate effects. These new formulas much better represent the climate impact of non-CO2 effects compared to a constant CO_2 multiplier. The mean square error decrease from 1.18 for a constant factor down to 0.24 for distance dependent factors and can be reduced even further to 0.19 for a distance and latitude dependent factor.

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Aviation; carbon footprint; climate impact; CO_2 equivalents; non-CO_2 effects; response model

1. Introduction

Aviation is an integral part of our globalized world and contributes with about 3–5% to the total anthropogenic climate impact in terms of radiative forcing (RF) (Lee et al., 2009). As aviation is one of the fastest growing sectors, the share in global CO_2 emission could rise from currently about 2 up to even 22% in 2050 (Cames et al., 2015). Although world passenger flights drastically decreased in April 2020 due to COVID19-Pandemic by more than 80% of seat capacity, it is assumed that it recovers to 60 to 80% of the previous year values already by end of 2021 (ICAO, 2021). Therefore, it will be important to reduce aviation's contribution to climate impact to achieve the 2 °C goal.

As climate impact is more and more of public concern, people become aware that they have to contribute to reduce their climate impact. A first order estimate of the climate impact of an individual flight is interesting to know, e.g., for compensating climate impact or carbon footprint of a flight, or for companies which want to become climate neutral. But while the climate impact of CO_2 emissions can be directly calculated, impacts of non-CO_2 emissions are much more complex to determine.

Climate impact of aviation is caused beside CO_2 emissions also by non- CO_2 effects (e.g., Grewe et al., 2017; Lee et al., 2009) which contribute to the total climate impact of aviation. Among those non-CO_2 effects especially the climate impact caused by contrails, nitrogen oxides (NO_x), and particle emissions, which influence cloud formation, play an important role, as impacts are of the same order of magnitude as the CO_2 climate impact. Non-CO_2 emissions contribute to global warming by an increase of the greenhouse gases ozone (O_3) and water vapor (H_2O), as well as particles, and the formation of contrails and contrail-cirrus (contrail induced cloudiness, CiC). While an increase in ozone and water vapor concentration always lead to a warming, contrails may lead to a cooling, depending on time of day, meteorology, and other factors (Grewe et al., 2014; Meerkötter et al., 1999; Schumann, 1996). Additionally, indirect NO_x effects lead (beside ozone formation and warming) to destruction of methane (CH_4) and a subsequent reduction in the O_3 productivity, which reduce the ozone concentration (PMO, primary mode ozone), causing a reduced warming, i.e., net-cooling effect.

CONTACT K. Dahlmann Katrin.Dahlmann@dlr.de Institut für Physik der Atmosphäre, Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen, Germany.

In contrast to the impact of CO_2, the impacts of non-CO_2 emissions depend, apart from the emitted amounts, on the emission location, especially on the altitude and on the latitude where the emission takes place. Although many studies focus on impacts of non-CO_2 emissions (e.g., Frömming et al., 2012; Köhler et al., 2008), there is no study which proposes a simple mathematical formula to calculate the climate impact of an individual flight.

To compensate the personal carbon footprint, a voluntary market exists, in which people or companies try to compensate for their contribution to climate change, e.g., they can pay for their emitted CO_2 emissions to support ecological projects to reduce the climate impact e.g., tree planting or provision of efficient stoves in poor regions to reduce fuel burn and deforestation (e.g., Atmosfair, 2018; Grenzen, 2018). In total, a compensation contribution of 84 Mt CO_2-equivalent was paid in 2015 (Hamrick & Goldstein, 2016). These voluntary market providers often account only for CO_2 emissions or use simplified assumptions about the climate impact of non-CO_2 emissions. Atmosfair for example uses a constant factor of 3 for flight sectors in altitudes higher than 9 km to account for non-CO_2 effects (Atmosfair, 2016). As no factor is used for flight sectors lower than 9 km, a mean factor of 2.7 is used. Myclimate uses a factor of 2 (Myclimate, 2015). These factors are based on the Radiative Forcing Index (RFI) reported by IPCC (1999) and Sausen et al. (2005). This RFI represents the contribution of non-CO_2 effects to the total aviation Radiative Forcing (RF) in 2000. Although RFI is widely used for compensation market, several studies show that RFI is not well suited for this purpose, as it does not account for the different lifetime and climate sensitivity of the different species (e.g., Forster et al., 2006; IPCC, 2007). For that reason, this study analyses the climate impact in terms of average temperature response (ATR), which represents the near-surface average temperature change over a given time horizon, here 100 year. We use this climate metric of ATR as it accounts for the lifetime of the different species, the different climate sensitivities and the thermal inertia of the atmosphere-ocean system. However, other physical climate metrics, e.g., with a different time horizon, could be directly calculated from the results presented here following the same concept.

Hence, this study proposes a calculation method relying on a set of mathematical formulas which allow to establish a direct relationship between mission parameters and associated total climate impact. This method uses mission length together with departure and arrival airports to calculate associated climate impacts applying representative climate impact metrics. The objective of this paper is (1) to present dependence of CO_2 and non-CO_2 climate effects on specific mission parameters, comprising mission length and geographic flight regions of individual flights in a global representative route network and (2) to introduce calculation methods and corresponding formulas using mission parameters to calculate non-CO_2 effects, enabling to calculate total climate impact of aviation emission for individual flight missions.

We describe the global data set of aircraft trajectories used in this study (Section 2). Then we present in detail the overall climate impact of those aircraft trajectories (Section 3). Section 4 introduces the mathematical formulas allowing to estimate climate impact from mission parameters. In Section 5 we discuss shortcomings and strengths of the three mathematical relationships (simplified calculation methods) before we conclude the study in Section 6.

Note, that we analyzed in this study the impact of one typical long-haul aircraft type of A330-200 aircraft. The A330-200 was used as it is the most sold aircraft in the medium- and long-range category, besides the Boeing 777. Different types of aircraft or aviation fuels could lead to different results if, e.g., the emission composition, emission indices of NO_x or the flight profiles significantly differ which would influence the implicitly assumed flight altitude.

2. Dataset of aircraft trajectories and climate impact

Climate impact of aviation operations depend on the emitted amount of CO_2 and non-CO_2 climate agents, flown distance and location and time of emission. For the analysis of the dependence of climate impact on mission length and geographic flight region, we use results from a comprehensive climate impact assessment which was performed on a set of individual missions in a representative global route network calculated by Dahlmann, Koch et al. (2016) and Koch (2013), which provide individual trajectory parameters and the associated climate impact for more than 1000 routes. They analyzed the climate impact of all the routes which were flown in 2006 (according to OAG, Official Airline Guide) with a typical long-haul aircraft (Airbus A330-200) by applying a workflow, which consists of coupled multidisciplinary models. In this model workflow, engines and aircraft are modeled to generate a performance map which includes information about necessary thrust settings and correspondent emissions of CO_2, H_2O, and NO_x. For each individual route, the necessary fuel is estimated and it is checked whether the aircraft specific flight performance envelope is fitted to stall and buffet limits, and cruise altitude capability. The Trajectory Calculation Module (TCM, Linke 2016) uses the performance tables and calculates the exact 3D flight path as well as the emissions of CO_2, H_2O and NO_x. Emission amounts and locations (altitude, latitude, longitude) are used in the climate response model AirClim (Dahlmann, Grewe et al., 2016; Grewe & Stenke, 2008) to analyze the climate impact of each route. AirClim combines aircraft emission data (3D: longitude, latitude, and altitude) with a set of previously calculated atmospheric responses to calculate the temporal development of the global near-surface temperature change. The atmospheric responses for H_2O and NO_x-induced changes in O_3 and CH_4 are derived from 85 steady-state simulations for the year 2000 with the DLR climate-chemistry model E39/CA, prescribing normalized emissions of NO_x and H_2O at various atmospheric regions (Fichter, 2009). For the impact of CiC we use atmospheric and climate responses considering local probability of fulfilling the Schmidt-Appleman Criterion (SAC) as well as ice supersaturated regions, which were

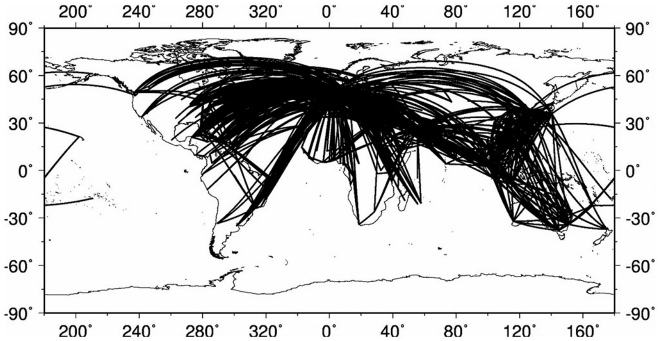


Figure 1. Analyzed global route network with all flights operated by an Airbus A330-200 aircraft in 2006. From Dahlmann, Koch et al. (2016).

obtained from simulations with ECHAM4-CCMod from Burkhardt and Kärcher (2009, 2011).

Note, that we follow a climatological approach in the calculation of the climate impact and the calculated values for the climate impact represent a mean over all weather situations averaging over individual spatially and temporally resolved responses. A detailed description of the workflow can be found in Dahlmann, Koch et al. (2016) and Koch (2013). For each of these routes, trajectories with different initial cruise altitude (ICA) and aircraft's flight speed (Mach number) were analyzed regarding the emissions, cash operating costs (COC) and climate impact of ATR100. The climate impact is calculated as average near surface temperature change over a time horizon of 100 years (Average Temperature Response, ATR_{100}) for a typical lifetime of aircraft of 32 years. For the systematic analysis presented in this study for each route flight trajectories with the lowest COC are analyzed, since they represent a reasonable representation of today's aircraft routings in a climatological sense.

In total 1178 different routes were analyzed, which can be seen in Figure 1. There are less flights between USA and Asia as Boeing aircraft are often used on these routes. For each of these routes the flight distance, fuel consumption, flight altitude, flight speed (Mach number), emissions of CO_2, H_2O, and NO_x, as well as climate impact of CO_2, H_2O, O_3, CH_4, PMO, and CiC were used for the analyses.

To compare the climate impact of different climate species, we calculate the climate impact of all species as CO_2 equivalents, which is the climate impact of each climate species relative to the climate impact of one kg CO_2. The CO_2 equivalent represents the amount of CO_2 which causes the same climate impact for the given climate metric (i.e., ATR_{100} and constant emissions over 32 years). Here we calculate the impact per emitted kg CO_2, as often only information about fuel consumption exists, but no detailed information about other emissions. Therefore, the results are only valid for similar specific fuel consumption and emission indices (see Section 5 for more details).

3. Aircraft trajectory characteristics and climate impact

The climate impact of an aircraft mission depends, in addition to the amount of emissions, on the emission location.

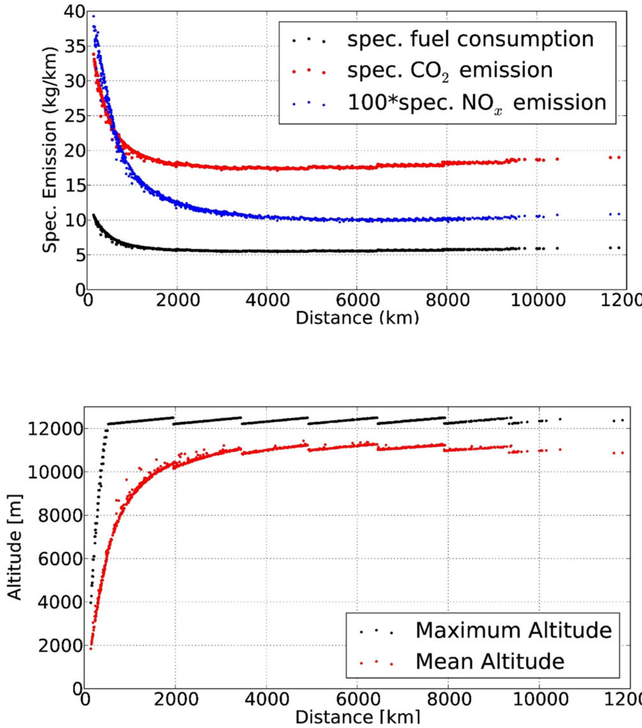


Figure 2. Fuel consumption and emissions of CO_2 and NO_x per flown distance in kg/km as a function of route distance (km) (a). For better visibility the NO_x emissions are multiplied with 100. (b) Maximum and mean altitude in m as a function of route distance (km).

From a comprehensive analysis of climate impact of individual missions in the global route network, we present in a first step how specific fuel consumption and emission altitude depend on mission length (Section 3.1). In a second step we present how climate impact of individual missions depends on geographic region where the aircraft is operated (Section 3.2).

3.1. Dependence of specific emissions and flight altitude on mission length

The specific fuel consumption (fuel consumption per flown kilometer) on short-haul missions (up to 1000 km) is larger than that on long-haul missions (black dots, Figure 2a). This is on the one hand due to the comparably high amount of fuel needed for take-off and on the other hand due to lower flight altitudes of short haul missions and the increased aerodynamic drag at these lower altitudes. Hence, specific fuel consumption decreases with increasing mission length, and only for missions longer than 5000 km the specific fuel consumption slightly increases due to the increasing weight of the necessary fuel, which increases aircraft take-off weight (TOW). The specific fuel consumption decreases by about 30% when mission length increases from 500 km to 2000 km.

The specific emissions of NO_x (measured as kilogram NO_x per flown kilometer, read dots, Figure 2a) show a similar decreasing trend for missions up to 4000 km, while reduction is more substantial dropping by 45% when mission length increases from 500 km to 2000 km, and even by about 60% when mission length increases from 500 km to 4000 km. For missions longer than 4000 km specific

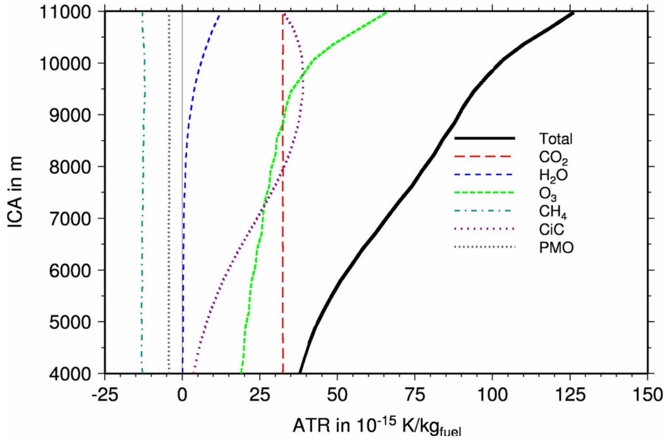


Figure 3. Specific climate impact in terms of ATR100 per kg fuel in dependence of ICA (Initial Cruise Altitude) for the flight route Detroit-Frankfurt (from Dahlmann, Koch et al., 2016).

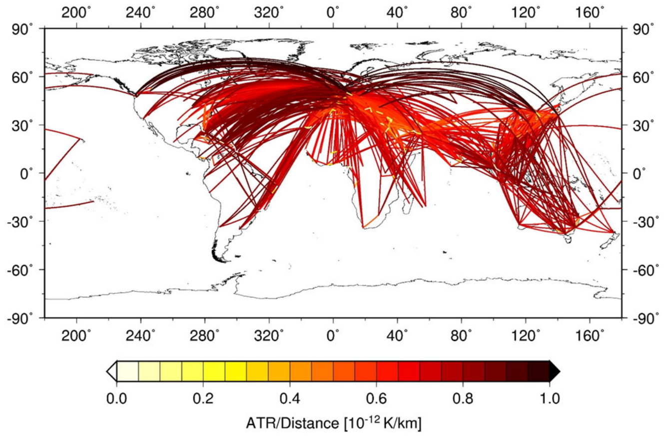


Figure 4. Specific climate impact in terms of ATR100 per km for all analyzed routes. From Dahlmann, Koch et al. (2016).

emissions of NO_x increases from 180g/km for 5000 km mission length by about 10% for 10,000 km mission length. Absolute values of the NO_x emission index ($EINO_x$, relation between NO_x emission and fuel consumption) decreases from about 38 g/kg for very short distances down to about 18 g/kg for long-haul missions.

Trajectories evaluated in our study have an average ICA of 36 kft (about 11,400 m), but the ICA as well as the mean and maximum flight altitude depends on the flown distances (Figure 2b). As continuous climb is assumed for the trajectories, increasing distances lead to increasing flight altitude, at least for short distances lower than 2000 km. For larger distances, the ICA needs to be reduced to avoid flight envelope violations, like altitude limitations. Therefore, mean and maximum flight altitude show steps at around 11,000 m.

3.2. Dependence of specific CO_2 and non-CO_2 climate effects on altitude and geographic region

Beyond specific emission also their associated climate forcing varies with emission altitude. Background concentrations, photochemical, and physical processes varying with altitude are at the origin of strong altitude dependence of non-CO_2 climate effects, comprising nitrogen oxides, water vapor or contrail-cirrus. As a result, climate impact given per kg fuel consumption shows a clear dependence on the altitude of emissions. Figure 3 shows the climate impact in terms of ATR_{100} per kg fuel of the different climate agents in dependence of the ICA for the flight route Detroit-Frankfurt (Main). Only for CO_2 the climate impact per kg fuel (red dashed line) does not depend on the emission altitude, as CO_2 emissions get homogeneously distributed in the atmosphere due to its long atmospheric lifetime. Climate impact per kg fuel of H_2O (blue dashed line) and that of O_3 (green dashed line) increase with altitude due to different photochemical regimes causing a longer lifetime at higher altitudes. The climate impact of CiC per kg fuel (magenta dotted line) has a maximum near the tropopause at about 9500 m, where it is cold and humid enough for contrail formation. The altitude dependencies of CH_4 (light blue dashed-dotted line) and PMO (black dotted line) are comparably low as the lifetime of a CH_4 perturbation is about 12 years. Overall, total climate impact per kg fuel (black thick line) increases with flight altitude by about 15% per 1000 m. The shown altitude dependency is for representative flight conditions in midlatitudes. In other latitudes climate impact increases as well with altitude, but may differ in terms of altitude and strength of the maximum impact, which can be associated with the latitudinal dependency of the tropopause altitude.

In Figure 4 the specific climate impact of each route, shown as climate impact in terms of ATR_{100} per flown distance, is presented. We normalize to flown distances in order to identify efficiencies of short-, middle-, and long-haul flights. Values of specific climate impact vary between 0.1 pK/km and 1 pK/km. It can be seen that the specific climate impact of routes at around 60 N is higher than that of tropical routes. In regions with dense air traffic like the North-Atlantic flight corridor (NAFC) smaller impacts can be found. Low specific climate impact appears on some of the short-haul routes.

In order to better explain these large variations in specific climate impact, we show impact per flown distance of individual species separately. As mentioned before specific climate impact of CO_2 does not depend on the flight altitude and region but only on specific fuel consumption (Figure 5a). As the fuel consumption and therewith the CO_2 emission is smallest for medium range distances (Figure 2a) the climate impact due to CO_2 is also smallest for medium range distances, while the impact of CO_2 is larger for short haul flights.

Figure 5b shows the lower specific climate impact of CiC in regions with dense air traffic like the NAFC due to contrail saturation effects (e.g., Dahlmann, 2012; Marquart et al., 2003). This is due to the fact that contrail formation reduces the ambient water vapor and hence lowers the possibility to form additional contrails in the same region. Furthermore, additional contrails above or below preexisting contrails have a lower radiative impact. Lower contrail climate impacts also occur for small flight distances as in low altitudes the temperature is too high for contrail formation.

NO_x emission leads to an enhanced ozone formation contributing to global warming, and to an enhanced

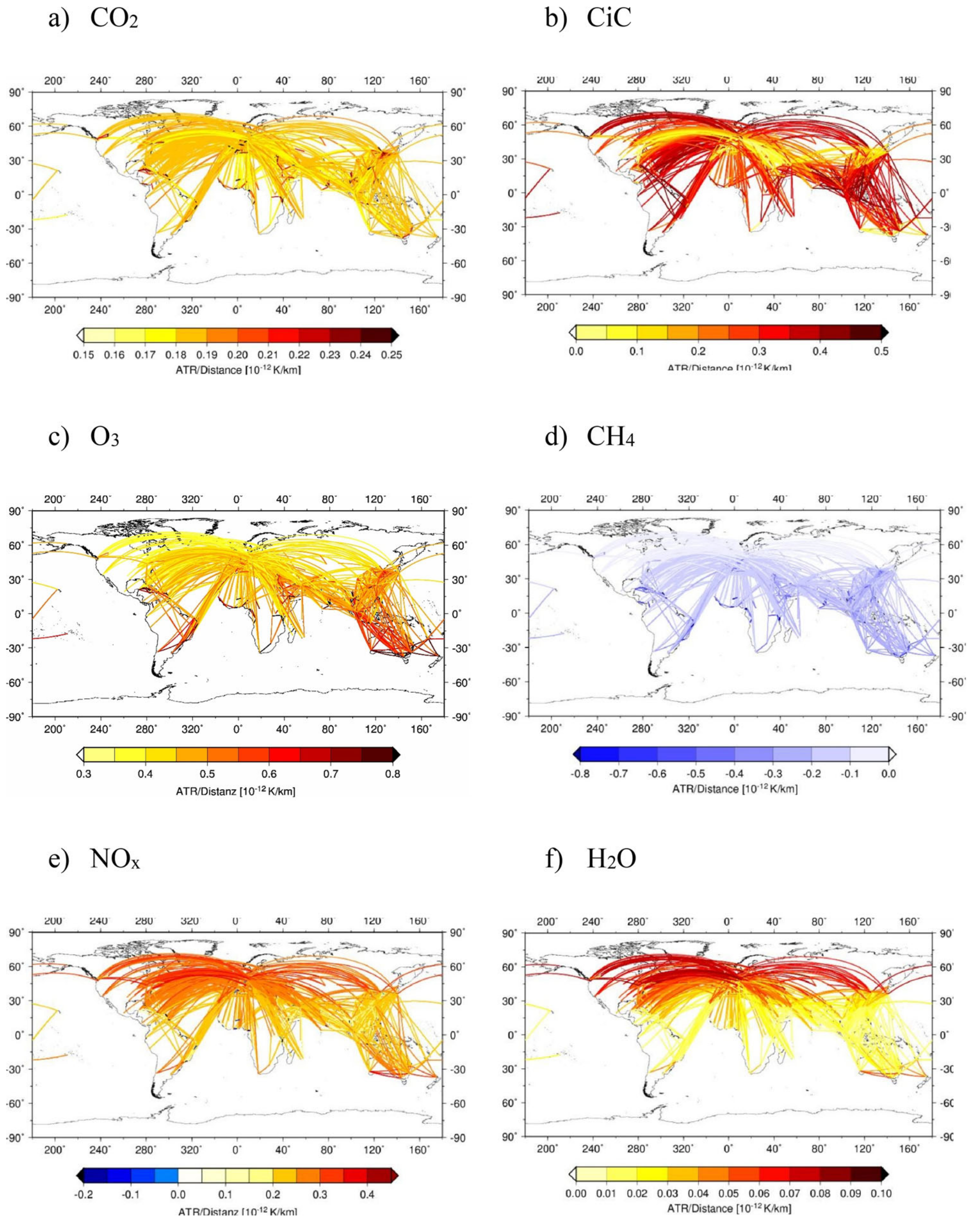


Figure 5. Specific climate impact in terms of ATR100 per km for individual climate species.

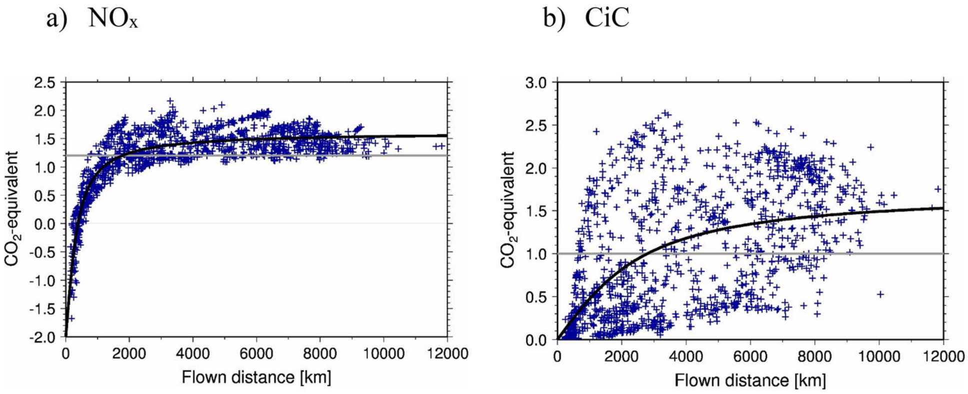
methane loss, causing a cooling effect. The specific ozone climate impact for individual trajectories decreases with increasing latitudes (Figure 5c), due to the decreasing photochemical activity of the atmosphere. The methane destruction is larger in the tropics and lower at higher latitudes (Figure 5d). Both effects partly compensate and their sum leads to smaller variations in the total specific climate impact of NO_x, which is shown in Figure 5e. The specific NO_x climate impact is higher at high latitudes and smaller in the tropics, as the variation in O_3 specific climate impact is larger than the variation of the CH_4 specific climate impact. The specific NO_x climate impact for short routes is small positive or even negative as the ozone impact increases faster with altitude than that of methane (Figure 3, Dahlmann, Koch et al., 2016).

Specific climate impact due to H_2O emissions shows higher values in Northern high-latitudes, while lowest values are found in the tropics. Impact of H_2O strongly increases with altitude when approaching the tropopause as the atmospheric lifetime in the troposphere is considerable shorter than in the stratosphere. As the altitude of the tropopause decreases with increasing latitude, the impact of H_2O also increases with latitude (Figure 5f). Hence larger specific climate impact at higher latitudes is a result from flights occurring more often in the stratosphere.

Overall, the large total climate impact at higher latitudes is a result of higher specific values of CiC, H_2O and only small compensation effects from CH_4. Lower values in the NAFC results from contrail saturation effects.

4. Mathematical formulas to calculate total climate impact of aviation

In this section we present three types of mathematical formulas for aviation's CO_2 and non-CO_2 climate impact. The


a) NO_x b) CiC

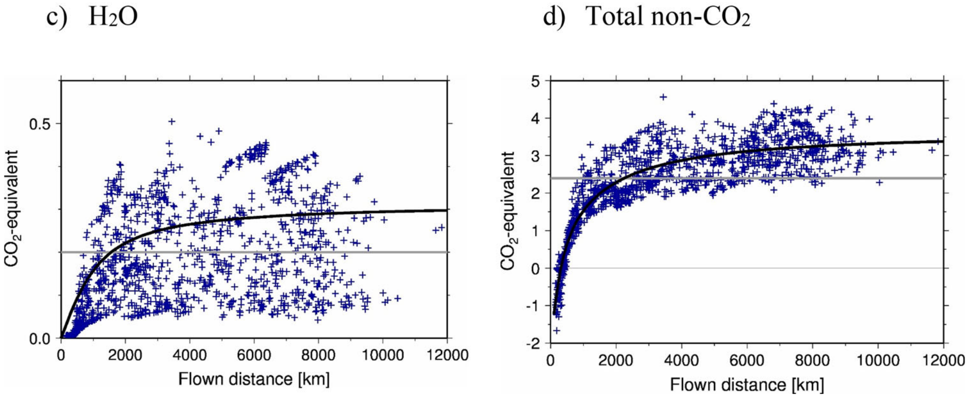

c) H_2O d) Total non-CO_2

Figure 6. Climate impact in CO_2 equivalent factors of NO_x (a), CiC (b), H_2O (c), and total non-CO_2 (d) emissions in dependency of flight distances (blue crosses) as well as the constant factor (gray line) and the parametric values analyzed with the function including flight distance dependency (black line).

climate impact is given as CO_2 equivalent factor (climate impact of an emission of 1 kg of a species relative to that of 1 kg CO_2 emission) using ATR100 as climate metric. The values represent annual and global mean values. The first is a very simple constant factor, the second includes a distance dependency and the third additionally includes a latitude dependency. Hence, instead of using global mean values we aim at stepwise capturing some main sensitivities of the non-CO_2 impacts, as shown in the previous section, by using easily available information like flight distance and geographical latitude.

4.1. Climate impact as a direct proportional function of CO_2 emissions

The easiest way to estimate the climate impact of non-CO_2 emissions, though not recommended (see below), is to use constant factors for CO_2 equivalent factors. They can be calculated by averaging the non-CO_2 impacts for all analyzed flight trajectories. The CO_2 equivalents per emitted kg CO_2 are:

$$^{eq}CO_2{}^{CO_2} = 1.0 \tag{1}$$

$$^{eq}CO_2{}^{NO_x} = 1.2 \tag{2}$$

$$^{eq}CO_2{}^{CiC} = 1.0 \tag{3}$$

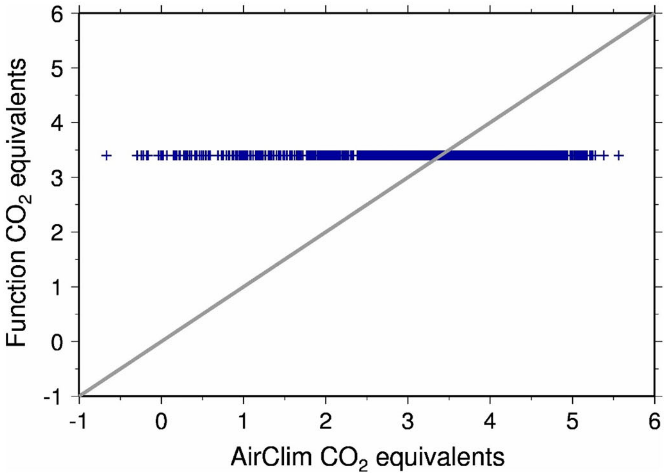
$$^{eq}CO_2{}^{H_2O} = 0.2 \tag{4}$$

$$^{eq}CO_2{}^{Tot} = 3.4 \tag{5}$$

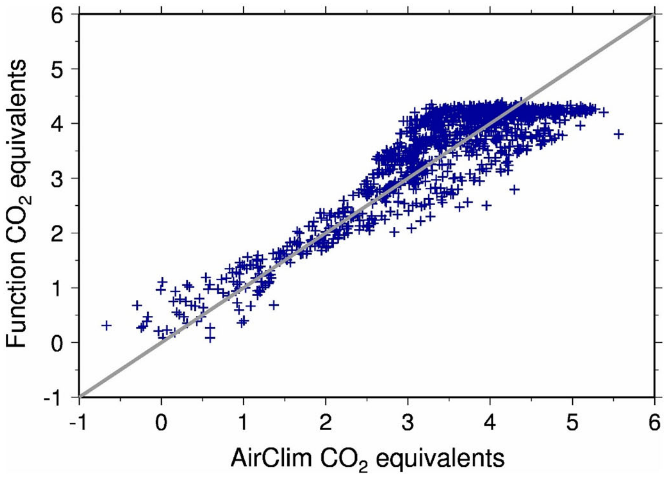
The obtained factors indicate that the impact of all emissions is 3.4 times the impact of CO_2 over the considered time horizon. The impact of NO_x and CiC are in the same order of magnitude as the climate impact of CO_2.

This calculation method is easy to use, as the total CO_2 emissions only have to be multiplied with those constant factors. Figure 6 presents the CO_2 equivalent factors for the climate agents in dependency of the flight distance together with the simplified CO_2 equivalent estimations (constant factor is shown as grey line). For NO_x emissions (Figure 6a) the constant factor overestimates the impact for distances shorter than 2000 km and even provides the opposite sign for distances less than 500 km. For distances larger than 2000 km the factor underestimates the impact. For CiC (Figure 6b) and H_2O (Figure 6c) the climate impacts show a very wide spread and the constant factors do not well represent the calculated impacts. For the total non-CO_2 effect (Figure 6d) the constant factors overestimate the impact for flown distances lower than 2000 km and underestimates the impact for longer than 2000 km flown distances. This can also be seen in Figure 7a, where the correlation between CO_2 equivalent factors calculated with AirClim and the constant CO_2 equivalent factor is presented. The gray line represents perfect agreement. It can be seen that only very few missions are correctly represented. Applying a constant factor underestimates the specific climate impact by up to about 40% or shows even a wrong sign compared to the AirClim results. Applying a constant factor shows that 80% of the estimates lie within a ±20% range. The mean square error is about 1.18.

a) Constant factor



b) Distance dependency



c) Distance and regional dependency

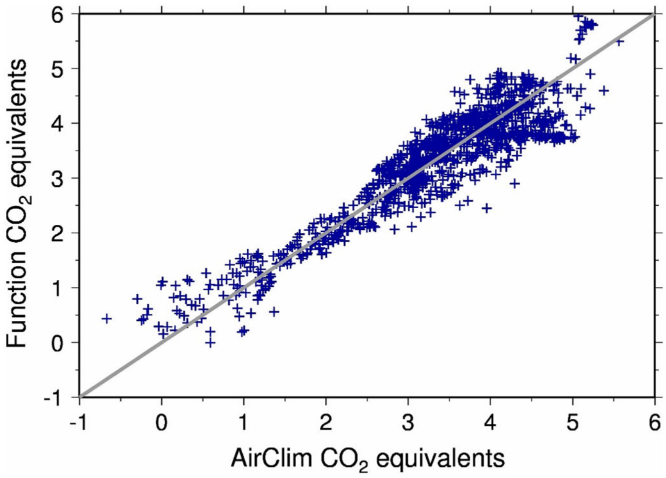


Figure 7. Correlation between total CO_2 equivalent factors calculated with AirClim and total CO_2 equivalent factors calculated with constant factor (a), distance dependent (b), and latitudinal dependent (c), respectively. Note that the constant factor for non-CO_2 effects exclude CO_2 and therefore is 2.4.

4.2. Climate impact as a function of flight distance

In Figure 6d, the CO_2 equivalent factors per emitted CO_2 for non-CO_2 effects are shown as a function of the flight distances. For very short distances, lower than 500 km, the CO_2 equivalent factor is small positive or even negative, as those flights are operated in low altitudes (Figure 2). At these altitudes it is too warm for contrail formation and the impact of H_2O is very low (see Figure 3). The impact of NO_x emissions is even negative as the low altitude of these short distances leads to a low positive contribution of the ozone production and larger negative contribution by methane destruction, especially since many short flights occur in tropical regions in the route network used here.

For flown distances between 500 and 4000 km the CO_2 equivalent factors of non-CO_2 species increase with the flown distance, as the mean flight altitude increases leading to the larger climate impact. For flown distances larger than 4000 km the impact of non-CO_2 effects shows only a small increase between 2.8 and 3.4 times the impact of CO_2. The mean flight altitude hardly changes for those long-haul flights and hence the CO_2 equivalent factors are almost unaffected. Note, that the impact of larger fuel consumption for longer flights as well as large specific fuel consumption for very short flights is contained in the CO_2 emission and cannot be seen in this kind of figure. Hence, very short distances as well as very long distances are less climate friendly than a comparison of the CO_2 equivalent factors would suggest.

As the dependency of CO_2-equivalents on the distance shows a large change for low distances but a smaller one for large distances, we fit arc tangent functions to the results (Figure 6, black lines). The resulting CO_2 equivalents for the different climate species are:

$$^{eq}CO_2{}^{CO_2} = 1.0 \tag{6}$$

$$^{eq}CO_2{}^{NO_x} = 2.3\arctan(3.1D) - 2.0 \tag{7}$$

$$^{eq}CO_2{}^{CiC} = 1.1\ \arctan(0.5D) \tag{8}$$

$$^{eq}CO_2{}^{H_2O} = 0.2\arctan(D) \tag{9}$$

where D is the flown distance in 1000 km. While the constant factors show large deviations from the calculated CO_2 equivalents, the distance dependent calculation factors show, especially for the NO_x emissions and the total non-CO_2 climate impact, quite good agreement (see Figure 6, black lines). This can also be seen in Figure 7b, where the correlation between the CO_2 equivalent factors calculated with AirClim and the distance dependent CO_2 equivalent factor is presented. Applying a flight distance dependent factor shows that 95% of the estimates lie within a ±20% range. The mean square error is reduced to about 0.24.

4.3. Climate impact as a function of flight distance and latitudinal dependency

A more comprehensive formulation relies on an algorithm which identifies climate impact of an individual flight using flight distance and latitude of flight. As shown in Section 3

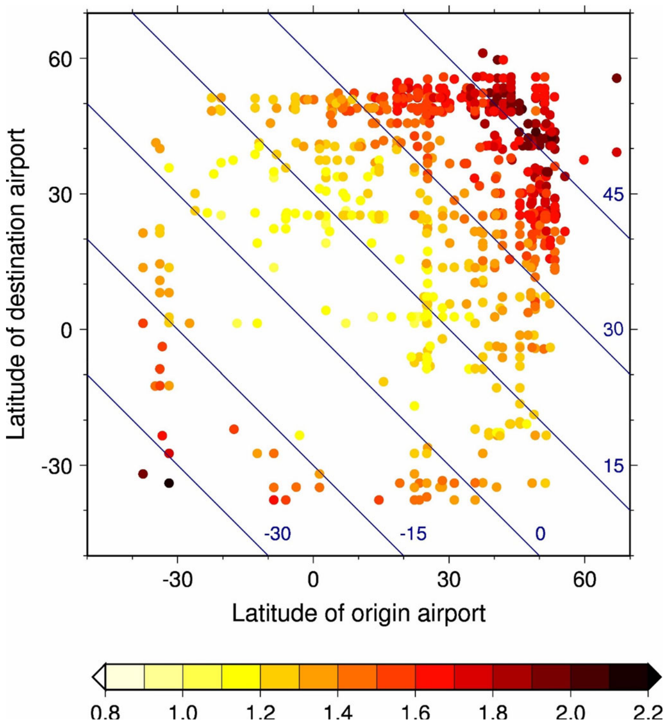


Figure 8. CO_2 equivalents from NO_x emissions depending on latitude of origin and destination airports for routes with flight distances of more than 2500 km. The blue lines indicate constant mean latitudes.

the climate impact of individual flights depends, beside the fuel consumption, also on the flown distance and on the flight region. In Figure 8 the climate impact of NO_x emissions is exemplarily shown as a function of latitude of origin and destination airports for routes with flight distances longer than 2500 km. The impact of NO_x emissions increases with increasing mean latitude (average of origin airport latitude and destination latitude, blue lines) and increasing negative mean latitudes, which means that the impact of NO_x emissions is lowest near the tropics (see Section 3).

As seen in Figure 8 the mean latitude is a good proxy for the latitude dependency. Therefore, we further use the mean latitude in this study. The CO_2 equivalent factors in dependency of the flown distances and mean latitude are show in Figure 9. Especially for flight distances longer than 1500 km, the CO_2 equivalent factor of NO_x depends on the mean latitude (Figure 9a). The impact increases from the tropics to mid and high latitudes. The CO_2 equivalent factor of CiC (Figure 9b) provides a clear latitude dependency especially between 1000 and 7000 km. For longer than 7000 km flight distances the climate impact depends on whether the flights really occur in the tropical region or a large share of the flight sectors are in midlatitudes. The H_2O shows a clear dependency from the mean latitude for distances larger than 1000 km (Figure 9c). The impact increases from tropics to higher latitudes, as the share of flight sectors in the stratosphere increases and the impact becomes larger due to the longer lifetime in the stratosphere (see Section 3). The total non-CO_2 climate impact (Figure 9d) shows a lower dependency of the latitude, as the impact of NO_x and H_2O provides counteracting latitudinal dependencies as CiC. While the impact of NO_x and H_2O increases from the tropics to higher latitudes, the impact of CiC decreases.

To account for this additional latitudinal dependency of the CO_2 equivalent factors the difference between the AirClim results and the distance dependent CO_2 equivalent factors from Section 4.2 are calculated and the common 4th order polynomial equation was defined for fitting on NO_x, CiC and H_2O (called user-defined function here):

$$^{eq}CO_2(L,D) = (aL^4 + bL^3 + cL^2 + dL + e) \times \ ^{eq}CO_2(D)$$

where L is the mean-latitude in deg North and D is the flown distance in 1000 km. We fitted this user-defined function to the AirClim results by using the non-linear least-squares Marquardt-Levenberg algorithm implemented in gnuplot, where the weighting was set to 1.0 for both mean-latitude and flight distance. The final set of coefficients (a to e) were found (see Table 1) and we obtained Equations (11)–(13):

$$^{eq}CO_2^{CO_2} = 1.0 \tag{10}$$

$$^{eq}CO_2^{NO_x} = \left(2.3\arctan(3.1D) - 2.0\right)\left(c_{NO_x}L^2 + d_{NO_x}L + e_{NOx}\right) \tag{11}$$

$$^{eq}CO_2^{CiC} = 1.1\arctan(0.5D)(a_{CiC}L^4 + b_{CiC}L^3 + c_{CiC}L^2 + d_{CiC}L + e_{CiC}) \tag{12}$$

$$^{eq}CO_2^{H_2O} = 0.2\arctan(D)(b_{H_2O}L^3 + c_{H_2O}L^2 + d_{H_2O}L + e_{H_2O}) \tag{13}$$

Including the latitudinal dependency in addition to the distance dependency in the calculation formulas further increases the accuracy of the results. This can be seen in Figure 7c, where the correlation between CO_2 equivalent factors calculated with AirClim and the distance and latitudinal dependent CO_2 equivalent factors are presented. Applying a distance and latitudinal factor shows that 92% of the estimates lie within a ±20% range. The mean square error is reduced to about 0.19.

5. Discussion and terms of use of calculation methods

This study introduces three calculation methods, how to calculate climate impact of a flight mission, using mission parameters. These simplified calculation methods provide approximations of total climate impact, while due to individual definitions each method has its own specific strengths and limitations. However, simplifications proposed, exhibit as well short comings, which are described in detail within this section. Here we discuss general principles of each climate impact calculation method, assess their limitations and provide a recommendation which method to adopt preferably for which purpose, in order to allow estimating total climate impacts of aircraft missions, comprising non-CO_2 effects.

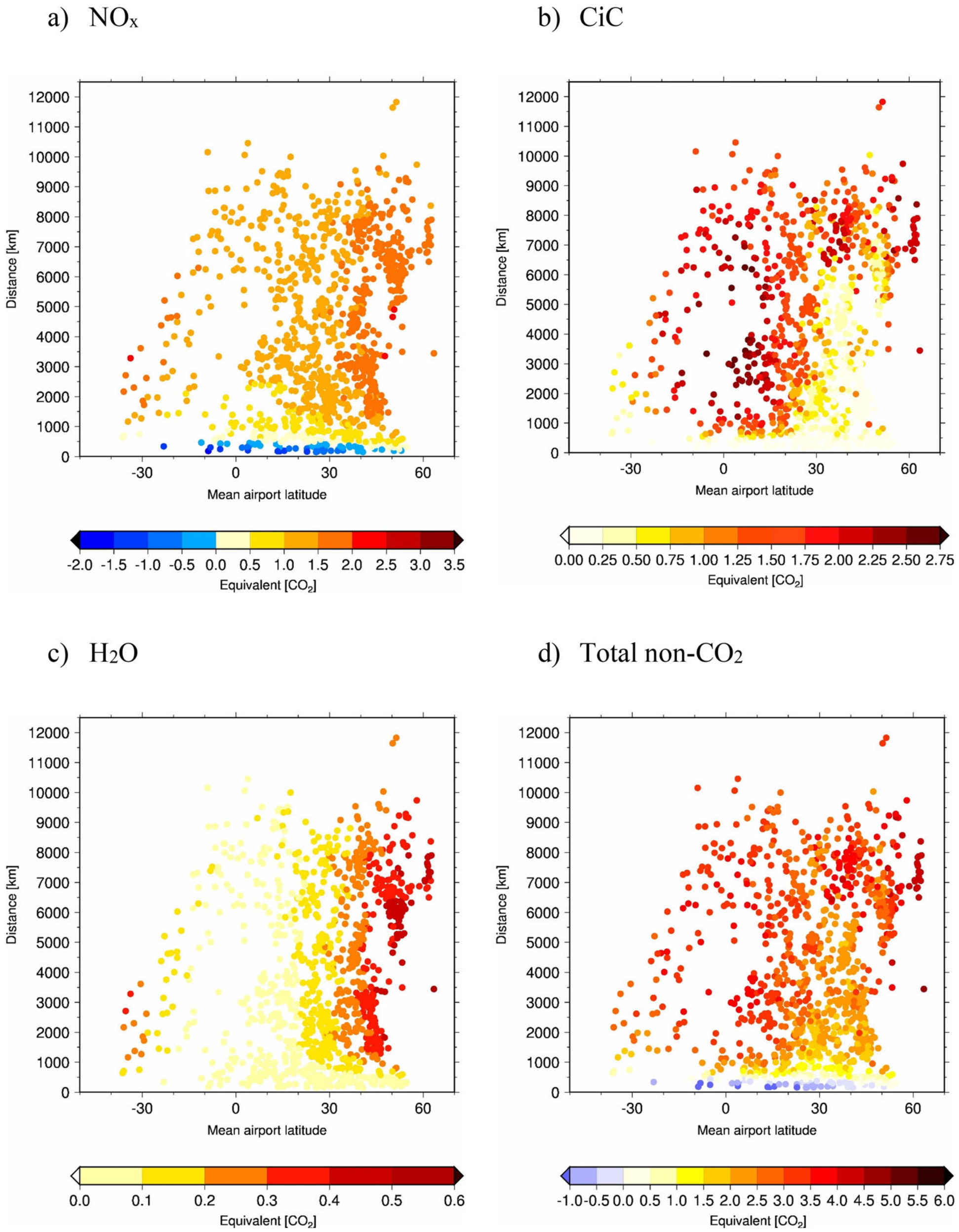


Figure 9. CO_2 equivalent factors for NO_x (a), CiC (b), H_2O (c), and total non-CO_2 (d) emissions depending on mean latitude and flight distance.

Table 1. Coefficients for the calculation formulas for latitudinal dependent CO_2 equivalent factors.

	NO_x	CiC	H_2O
a	–	$2.8 \cdot 10^{-7}$	–
b	–	$1.9 \cdot 10^{-6}$	$-7.6 \cdot 10^{-6}$
c	$1.6 \cdot 10^{-4}$	$-1.2 \cdot 10^{-3}$	$8.2 \cdot 10^{-4}$
d	$-1.6 \cdot 10^{-3}$	$-7.7 \cdot 10^{-4}$	$1.4 \cdot 10^{-3}$
e	0.86	1.7	0.15

5.1. Constant factor method using fuel consumption

The first, very simple option introduced to calculate the climate impact of aviation's non-CO_2 impacts from available information on CO_2 emissions (or fuel consumption) is to use constant factors, which represent a typical relationship between CO_2 emissions and associated non-CO_2 impacts occurring. These constant CO_2 equivalent factors are then simply multiplied with the CO_2 emissions, e.g., known from the fuel consumption (consumption of 1 kg jet fuel emits 3.15 kg CO_2). As this option is very simple to use, such constant factors are often asked for e.g., by politicians or companies. Such simple constant factors can only provide a first order approximation, and can only be used for an initial estimate of the magnitude of non-CO_2 effects from aviation, in particular on an average basis. However, for single aircraft missions, such a constant factor approach represents an inadequate simplification, as it does not include any influences of different flight altitudes, emitted non-CO_2 amounts, and flown regions. Therefore, such constant factors cannot be used for providing quantitative estimates as required when analyzing individual trajectories, e.g., in a technology assessment or as a possible metric for emission trading. Additionally, such constant factors would lead to an artifact as the only option to reduce overall climate impact is a reduction of fuel consumption (hence CO_2 emission), which neglects any mitigation potential resulting from non-CO_2 effects. This would introduce a falsification when providing strategic guidance and analysis of technology options toward development of sustainable aviation.

5.2. Distance dependent factors using fuel consumption and mission length

In order to avoid such falsification introduced by using a constant factor, we suggest as an initial improvement of the calculation method, to use the distance dependent factors for estimating non-CO_2 effects, which results in a better representation of total climate impact of aviation (Figure 7). As the average flight altitude calculated over the full mission increases with distance, due to higher fraction of cruise phase, these factors implicitly integrate altitude dependency of aviation emission impact. Therefore, the climate impact is represented more realistically by second method proposed. To apply this calculation, only the flight distance has to be known as additional information, which makes this improved representation of non-CO_2 effects still easy to use. Such simple factors could be used even for the general public to show more realistic estimates of the total climate impact of aviation, e.g., for a compensation market or for considering personal CO_2 footprint. Using such distance dependent factors leads to more realistic estimates; however, it generates insufficient guidance (or incentives) for airlines to reduce climate impact of non-CO_2 effects by considering alternative altitudes or flight regions during trajectory optimization. This calculation method with the factors is therefore unsuitable for emission trading or mitigation strategy development, as changes in flight regions or altitude and reduction in NO_x emissions would erroneously not reduce calculated climate impact, e.g., CO_2 equivalents.

5.3. Latitudinal dependent factors using fuel consumption, mission length, and mission latitude

Using additionally latitudinal dependent factors, beside mission length and fuel consumption, increases the accuracy of climate impact calculation further on. In this third formula individual effects are represented on a climatological basis, representing typical averaged synoptic conditions. However, this method using those factors still does not provide incentives to reduce the climate impact of aviation's non-CO_2 emissions for specific routes, as would be needed for concepts on climate-optimization of individual trajectories (e.g., Matthes et al., 2020). Nevertheless, it enables a more realistic calculation of non-CO_2 impacts, leading to more realistic estimates of total climate impact of aircraft operations, e.g., for compensation market.

5.4. Further developments of proposed calculation method

Based on the proposed calculation methods a set of further developments are discussed here. First, the applied method can be expanded by analyzing different aircraft engine/type configurations. The results, presented here, were obtained from analyzing the impact of one typical long-haul aircraft type of A330-200 aircraft. The A330-200 was used as it is the most sold aircraft in the medium- and long-range category, besides the Boeing 777. In 2015 still about 5% of flown ASK (available seat kilometers) was served by A330-200. The A330 is a similar aircraft type as B777, with similar flight profiles. Both aircrafts together serve still (in 2015) about 25% of global ASK. Different types of aircraft (e.g., turboprop instead of turbofan) could lead to different results if, e.g., the emission composition (emission indices of NO_x) or the flight profiles significantly differ (which would influence the implicitly assumed flight altitude).

The presented calculation method could also be expanded to consider alternative aircraft types or emission compositions. Although this would further increase the accuracy, it also increases the complexity of the calculations and the need for further information, which often are not available. The analyzed aircraft is a long-haul aircraft, which is used nevertheless for short- and middle-haul flights, resulting in inefficiencies in the overall analysis. Therefore, the results for short and middle haul flights might overestimate total climate impact, hence should be used with limitations.

The climate impact here is analyzed on a climatological base. It is assumed that the aircraft are operated whole year over in a lot of different weather situations. The obtained results are hence valid on an annual mean basis, while individual flights under specific weather conditions can have completely different climate impact, compared to the impact of the annual mean basis. The presented calculation method could in principle be used to derive mathematical formulas for different weather situations, but this would largely extend the complexity of the method and the need for detailed weather information. Therefore, the presented formulas are intended to capture the overall climate impact, neglecting specific weather situations, as such detailed information is often not available for individual aircraft missions.

5.5. Application of calculation methods

For all above introduced mathematical formulas, an important limitation applies in application of these calculation methods for identification of mitigation strategies, as it does not create any incentives to reduce the impact of non-CO_2 effects, but only incentives for reducing CO_2 emissions, as the calculated ${}^{eq}CO_2$-factors are multiplied with CO_2 emissions to gain the total ${}^{eq}CO_2$ of a flight. Hence, for technology assessments of mitigation options or emission trading it is recommended to use a model which at least includes explicitly an altitude dependency and the real emitted amounts of individual species. In order to optimize an individual mission on a specific day, a calculation model would need to be used which considers real emissions and associated impacts. With such comprehensive climate impact assessment, one could work on inclusion of such external effects and associated costs with the help of market-based measures (Scheelhaase, 2019). For using such comprehensive climate impact assessments, a large amount of additional data has to be provided (e.g., time of flight, emissions along flight trajectory). The ${}^{eq}CO_2$ factors, which are assessed in this study, could be used as a kind of fallback option if airlines are not able or willing to provide detailed flight information. The airlines have to pay for the ${}^{eq}CO_2$ calculated with such an approach or provide sufficient data about the real flights, which can reduce the costs if they fly more climate friendly.

In this study we use the ATR with a time horizon of 100 years as climate metric to compare CO_2 and non-CO_2 effects. Benefit of using ATR is that it accounts for the lifetime of the different climate agents as well as for the climate sensitivity parameter. However, compensation on a voluntary basis currently relies on RFI as calculation method, which neglects lifetime and climate sensitivity of different effects. With the calculation formulas proposed here, this shortcoming is overcome providing more realistic estimates. Applying our simple calculation method leads to a factor of 3.4 (total climate impact is 3.4 times the CO_2 impact) and is comparably higher than the RFI value of about 1.9 from Sausen et al. (2005) or 2.7 from IPCC (1999). But both approximations only include line-shaped contrails but no contrail cirrus, as we include.

Note, that on the one hand side specific CO_2 equivalent factors for short flight distances are lower than those for long flight distances. However, their specific fuel consumption is considerably larger for the short flight distances (see Section 3). Therefore, short flight distances are less climate friendly than a comparison of specific CO_2 equivalent factors would suggest. Nevertheless, the total climate impact of short haul flights is, at least for this aircraft type, smaller than for long-haul flights.

6. Conclusions

In this study we present three mathematical formulas for assessing non-CO_2 effects from aviation of individual aircraft missions of different complexity. In order to identify these mathematical formulas, we analyze the dependence of climate impacts on different routes, regions and altitudes to estimate the total climate impact derived from a comprehensive performance assessment of a global route network with the climate response model AirClim. The overall idea is to have as few additional parameters as possible, while considering as many as needed. The first mathematical formulas are composed of simple constant factors, which can be multiplied with the CO_2 emissions to get a first order estimate of aviation's non-CO_2 effects. The second formulas use the flown distance as additional information to increases the accuracy of the climate impact calculation as this implicitly includes the influence of flight altitude. In the third set of mathematical formulas, we introduce latitudinal information which increases the accuracy of the CO_2 equivalent calculation further on. As the additional information (region factor) only the mean latitude is needed, which can be directly calculated from geographical positions of origin and destination airports. This calculation method is able to represent geographic, in particular, latitudinal dependence of non-CO_2 impacts, resulting in a more accurate estimate of aviation's total climate impact than the two other calculation formulas.

Including distance and latitudinal dependent CO_2 equivalent factors increases the accuracy of the results significantly. However, it generates insufficient incentives for airlines to reduce climate impact of non-CO_2 effects by considering alternative altitudes or flight regions during trajectory optimization. Nevertheless, formulas introduced allow to provide a more realistic quantitative estimate of total climate impact of aircraft missions.

Using additionally latitudinal dependent factors, beside mission length and fuel consumption, increases the accuracy of climate impact calculation further on. Now, individual effects are represented on a climatological basis, representing typical averaged synoptical conditions. Nevertheless, it enables a more realistic calculation of non-CO_2 impacts, leading to more realistic estimates of total climate impact of aircraft operations, e.g., for compensation market.

This calculation method with the factors is therefore unsuitable for emission trading or mitigation strategy development, as changes in flight regions or altitude and reduction in NO_x emissions would erroneously not reduce calculated climate impact, e.g., CO_2 equivalents. The formulas introduced have limitations as they are derived from one single aircraft type of A330-200 aircraft. For different aircraft types the NO_x emission per fuel consumption as well as the probability to produce contrails or the flight profiles may change. Using different aircraft types and different emission compositions would further increase the accuracy, but also the complexity of the calculations and the need for further information, which often are not available. The climate impact here is analyzed on a climatological base. It is assumed that the aircraft flies the whole year in a lot of different weather situations. The obtained results are valid on an annual mean basis, while one single flight under specific weather conditions can have completely different climate impact, compared to the impact of the annual mean basis. Similar to the different aircraft types, the inclusion of such information would increase on the one hand side the accuracy, but on the other hand increase the amount of information and increase the complexity of the calculation.

Competing interest

No potential competing interest was reported by the authors.

Data availability

The data that support the findings of this study are available from the corresponding author, K.D., upon reasonable request.

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