Aviation Non-CO_2 estimator (ANCO)

A tool for quantifying the non-CO_2 climate impact of aviation

CE Delft

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Delft, CE Delft, June 2023

Publication code: 23.220402.096

Client: Ministry of Infrastructure and Watermanagment
Your reference: 31184570

Publications of CE Delft are available from www.cedelft.eu

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Content

Summary

Next to the emissions of greenhouse gases (GHGs), aviation impacts climate through indirect effects of emissions and changes to the atmosphere. The best estimate of the combined worldwide non-CO_2 climate impacts of aviation from 1940 to 2018 in terms of the current effective radiative forcing are twice as large as the CO_2 impacts, although there is still a considerable scientific uncertainty about their quantification. Despite their importance, there has been very limited policy action to address the non-CO_2 impact.

In March 2023, the minister of Infrastructure and Water Management informed the Dutch parliament about the national policy approach to address the non-CO_2 impact of flights departing from the Netherlands. In the letter the minister also refers to a tool that will be developed to include the non-CO_2 effects of aviation on route-level in social cost-benefit analyses. In this report, the Dutch Aviation Non-CO_2 estimator ANCO is described. In addition, estimates of the non-CO_2 climate impact of flights departing from the Netherlands are presented for the current situations and for future forecasts until 2050.

Non-CO_2 climate effects of aviation

In addition to CO_2, aviation emits NO_x, sulphate aerosols, soot particles and water vapour on a cruise height of about 10 kilometres. These emissions also occur at ground level from other sectors, but there they do not contribute as greenhouse gases. In the atmosphere they have chemical and physical effects which contribute to global warming. The two largest non-CO_2 climate impacts of aviation come from contrail-cirrus formation and NO_x emissions. The impact of non-CO_2 depends in addition to the emitted amounts on the emission location (mainly altitude and latitude) and the actual atmospheric conditions (weather, day-time).

In contrast to CO_2, the time horizon of the non-CO_2 effects is much shorter, as CO_2 remains in the atmosphere for a relatively long period of time, but the non-CO_2 emissions are short-lived as they break down quicker through chemical reactions. The different timescales of the CO_2 and non-CO_2 effects make it difficult to compare the effects to global warming. An attempt to make them comparable is to define CO_2 equivalents (CO_2e). They can be estimated for different metrics and time horizons.

Basic principle of the Aviation Non-CO_2 estimator ANCO

The functionality of ANCO to estimate the non-CO_2 impacts is taken from the DLR CO2eEstimator. In this tool a simplified calculation method with direct functional relationships was established to calculate non-CO_2 impacts based on mission parameters, involving distance and geographic flight region. The required inputs are the origin and destination airport and a generic aircraft type. Non-CO_2 impacts and CO_2e factors can be estimated for the metrics Average Temperature Response (ATR100) and Global Warming Potential (GWP100), both evaluated for a time horizon of 100 years. However, the tool does not take into account the large difference between the impacts of individual flights on the same route due to the atmospheric conditions during the flight.

The required input (flights between airport-pairs in generalised aircraft types) can be provided by Aeolus, the national Dutch aviation model or from another source. Aeolus provides mid-term and long-term forecast for the development of passengers, cargo and aircraft movements at Dutch airports. Since the flights are modelled to destination zones, the distribution to individual destination airports is estimated within ANCO based on historical data.

Based on the AEOLUS output, ANCO estimates the total non-CO_2 effect for all flights departing from Dutch airports for the years 2017, 2030, 2040 and 2050. The (aggregated) data can be used for further analyses for instance in Social Cost Benefit Analyses (SCBA). However, the guideline is not explicit how to monetise non-CO_2 effects in Dutch aviation SCBA. This is outside the scope of this study but should be discussed with the relevant stakeholders and experts.

Differences of the non-CO_2 effects on route level

For individual flights the CO_2e factor varies by approximately a factor of 10, with the depend variables flight distance, average latitude and aircraft size. The lowest value is found for flights to Lille in France with a factor of 1.2 and the highest (12.8) for flights to Svalbard Airport in Norway, which is the northernmost airport in the world with scheduled flights. For the popular destination London Heathrow the CO_2e factor is between 1.4 (seat class 51-100) and 2.4 (seat class 101-151). In general, smaller aircraft types have higher CO_2e factors than larger aircrafts; however, the smallest aircraft types generally fly at lower altitudes where they do not cause contrails at mid-latitudes.

Northern European destinations like Helsinki (average 4.5) and Stockholm (average 3.9) have higher CO_2e factors than Southern destinations like Barcelona (average 2.6) and Athens 3.0). For intercontinental flights a similar latitude dependence is found. The CO_2e factors decrease from Vancouver (average 8.6) via New York (average 3.6) to Bali (average 2.6). Comparing destinations at the same latitude shows that long-haul flights have higher factors than short-haul flights.

Non-CO_2 climate impact of Dutch aviation

In 2017, the average CO_2e factor for all departing flights from Schiphol was 4.0, which implies that the contribution of the non-CO_2 effects to the overall climate impact was 75% according to the ATR100 metric. The average CO_2e factor of all flights in the DLR CO_2eEstimator is 4.3, which is significantly higher than the 66% reported by Lee et al. (CO_2e = 3.0). Since the 66% are often seen as the best current estimate, it should be considered to scale the observed CO_2e factors to this number.

Mainly due to SAF blending (5% in 2030, 32% in 2040 and 63% in 2050) the share of the non-CO_2 effects increases further over time and reaches almost 90% in 2050. For the CO_2 emissions, SAF is counted as zero-emission here, since we only consider the tank-to-wing, whereas for SAF the assumed reduction of the non-CO_2 effects is only 25%. These are very rough assumptions and further research is needed to estimate the effect of SAF blending on the non-CO2 effects. However, it is obvious that addressing the non-CO_2 emissions of aviation is absolutely necessary to reduce the climate impact of aviation.

1 Introduction

In order to achieve the overarching goals of the Paris Agreement, the aviation sector has to reduce its climate impact. Next to the emissions of greenhouse gases (GHGs), aviation impacts climate through indirect effects of emissions and changes to the atmosphere.
In terms of the current effective radiative forcing, the combined worldwide non-CO_2 climate impacts of aviation are twice as large as the impacts of CO_2 from 1940 to 2018 (Lee et al., 2021). However, until now there has been very limited policy action to address the non-CO_2 impact.

1.1 Purpose of this study

In March 2023, the minister of Infrastructure and Water Management informed the Dutch parliament (Ministerie van infrastructuur en Waterstaat, 2023) about the national policy approach to address the non-CO_2 climate impact of flights departing from the Netherlands. In the letter the minister also refers to a tool that will be developed to include the non-CO_2 effects of aviation on route-level in social cost-benefit analyses.

The Dutch Ministry of Infrastructure and Water Management has commissioned CE Delft and German Aerospace Centre (DLR) to develop this tool to calculate the non-CO_2 climate impacts of Dutch aviation and to link the tool to the Dutch national aviation forecasting model Aeolus. This report provides the background information for the Dutch Aviation Non-CO_2 estimator ANCO. This new tool restructures the data, processes it through the DLR CO2eEstimator, which is fully incorporated in ANCO, and provides output tables with the main results. The output can be used in further analysis, for instance as part of societal cost-benefit analyses (SCBA). In the Netherlands practical guidelines for aviation SCBAs are defined in SEO et al., (2021).

1.2 Non-CO_2 climate effects

Anthropogenic greenhouse gas emissions are drivers of global warming, with CO_2 as the most important component. The gas stays in the atmosphere for hundreds of years and hence contributes to global warming for a very long time. For almost all sectors addressing CO_2 emissions tackles the main source of global warming. Other well-understood greenhouse gases include water vapour (H_2O), methane (CH_4) and nitrous oxide (N_2O). Sectors with significant non-CO_2 forcings include agriculture (net warming), maritime shipping (net-negative due to sulphur) and the aviation sector (net warming). For agriculture and maritime shipping the climate impact of non-CO_2 effects is well understood, predictable and included in climate policies as CO_2 equivalent emissions. In the Netherlands, the contribution of these well-understood non-CO_2 emissions is about 15% of the total GHG emissions (PBL, 2022). The contribution of aviation to the stable non-CO_2 emissions is marginal due to the high combustion temperatures.

In addition to CO_2, aviation emits NO_x, sulphate aerosols, soot particles and water vapour on a cruise height of about 10 kilometres. These emissions also occur at ground level from other sectors, but there they do not contribute as greenhouse gases. In the atmosphere they have chemical and physical effects which contribute to global warming. The two largest non-CO_2 climate impacts of aviation come from contrail-cirrus formation and NO_x emissions. A detailed description is given in (EASA et al., 2020). The radiative forcing effect are estimated to be between a factor of 2 to 4 times bigger than those of CO_2 (European Commission, 2020). Lee et al., (2021) have investigated that the cumulative contribution of the non-CO_2 effects of aviation between 1940 and 2018 is around 66%. Including the non-CO_2 emissions of aviation would make addressing its climate impact more complete.

In contrast to CO_2, the time horizon of the non-CO_2 effects is much shorter and varies between hours for contrails and decades for other species[1]. The different timescales of the CO_2 and non-CO_2 effects make it difficult to compare the effects to global warming. An attempt to make them comparable is to define CO_2 equivalents (CO_2e).

1.3 CO_2 equivalents

There are different metrics available to indicate the climate impact of non-CO_2 emissions. Metrics that are widely used, are the:

1. Global Temperature change Potential (GTP): is the resultant change in global mean surface temperature at a given time horizon. It is an 'end point' metric.
2. Average Temperature Response (ATR): the average near-surface temperature change over a specific time horizon. This is an application of a GTP.
3. The Global Warming Potential (GWP) for a specific time horizon. This metric is generally used within climate policies such as the EU ETS for non-CO_2 emissions from other sectors. GWP is an integrating metric.
4. GWP*: an alternative usage of GWP that equates an increase in the emission rate of short-lived climate forcers with a one-off 'pulse' emission of CO_2.

For a more detailed description, a summary of the current status of science and the remaining uncertainties, see EASA et al., (2020). These metrics can be evaluated on different timescales, resulting in a broad range of CO_2 equivalent factors (see Table 1).

Table 1 - CO_2 equivalents for the Global Warming Potential (GWP), the Global Temperature change Potential (GTP) estimated for 20-, 50-, and 100-year time horizons and a so-called 'flow-based' metric GWP*

ERF term	GWP_{20}	GWP_{50}	GWP_{100}	GTP_{20}	GTP_{50}	GTP_{100}	GWP^*_{100} (E^*_{CO2e})
Total CO_2e/CO_2	4.0	2.3	1.7	1.3	1.0	1.1	3.0

Source: (Lee et al., 2021).

This illustrates that defining a single multiplier has downsides since the magnitude of the multiplier depends on the metric chosen and the time horizon considered. These are subjective choices. However, policy makers, airlines, aircraft engineers and other stakeholders need guidelines to implement the right measures to limit the climate impact of aviation and hence take both CO_2 and non-CO_2 emissions into account. For a more detailed discussion on the metrics and timescales see Lee et al., (2021).

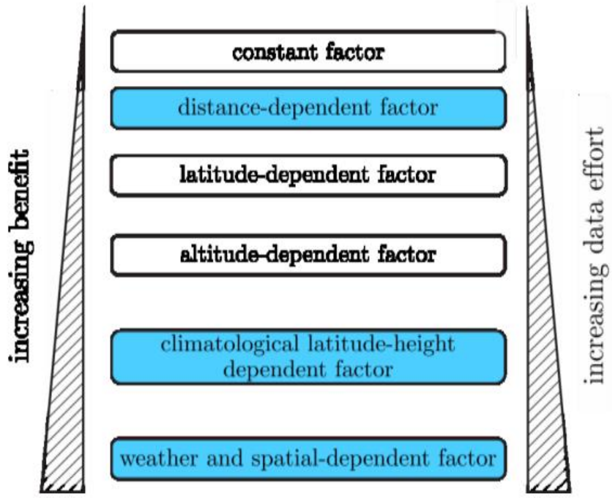
Besides these generic differences between the CO_2 equivalents as a consequence of the chosen metric and the time horizon, the CO_2 equivalents depend on the flight paths and the atmospheric conditions.

[1] The lifetime of water vapours varies between hours at ground level and months at the cruise altitude of aircrafts in the stratosphere. Nitrogen oxides (NO_x) emissions lead to increased ozone (O_3) concentration, which has a lifetime of weeks, and decreasing methane (CH_4) concentrations, which have a lifetime of 12 years.

1.4 General concept to calculate CO_2 equivalents in ANCO

The climate impact of CO_2 is well understood and independent of the emission source and location. This implies that CO_2 emission on the ground has the same warming effect as CO_2 emission of aircrafts on cruise height. In contrast to CO_2, the impact of non-CO_2 depends on the emission location (mainly altitude and latitude) as well as the actual atmospheric conditions (weather, day-time) in addition to the emitted amounts. Figure 1 shows different abstraction levels to estimate CO_2 equivalents. From top to bottom the methods become more accurate with the downside that data requirements and computational effort are increasing.

Figure 1 - Schematic overview of different possible abstraction levels to estimate aviation non-CO_2 effects



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Source: (Niklaß et al., 2019).

The goal of ANCO is to process the data of aviation forecasts of the Dutch aviation model Aeolus. Hence, it is not possible to take into account weather- and detailed spatial-dependent factors, since they are totally unknown for future flights. The DLR CO2eEstimator provides a simplified (distance- and latitude-dependent) calculation methodology for estimating the total ecological footprint of individual flights. A detailed description is presented in Annex A and (Thor et al., 2023) and .Niklaß et al., (2019). Based on the combination of aircraft type with origin and destination airports, ANCO estimates the non-CO_2 impacts of individual flights for ATR100 and GWP100 metrics. This provides a more precise estimation of the non-CO_2 effect of flights departing from Dutch airports than a generic factor.

However, this approach does not take into account the large difference between the impacts of individual flights on the same route due to the atmospheric conditions during the flight. It is known that winter flights have a far bigger overall warming effect due to a higher likeliness of forming contrails than those taken during the rest of the year (Stuber et al., 2006), but this variation is not considered. In addition, the method is not able to estimate the effects of changes in operational procedures, such as air traffic management, which could reduce the impact of non-CO_2 more than for CO_2 emission. Grewe, V. et al.,

(2014) found that rerouting flights could reduce the non-CO_2 climate impact by 25% at a cost increase of only 0.5%.

1.5 Outline of the report

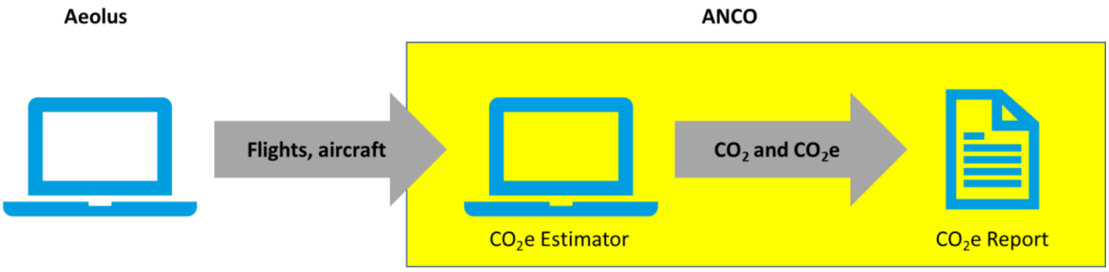
Chapter 2 discusses the basic principle of ANCO, its input and its output. In Chapter 3 the non-CO_2 emissions for a selection of example flights and for the future forecasts for aviation departing from the Netherlands are described. Conclusions are presented in Chapter 4.
The Annexes contain a more detailed description of the DLR CO2eEstimator and an overview of the geographical zones of the Aeolus model. In addition to this report, a Users Guide of ANCO has been composed, which will be distributed with the tool to users.

2 ANCO: basic principle, input and output

This chapter describes the basic principle of the Aviation Non-CO_2 estimator ANCO (Section 2.1). Afterwards, in Section 2.2 the default settings and main assumptions are discussed. In Section 2.3 the version number is introduced and in Section 2.4 the required input data is defined. Finally, the output of ANCO is presented in Section 2.5.

2.1 Basic principle

Figure 2 - Schematic overview of the interaction between the Dutch national aviation model Aeolus and the non-CO_2 estimator ANCO



Aeolus[2] is the national Dutch aviation model that provides middle- and long-term forecast for the development of passengers, cargo and aircraft movements at Dutch airports. Aeolus models the travel choices of passengers with discrete choice models. It requires input for the socio-economic development, aircraft technology, ticket prices, etc. and takes capacity restrictions into account. The model provides detailed output of the number of aircraft movements per aircraft type to destination zones for future years until 2050. For a more detailed description of Aeolus and the applicability of the model, see Significance & To70, (2019).

The distribution of aircraft movements (per generic aircraft type and geographic destination zone) for all Dutch airports is available via Aeolus standard output files. This detail level fits very well with the approach of the DLR CO2eEstimator, which estimates the CO_2 and non-CO_2 emissions for flights between specific airport pairs in generic aircraft types (different definition as in Aeolus). A more detailed description of the CO2eEstimator is given in Annex A.

The Aeolus output can be copied in the Excel tool ANCO and processed further. Within ANCO, the data is internally processed into input for the DLR CO2eEstimator, which is fully incorporated. The non-CO_2 effects are estimated per flight departing from Dutch airports. This information is fully accessible to the user. In addition, aggregated results are estimated in an output sheet per airport distinguishing European vs. intercontinental destinations and passenger vs. full freighter aircraft. An schematic overview of the link between Aeolus and ANCO is shown in Figure 2.

[2] For the Aeolus model updates are planned. It is possible that these updates require updates of ANCO as-well.

2.2 Default settings and main assumptions

The DLR CO2eEstimator estimates the non-CO_2 effects of aviation for currently operational aircraft types that burn 100% fossil fuel. In the future, aircraft are likely to become more efficient, routes might change due to adaptions of air space usage and renewable fuels will subsequently gain market share. In this section, the main assumptions and default settings of ANCO are summarised.

Climate metric

Two metrics are implemented in the tool and can be selected by the user:
1. Average Temperature Response for a time horizon of 100 years (ATR100).
2. Global Warming Potential for a time period of 100 years (GWP100).

GWP100 is set as default.

SAF blending

Currently, aircraft engines run on fossil kerosine (Jet-A). Recently, airlines have started to blend Sustainable Aviation Fuel (SAF) and the share of SAF will increase significantly in the upcoming years. Table 2 shows the SAF blending obligation of the ReFuelEU aviation proposal (European Parliament, 2023)[3]. These percentages are implemented as default values in the tool, but can be adjusted by the user.

Table 2 - SAF blending obligations as proposed in ReFuelEU aviation

Year	2017	2030	2040	2050
SAF %	0%	5%	32%	63%

Blending SAF does not only reduce the CO_2-emissions of flying, but also reduces the non-CO_2 impact. The use of SAF can decrease contrail formation, because SAF generally has a lower concentration of aromatics, including naphtalenes, which drive particulate matter (soot) emissions (CE Delft et al., 2022). The current version of the DLR CO_2eEstimator cannot take into account SAF. In ANCO, it is possible to apply a global correction factor in post-processing on the outcomes of the DLR CO_2eEstimator. This factor can be set by the user. As default value a reduction of 25% for the non-CO_2 effects is implemented, based on the assumption of 50% less contrail formation of SAF compared to fossil kerosene (CE Delft et al., 2022). This implies that the non-CO_2 effects for 2030 are corrected by 1.25%, those for 2040 by 8.00% and in 2050 by 15.75%[4].

[3] In the final agreement these numbers have been slightly adjusted (for instance 70% in 2050). The user of ANCO can set the values before estimating the CO_2 and non-CO_2 climate effects.

[4] It would be better to estimate the effects of blending SAF directly in the modelling software which was used to estimate the formulas in the DLR CO2eEstimator. However, in the current version this feature is not available.

Efficiency improvements

New generations of aircraft require less fuel than current models. Within Aeolus this is partly implemented by a shift to more efficient aircraft technology classes and partly by additional internal correction factors on the estimated CO_2 emissions. In this way the model can reproduce exogenous input for efficiency gains.

In ANCO, general correction factors are implemented that can be set by the user for periods of 10 years. The default values are annual efficiency improvements of 0.6% (low scenario) and 1.5% (high scenario) as defined in the Dutch WLO scenarios (Planbureau voor de Leefomgeving, 2020). Note, ANCO cannot recognise from the data which scenario has been estimated. Hence, the user has to select the proper efficiency improvements manually in the 'User Settings' sheet. In this sheet annual reduction rate for fuel and for NO_x emissions can be set.

Same growth[5] rates to all airports with destination zones

Aeolus estimates the number of flights (per type of aircraft) to destination zones (for instance Spain or SouthnAmerica) and not to individual destination airports. Hence, Aeolus does not provide growth rates per destination airport. ANCO assumes that the growth rates for all airports within a destination zone are identical[6] and applies the estimated growth rates to all airport pairs.

No distinction in the aircraft size distributions to destination zones for the regional airports

For Schiphol, the ministry of Infrastructure and Water Management has provided a data set which included all necessary information on individual flight level that is required by the DLR CO_2eEstimator (Schiphol Statistics, 2017)[7]. For the regional airports such a data set was not available. Instead two publicly available data sets from Eurostat[8] have been used and combined: a) the number of flights per aircraft type and Dutch airport and b) the number of flights from Dutch airports to destination airports (Eurostat, 2023a) (Eurostat, 2023c). We have assumed that the distribution of aircraft types is identical to all destination airports.

2.3 Version

This report describes ANCO_v1.0. It is based on the DLR CO_2eEstimator v108.v1084R2. The input data set is generated with the latest model version Aeolus GAMS-G5.3.

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5 The growth rates can also be negative in case of frequency reductions.

6 It is likely that in an updated Aeolus version some zones will be split into multiple smaller zones. This would provide more detailed forecasts for the distribution of flights and would improve the ANCO estimates.

7 Within the Schiphol Statistics dataset, there is one full freighter flight to Sydney that flies a distance of 16,659 kilometres. The maximum range for the DLR CO_2eEstimator is 14,500 kilometres, which does not allow this flight to give results. Because it only concerns one flight, it is not used in the calculations.

8 Within the Eurostat dataset, 364 flights in 2017 have been mentioned between Eindhoven and Roma Airport (IATA: RMA), which is an airport in Australia, using an aircraft with a seat class of 152-201 which would be far too small for similar flights in general. When comparing this to the flight schedule of Eindhoven Airport and looking at the amount of flights, this most likely are flights between Eindhoven and Fiumicino Airport in Roma, Italy. We have changed this in the dataset.

2.4 Aeolus data input

As part of a standard set of output files, Aeolus generates detailed output for aircraft movements. These files are separately available for passenger aircrafts and for full freighter aircrafts. The passenger and full freighter files are generated for each selected output year (base year 2017 and selected future years) and scenario (for instance WLO Low, WLO High, KEV or a policy option based on these reference scenarios). The file names are:
- Passenger flights: Aeolus_[scenario description]_pax_vluchten_dest[year].csv;
- Full Freighters: Aeolus_[scenario description]_vra_vluchten_dest[year].csv.

Each line in these comma-separated files describes the number of flights for a unique combination of a Dutch airport, destination zone, alliance and aircraft type. The structure of the files is as follows:
- Dutch airport of departure (Amsterdam, Eindhoven, Groningen, Maastricht, Lelystad, Rotterdam);
- Alliance (Sky Team, Star Alliance, One World, other full-service carriers, low-cost carriers);
- aircraft size class (G1, …, G9);
- aircraft technology class (TA, TB, …);
- flight destination (Aeolus destination zones: see Annex A);
- number of flights (departures per year);
- distance between airport and destination zone;
- average seat capacity per flight.

From this data the fields Dutch airport, aircraft size class, aircraft technology class, flight destination and number of flights are used. The number of aircraft movements per Alliance are aggregated within ANCO. The distances and the average seats per flight from the data are not used for the estimation of the non-CO_2 effects.

2.5 Output

The DLR CO_2eEstimator estimates per flight the following output variables:
- estimated CO_2 (kg);
- estimated NO_x (kg);
- estimated CO_2e of all non-CO_2 effects (kg);
- estimated CO_2 equivalents (kg);
- CO_2e factor.

Based on the output per flight, ANCO estimates the total non-CO_2 effect for all flights departing from Dutch airports for the years 2017, 2030, 2040 and 2050[9] and segmented in emissions per airport, European/intercontinental destinations and passenger/full freighter aircraft. Table 3 indicates the dimensions of the aggregated output.

Table 3 - Output format of ANCO

Type aircraft	Airport	Destination	2017	2030	2040	2050
Passenger	AMS	Europe				
Passenger	AMS	ICA				

9 The current Aeolus version estimates the number of aircraft movements for all years between 2017 and 2050. The required output for ANCO could be written to files for all individual years, if required. It is also foreseen to extend the forecasts until 2060 in the new version of the WLO scenarios. A (simple) update of ANCO is required to make it possible to process different future years.

Type aircraft	Airport	Destination	2017	2030	2040	2050
Passenger	EIN	Europe				
Passenger	EIN	ICA				
Passenger	RTM	Europe				
Passenger	RTM	ICA				
Passenger	MST	Europe				
Passenger	MST	ICA				
Passenger	GRQ	Europe				
Passenger	GRQ	ICA				
Passenger	LEY	Europe	–			
Passenger	LEY	ICA	–			
Full Freighter	AMS	Europe				
Full Freighter	AMS	ICA				
Full Freighter	MST	Europe				
Full Freighter	MST	ICA				

2.6 Conversion of Aeolus data for the CO_2eEstimator

The DLR CO_2eEstimator estimates the CO_2 and non-CO_2 effects for flights between distinct airport pairs, whereas the Aeolus model estimates the number of aircraft movements between individual airports in the catchment area (the Netherlands, Belgium, Luxemburg, Western part of Germany and Northern part of France) and destinations zones (for example Spain or Africa). In addition, the classification in aircraft types is not identical between the models and requires matching. In this section we describe the method which has been developed to match the Aeolus output with the required input fields of the CO_2eEstimator.

The method consists of the following steps:
1. Conversion of Aeolus G-classes to DLR seat classes for Schiphol.
2. Aircraft types at regional airports.
3. Destination airports for passenger flights.
4. Destination airports for full freighters.

We expect that the simplifications and assumptions that are necessary to link Aeolus to the CO_2eEstimator have a smaller effect on the outcomes than the intrinsic uncertainties of calculating non-CO_2 climate impacts of aviation and the necessary simplification in the CO_2eEstimator.

In the following subsections the conversion and the necessary assumptions are described.

2.6.1 Conversion of Aeolus G-classes to DLR seat classes for Schiphol

The aircraft size classes (G-classes) in Aeolus are based on aircraft types, whereas DLR uses categories based on the number of seats. Since the Schiphol statistics 2017 includes information on both the aircraft types and the number of seats, we used this data set as a lookup table to link the Aeolus G-classes to the DLR seat classes. Table 4 shows the comparison. The correlation between the G-classes and seat categories is clearly visible, but there is no distinct match between the classifications.

Table 4 - Number of aircraft movements at Schiphol in 2017, assigned to the Aeolus size categories (G1-G9) based on the aircraft type and the DLR seat categories

	1-100 seats	101-151 seats	152-201 seats	202-251 seats	252-301 seats	302-600 seats
G1	636	–	–	–	–	–
G2	58,666	–	–	–	–	–
G3	72,522	9,869	26	–	–	–
G4	–	54,988	201,645	10,412	158	–
G5	–	–	1,999	450	1	–
G6	–	–	660	3,964	15,158	2,673
G7	–	–	–	4,949	11,984	10,426
G8	–	–	–	391	4,508	26,760
G9	–	–	–	–	–	3,879

As basic principle the Aeolus G-classes are coupled to the DLR classes, which corresponds best in terms of the number of entries in Table 4. This results in reliable results for G1, G2, G4, G6, G7, G8 and G9. For G3 (most entries in 1-100 seats) and for G5 (most entries in 152-201 seats) we have chosen to deviate from this rule, since otherwise the seat categories 101-151 and 202-251 would not occur in ANCO. A possible consequence could be jumps in the final results. Therefore, for G3 and G5 the seat categories with the second most entries are chosen. The result is that all seat categories in the CO_2eEstimator are filled. Table 5 depicts the final conversion table.

Table 5 - Coupling of Aeolus G-classes to DLR seat categories

G-class Aeolus	Seat class DLR
1	1-100
2	1-100
3	101-151
4	152-201
5	202-251
6	252-301
7	252-301
8	302-600
9	302-600

Full freighter aircrafts can be assigned in the same way to a seat category for the purpose of estimating the non-CO_2 emissions. In Aeolus the cargo version of an aircraft is assigned to the same G-class as the corresponding passenger aircraft or if not available,
the classification is based on the maximum take-off weight (MTOW). This implies that the emissions of for instance an A350F full freighter are assumed to be identical with the passenger version A350.

The DLR CO_2eEstimator includes seat categories that also depend on the distance that is being flown. For an aircraft with a seat capacity of less than 100, this maximum distance range is for example 2,000 km. This means that if an aircraft flies further than its designated maximum range, that the estimated emissions cannot be calculated. Whenever this occurs, the seat capacity has to be changed to the lowest seat capacity that does give emissions output, to make sure that the output will be as complete as possible.

2.6.2 Aircraft types at regional airports

To establish the seat categories for the regional airports, we used Eurostat data to identify the aircraft types for the specific airports (Eurostat, 2023b). Based on this data, we have made a distribution of seat categories for each Dutch airport using the link between the aircraft types and Aeolus G-class in combination with Table 4. Aircrafts that have been classified as 'other' in the Eurostat data cannot be coupled to the seat categories of the tool. Therefore, they are not considered. In addition, seat categories with a share of less than 10% are rejected to limit the amount of individual entries. The remaining distributions are normalised to 100%.

Eindhoven

In 2017, the main aircraft used at Eindhoven Airport were Boeing 737, Airbus A320 and Airbus A321, all in seat class 152-201. For 2.8% the aircraft type is unknown. We assume that all flights are performed in seat category 152-201.

Rotterdam

In 2017, the main aircraft used at Rotterdam Airport were Boeing 737 (average seat class of 152-201), and Embraer 170 (average seat class of 1-100). 28% of the flights have been performed using aircraft categorised as 'Other Embraer models', of which the exact aircraft type is unknown. The final distribution is 90% of flights in seat class 152-201 and 10% in seat class of 1-100.

Groningen

In 2017, the main aircraft at Groningen Eelde Airport were Boeing 737 (average seat class of 152-201), and Embraer 145 (average seat class of 1-100). 32% of the flights have been performed using aircraft categorised as 'Other'. The final distribution is 50% of flights in seat class 1-100 and 50% in seat class 152-201.

Maastricht

Passenger

In 2017, the main aircraft at Maastricht Aachen Airport for passenger flights were Boeing 737 and Airbus A320, both in average seat class 151-201. 42% of the flights have been performed using aircraft categorised as 'Other', of which the exact aircraft type is unknown. The final distribution is 100% of flights in seat class 152-201.

Freight

In 2017, the main full freighter aircraft at Maastricht Aachen Airport were Boeing 747 (average seat class of 302-600), Airbus A310 (average seat class of 202-251 based on size), Airbus A330 (average seat class of 202-251), and Aerospatiale ATR 72 (average seat class of 1-100). The final distribution is 16% of flights in seat class 1-100, 50% of flights in seat class 202-251 and 34% of flights in seat class 302-600.

2.6.3 Destination airports for passenger flights

Aeolus distinguishes 29 destinations zones for passenger flights departing from the Netherlands (zone numbers 28 to 56, see Table 11 in Annex B and (Significance, 2020)). The destination zones increase in size with increasing flight distance and vary from regions like Hamburg to entire continents, like South America. Each of the Aeolus regions includes multiple airports, but Aeolus does not provide information on the distribution of flights between the airports, which is the required input for the DLR CO_2eEstimator.

For the base year (2017) of Aeolus, the realised number of flights between the Dutch airports and other airports are specified in the Schiphol Statistics 2017 for Schiphol (Schiphol Statistics, 2017), and in the Eurostat 2017 data for the regional airports (Eurostat, 2023a). The Schiphol data provides detailed information on all aircraft movements to and from Schiphol, including the destination airport and the used aircraft type. Based on this data, it was possible to assign each airport unambiguously to a destination zone per seat category.

For the regional airports the coupling of Aeolus zones to destination airports is based on Eurostat data, which does not provide the combined information of the aircraft types and the destination airports. Therefore, we analysed the distribution of flights to destination airports for all regional airports and applied the distributions from Section 2.6.2 to all destination airports.

In a next step, changes in the number of aircraft movements have been calculated for each Dutch airport by comparing the different estimated flights in 2017, 2030, 2040 and 2050 to each destination region per seat category.

Data in the Aeolus format that has identical input fields in the DLR CO_2eEstimator (for instance for different Alliances) is aggregated to reduce the size of the dataset. After this processing step, the data is read automatically by the incorporated DLR CO_2eEstimator.

2.6.4 Destination airports for full freighters

For full freighters Aeolus models the destinations on a more aggregated level, between the Dutch airports Schiphol and Maastricht and seven world regions (Western Europe, Eastern Europe, North America, Latin America, Africa, Middle East and Far East, including Oceania). With the same approach as for the passenger aircraft, the market share of flights per aircraft type (seat category) to individual airports within the Aeolus destinations zones for 2017 are identified based on the Schiphol Statistics for Schiphol and Eurostat for Maastricht (Eurostat, 2023c). The distributions are assumed to stay constant over time. However, there are more possibilities for changes which could lead to larger systematic errors.

For future years the same approach is followed as for passenger aircraft. Growth rates are calculated from the aggregated Aeolus output and applied to the detailed distributions determined for 2017 on destination airport level.

3 Non-CO_2 impact of aviation departing from Dutch airports

3.1 Introduction

In this section, we describe the non-CO_2 effects of all aircraft movements from Dutch airports. We report the numbers for four different years, 2017 (the base year of the Aeolus model), 2030, 2040 and 2050. For the future years two scenarios are distinguished: WLO Low and WLO High (Significance, 2023). In these scenarios the number of aircraft movements at Schiphol is limited to 500,000 per year until 2050. Due to fleet renewal and efficiency improvements the fuel consumption is reduced by 0.6% per year in WLO Low and by 1.5% in WLO High. In these scenarios Sustainable Aviation Fuels (SAF) are not considered. For the estimation of the CO_2 and non-CO_2 effects in this section, it is assumed that the proposed blending obligation of ReFuelEU Aviation will be applied on all departing flights from Dutch airports. The shares of SAF per year are summarised in Table 6.

Table 6 - Blending obligation of Sustainable Aviation Fuel (SAF) as proposed in ReFuel EU Aviation[10]

Year	2017	2030	2040	2050
SAF %	0%	5%	32%	63%

3.2 Variation of non-CO_2 effects at route level

In this section, we discuss the variation of the non-CO_2 effects of aviation for individual routes. We have selected example flights from Amsterdam Airport Schiphol in 2017 and estimate the effects in the GWP100 metric. In the ATR100 metric the dependencies are very similar. For both metrics the results for the WLO scenarios are discussed in Section 3.3.

The CO_2e factor is defined as the total climate impact (CO_2 plus non-CO_2) divided by the CO_2 impact. In 2017, the average CO_2e factor for all departing flights from Schiphol was 3.7, which implies that the contribution of the non-CO_2 effects to the overall climate impact was 73% according to the GWP100 metric. For individual flights the CO_2e factors vary by almost a factor of 10. The lowest value is found for flights (in seat class 51-100) to Lille in France with a factor of 1.2 and the highest (12.8) for flights (in seat class 152-201) to Svalbard Airport in Norway, which is the northernmost airport in the world with scheduled flights.

The smallest aircraft types (up to 100 seats) have the lowest CO_2e factors, since they generally fly at lower altitudes where they do not cause contrails. The category of aircrafts with 101-151 seats have the highest CO_2e factors for a given flight distance and the factor decreases with increasing aircraft size. For the popular destination London Heathrow the CO_2e factor is between 1.4 (seat classes below 100 seats) and 2.1 (seat class 101-151).

[10] In the final agreement these numbers have been slightly adjusted (for instance 70% in 2050). The user of ANCO can set the values before estimating the CO_2 and non-CO_2 climate effects.

The factors for the larger seat classes are 2.0 (152-201), 1.9 (202-251), 1,7 (252-301) and 1.7 (302-600).

Northern European destinations like Helsinki (average 4.5) and Stockholm (average 3.9) have higher CO_2e factors than Southern destinations like Barcelona (average 2.6) and Athens 3.0). For intercontinental flights a similar latitude dependence is found. The CO_2e factors decrease from Vancouver (average 8.6) via New York (average 3.6) to Bali (average 2.6). Comparing destinations at the same latitude show that long-haul flights have higher factors than short-haul flights. A detailed description of the variation in the non-CO_2 climate impacts of individual flights is given in (Thor et al., 2023).

The user can assess the results for individual routes in the Sheets 'Calculator' for 2017 and in the sheet 'Fleet Forecast' for future years.

3.3 Results for WLO scenarios

The CO_2 emissions and equivalent non-CO_2 emissions of flights departing from the Netherlands estimated with ANCO are displayed in Table 7. The CO_2 estimates deviate from the estimates within the AEOLUS model (see Table 8), since different algorithms are applied and AEOLUS in calibrated on the emissions of sold bunker fuels in the base year. A detailed comparison between the differences between the two CO_2 estimates is outside the scope of this study. For the further discussion and calculation of the CO_2 equivalence factors, the factors from ANCO are applied.

Table 7 - Estimated Tank-To-Wing CO_2 and non-CO_2 effects with ANCO in the ATR100 and GWP100 metric of all departing flights from the Netherlands, the corresponding CO_2e factors and shares of non-CO_2 on the overall emissions for the WLO scenarios

	Year	2017	2030		2040		2050	
Metric	WLO scenario		Low	High	Low	High	Low	High
	Estimated TTW CO_2 (million tonnes)	10.2	10.3	8.6	7.1	5.1	3.6	2.2
ATR100	Estimated CO_2e from non-CO_2 effects (million tonnes)	30.8	32.2	26.9	28.6	20.6	24.5	15.2
	CO_2e factor	4.0	4.1	4.1	5.0	5.0	7.8	8.0
	Share non-CO_2 effects	75%	76%	76%	80%	80%	87%	87%
GWP 100	Estimated CO_2e from non-CO_2 effects (million tonnes)	27.1	28.9	25.7	26.4	20.8	23.1	16.4
	CO_2e factor	3.7	3.8	4.0	4.7	5.1	7.4	9.2
	Share non-CO_2 effects	73%	74%	75%	79%	80%	86%	89%

Table 8 - Estimated Tank-To-Wing CO_2 emissions with Aeolus of all departing flights from the Netherlands for the WLO scenarios

Year	2017	2030		2040		2050	
WLO scenario		Low	High	Low	High	Low	High
Estimated TTW CO_2 (million tonnes) in AEOLUS (corrected for SAF blending)	12.0	11.3	11.6	8.0	7.5	4.2	3.4

In 2017, the CO_2e factor of all departing flights from the Netherlands in the ATR100 metric is 4.0. This implies that the CO_2 emissions were responsible for 25% of the global warming effect from aviation and the non-CO_2 for the remaining 75%. In the GWP metric the CO_2e factor is slightly lower (3.7). This implies that with this calculation method the warming effect of the non-CO_2 component of aviation is 73%. Hence, both methods have similar results, indicating that the actual share of the non-CO_2 emissions to aviation's global warming effect is about ¾. This is higher than the factor 2 to 3 known from the literature for the impact of non-CO_2. The main reason is that in other papers the historic cumulative CO_2 emissions are used as a reference (for instance since 1940 in (Klöwer et al., 2021)), but in the approach of this study climate functions are defined that estimate the climate impact of current and future flights. As the climate impact of CO_2 lasts much longer in the atmosfere than the impact of non-CO_2 effects this definition leads to higher CO2e-factors. It is important to note that in the simplified DLR CO_2eEstimator and thus in ANCO increasing emissions for the aviation sector are assumed. For a more detailed explanation see Textbox 1 and (Thor et al., 2023).

Textbox 1 - Comments from the authors from DLR on the magnitude of the CO_2e factors in the DLR CO_2eEstimator

The level of the CO_2e factors strongly depends on the level of the CO_2 reference. Since EU ETS is designed to estimate the climate impact of present and future flights, the DLR CO_2eEstimator does not consider any emissions of historic aviation. As the climate impact of CO_2 is more affected by the historical emission than short-lived non-CO_2 effects, the currently calculated relation between non-CO_2 effects and CO_2 is higher than the factor of 2-3 known from the literature for non-CO_2 effects of aviation, which is based on the total CO_2 level from preindustrial times (e.g. from 1940 to 2018 for Lee et al., (2021)).

In addition, the DLR CO_2eEstimator sees relatively high CO_2 equivalents from contrail cirrus. These are high for four reasons:

1. The AirClim response functions that include implicitly the effects of contrail lifetime, optical properties and radiation effects dates back to the work of Dahlmann et al., (2016) and relies on detailed simulation from Burkhardt and Kärcher (Kärcher & Yu, 2009) (Burkhardt & Kärcher, 2011). While the formation criterium of contrails is well described, the tropical contrail climate effects might be overestimated. The impact of tropical contrails is significantly larger than at mid-latitudes (Dahlmann et al., 2016) (Figure A2). A more thorough analysis and revision is currently in progress.
2. Contrail geometric dimension: the mass and thereby size of an aircraft largely controls the induced circulation behind the aircraft that is initiated by the wing tip vortices. These circulations have a large impact on the geometric size and thereby climate effects of a contrail (Unterstrasser & Görsch, 2014). This effect is not represented in AirClim, but applies to smaller aircraft. The effect is taken into account by a 50% reduction in the climate impact for small-scale aircraft based on the work of Unterstrasser & Görsch, (2014). A more thorough analysis and revision is currently in progress.
3. Previous studies presenting CO_2 equivalents for aviation sometimes only included line-shaped contrails and no contrail cirrus (e.g., IPCC, (1999); Sausen et al., (2005)) leading to lower CO_2e factors in those studies.
4. The simplified regression formulas derived for the implementation in the Excel tool are not a perfect fit to the climate effects computed by AirClim. For certain combinations of flight distance and mean latitude, they may overestimate the actual climate effects and therefore the CO_2e factors. This is particularly the case for flights that are unusually long for their seat category, such as flights in seat category 2 with a flight distance larger than 2,200 km. This phenomenon may contribute to increased CO_2e factors, not only through contrail cirrus, but also for H_2O and NO_x climate effects.

The average of the CO_2e values of all worldwide flights used for the computations in the CO_2eEstimator is 4.3 (in ATR100). The value of 4.0 for all departing flights in the Netherlands is slightly below the global average.

In 2030 the results are still very similar to 2017, but in 2040 larger effects are observed. The contribution of the non-CO_2 effects increases further over time and reaches almost 90% in 2050. The main reason for the increase of the CO_2e factor is SAF blending, which is assumed to be 5% in 2030, 32% in 2040 and 63% in 2050 according to the ReFuelEU blending obligation. For the CO_2 emissions, SAF is counted as zero-emission here, since we only consider the tank-to-wing emissions and not the emissions from SAF production (well-to-tank emissions), whereas for SAF the assumed reduction of the non-CO_2 effects is only 25%. However, further research and detailed modelling is required to derive better estimates for the effect of SAF blending on non-CO_2 effects.

In Table 9 and Table 10 the development of the CO_2e factor is displayed for segmentations in passenger/full freighter aircrafts, departure airports and European/intercontinental destinations for the metrics ATR100 and GWP100 respectively. In both metrics the main difference is found between European and international flights. For longer flight distances the non-CO_2 share is larger than for shorter flights. In 2017, for Schiphol the average CO_2e factor for European destinations is 3.2 in ATR100 and 2.9 in GWP100, for intercontinental destinations the factors are 4.3 (ATR100) and 4.0 (GWP100). Noticeable is that in the WLO High scenario from 2040 onwards the GWP metrics leads to higher CO_2e factors than the ATR metric. A crucial assumption here is that fuel efficiency improvements and NO_x emissions reductions are assumed to be in the same order in line with the assumptions in the WLO scenarios.

In 2017, around 75% of the CO_2 emissions of departing flights in the Netherlands was caused by intercontinental flights from Schiphol. Therefore, this segment also has a very strong effect on the estimated national average. For the regional airports, the results are in line with the European destinations from Schiphol.

Table 9 - CO_2 equivalence factors in ATR100 for flights departing from Dutch airports, distinguished in European and intercontinental destinations, passenger and full freighter aircrafts and different years

CO_2e factor			2017	2030		2040		2050	
Type aircraft	Airport	Destination		Low	High	Low	High	Low	High
Passenger	NL	Europe + ICA	4.0	4.1	4.1	5.1	5.1	7.8	8.0
Passenger	AMS	Europe	3.2	3.3	3.2	3.9	3.9	5.9	5.9
Passenger	AMS	ICA	4.3	4.4	4.4	5.4	5.4	8.3	8.6
Passenger	EIN	Europe	3.2	3.2	3.2	3.8	3.8	5.7	5.7
Passenger	EIN	ICA	3.4	3.5	3.5	4.2	4.2	6.4	6.5
Passenger	RTM	Europe	3.0	3.0	3.0	3.6	3.6	5.3	5.3
Passenger	RTM	ICA							
Passenger	MST	Europe	3.2	3.2	3.2	3.8	3.8	5.7	5.7
Passenger	MST	ICA							
Passenger	GRQ	Europe	3.3	3.3	3.4	4.0	4.1	5.9	6.2
Passenger	GRQ	ICA							
Passenger	LEY	Europe							
Passenger	LEY	ICA							
Full freighter	NL	Europe + ICA	4.0	4.1	3.9	4.9	4.7	7.5	7.3
Full freighter	AMS	Europe	3.2	3.2	3.2	3.9	3.7	5.8	5.5
Full freighter	AMS	ICA	4.0	4.1	3.9	4.9	4.8	7.6	7.4
Full freighter	MST	Europe	4.1	4.2	4.1	5.1	5.1	7.9	8.2
Full freighter	MST	ICA	3.8	3.9	3.8	4.7	4.7	7.2	7.3
Total	**NL**	**Europe + ICA**	**4.0**	**4.1**	**4.1**	**5.0**	**5.0**	**7.8**	**8.0**

Table 10 - CO_2 equivalence factors in GWP100 for flights departing from Dutch airports, distinguished in European and intercontinental destinations, passenger and full freighter aircrafts and different years

CO_2e factor			2017	2030		2040		2050	
Type aircraft	Airport	Destination		Low	High	Low	High	Low	High
Passenger	NL	Europe + ICA	3.7	3.9	4.0	4.8	5.2	7.6	8.6
Passenger	AMS	Europe	2.9	3.0	3.1	3.6	3.9	5.5	6.2
Passenger	AMS	ICA	4.0	4.1	4.3	5.2	5.5	8.1	9.2
Passenger	EIN	Europe	2.8	2.9	2.9	3.5	3.7	5.2	5.8
Passenger	EIN	ICA	3.1	3.2	3.3	3.9	4.2	6.0	6.8
Passenger	RTM	Europe	2.6	2.7	2.7	3.2	3.4	4.7	5.2
Passenger	RTM	ICA							
Passenger	MST	Europe	2.8	2.8	2.9	3.4	3.6	5.1	5.6
Passenger	MST	ICA							
Passenger	GRQ	Europe	3.0	3.0	3.2	3.7	4.0	5.6	6.4
Passenger	GRQ	ICA							
Passenger	LEY	Europe							
Passenger	LEY	ICA							
Full freighter	NL	Europe + ICA	3.4	3.6	3.5	4.4	4.5	6.7	7.2
Full freighter	AMS	Europe	2.6	2.7	2.7	3.2	3.3	4.7	4.9
Full freighter	AMS	ICA	3.4	3.6	3.6	4.4	4.5	6.8	7.4
Full freighter	MST	Europe	3.7	3.8	4.0	4.8	5.2	7.6	8.7
Full freighter	MST	ICA	3.3	3.4	3.5	4.2	4.5	6.5	7.4
Total	**NL**	**Europe + ICA**	**3.7**	**3.8**	**4.0**	**4.7**	**5.1**	**7.4**	**9.2**

3.4 Discussion

There are still large scientific uncertainties about the non-CO_2 climate impact of aviation. In addition, the way of comparing CO_2 and non-CO_2 climate impacts is not straight forward. Therefore, different metrics in combination with different time horizons for the evaluation are used. Furthermore, it is known that the actual atmospheric conditions have a very strong impact on the formation of contrails and hence the non-CO_2 climate impact. Teoh et al., (2020) concluded that diverting 1.7% of the flights could reduce the energy forcing from contrails by 59.3% with only a 0.014% fuel burn penalty. Three important remarks have to be taken into account here:

1. In our approach based on forecasts of the Aeolus model it is not possible to take into account actual atmospheric conditions. The CO_2eEstimator, which is incorporated into ANCO, estimates the effects for average atmospheric conditions and does not take into account the large variations between individual flights on the same route.
2. The simplifications in the regression formulas add additional uncertainties to the results. Therefore, the results can only be seen as a first step in the right direction to take the non-CO_2 effects of Dutch aviation better into account.
3. Results for future years assume no action to reduce the non-CO_2 climate effects. The results from ANCO have to be interpreted as a baseline for policies and options that mitigation options that have to be developed. In practice, it is very likely that the strong increase in non-CO_2 effects towards 2050 will not occur due to measures to reduce the impact.

For the application of the results a series of considerations should be taken into account, which are out of scope of this study:

1. The average CO_2e factor of the DLR CO_2eEstimator is 4.3, which is significantly higher than the 66% reported by Lee et al., (2021) ($CO_2e = 3.0$). This is due to the definition of not taking historic emissions into account (see Textbox 1). It is not obvious which choice is the right one and a methodological discussion of pros and cons of different calculation methods of non-CO_2 effects is out of scope of this study. We propose to address how to deal with these differences in the guidelines for Dutch aviation SCBA (SEO et al., (2021)). Two feasible possibilities are to use the results from ANCO directly or to scale the route dependent results with one global factor to bring the results in line with the 66% from Lee or any other source.
2. The guidelines for aviation SCBA contain recommendations for the valuation of CO_2-emissions. Applying the same costs to the non-CO_2 effects leads to large costs in SCBA, which seem to be much higher than the mitigation options for non-CO_2 reduction, see for instance Teoh et al., (2020). It has to be noted, that there are different opinions on the question whether a large reduction of the non-CO_2 effects justifies little extra CO_2 emissions, since the CO_2 stays much longer in the atmosphere and hence contributes much longer to global warming. However, it is necessary to discuss how to monetise non-CO_2 effects in Dutch aviation SCBA with all relevant stakeholders and experts.

4 Conclusions

According to Lee et al., (2021), the Effective Radiative Forcing (ERF) from the sum of non-CO_2 impacts accounts for 66% of the aviation net forcing in 2018. This corresponds to a CO_2 equivalence factor of 3. Due to this high number there is a growing interest in the non-CO_2 climate effect of aviation. However, significant scientific uncertainties are remaining in quantifying aviation's impact. The radiative forcing effects are estimated to be between a factor of 2 to 4 bigger than those of CO_2 .

The German Aerospace Centre DLR has developed the DLR CO_2eEstimator, which estimates the CO_2 and non-CO_2 emissions for flights between specific airport pairs in generic aircraft types. Within this project the DLR tool is incorporated in the Dutch Aviation Non-CO_2 estimator ANCO. ANCO is able to read in user defined sets of flights or forecasts of the Dutch national aviation model Aeolus and estimates the CO_2 and non-CO_2 effects of all flights departing from Dutch airports. In ANCO the climate metrics ATR100 and GWP100 can be selected. For future years blending of Sustainable Aviation Fuels and efficiency improvements are taken into account via simple corrections.

The results from ANCO can be used together with output from the Aeolus model in SCBA and Impact Assessments for policy makers and other stakeholders in the aviation industry. How to monetise the non-CO_2 effects in these kind of analyses is out of the scope of this study but a very relevant question which we recommend to address soon.

In 2017, the average CO_2e factor for all departing flights from Schiphol was 4.0, which implies that the contribution of the non-CO_2 effects to the overall climate impact was 75% according to the ATR100 metric. The average CO_2e factor of all flights from Dutch airports in the DLR CO_2eEstimator is 4.0, which is significantly higher than the global average of 66% reported by Lee et al., (2021). (CO_2e = 3.0). Since the 66% are often seen as the best current estimate, it should be considered to scale the observed CO_2e factors to this number.

For individual flights the CO_2e factors vary by approximately a factor of 10. The lowest value is found for flights to Lille in France with a factor of 1.2 and the highest (12.8) for flights to Svalbard Airport in Norway, which is the northernmost airport in the world with scheduled flights. These estimates do not include variations due to the actual atmospheric conditions, which are known to be even larger.

Mainly due to SAF blending (5% in 2030, 32% in 2040 and 63% in 2050) the share of the non-CO_2 effects increases further over time and reaches almost 90% in 2050. For the CO_2 emissions, SAF is counted as zero-emission here, since we only consider the tank-to-wing, whereas for SAF the assumed reduction of the non-CO_2 effects is only 25%. These are very rough assumptions and further research is needed to estimate the effect of SAF blending on the non-CO2 effects. It is obvious that addressing the non-CO_2 emissions of aviation would make addressing the climate impact of aviation more complete.

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A Simplified estimation of CO_2 equivalents of individual flights

This Annex has been written by Robin N. Thor, Katrin Dahlmann (both [11]), Malte Niklaß, Florian Linke (both [12]) and Volker Grewe ([7]and [13]).

A.1 Introduction

As aviation's contribution to anthropogenic climate change is increasing, industry aims at reducing the aircraft climate effect. However, the large contribution of non-CO_2 effects to the total climate effect of aviation and their large variability for each individual flight inhibit finding appropriate incentives. Here, we present a method for the simplified calculation of equivalent CO_2 emissions from CO_2 and non-CO_2 effects for a given flight. The simplified calculation method estimates non-CO_2 climate effects of air traffic as precisely as possible, without detailed information of the actual flight route, actual fuel burn and the current weather situation. For this purpose, we evaluate a data set containing a global set of detailed flight trajectories, flight emissions and climate responses, and derive a set regression formula for fuel consumption, NO_x emissions and climate responses. Compared to previous studies, this method is available for a larger number of aircraft types, including most commercial airliners of seven different seat categories, and delivers more specific results through a clustering approach. For seat capacities greater than 100 passengers, the climate effects calculated with the simplified regression formulas show a mean absolute relative error of 15.0 % and a root-mean-square error of 1.24 nK with respect to results from the climate response model AirClim, indicating a good representation of the latter's results.
This simplified estimate of CO_2 equivalents is designed for ecological footprint assessments. The tool is not designed for use in an emissions trading system, but could also be applied for plausibility checks or as a backup when airlines are unable to provide the required data.

A detailed description is in preparation for a peer-reviewed journal[14]:
Thor, R.; Niklaß, M.; Dahlmann, K., Linke, F.; Grewe, V.; Matthes, S.: (2023, in prep.) The CO2 and non-CO2 climate effects of individual flights:
simplified estimation of CO2 equivalent emission factorsfactorsSimplified Estimation of CO_2 Equivalents of Individual Flights, Geoscientific Model Development.

A.2 Global emission inventories and climate responses of the DLR project WeCare

As a basis for the derivation of regression formulas that allow for the determination of CO_2 equivalent climate effects, data from the former DLR internal project WeCare (Utilizing

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[14] www.gmd.copernicus.org/preprints/gmd-2023-126/gmd-2023-126.pdf

Weather information for Climate efficient and eco-efficient future aviation, (Grewe, V et al., 2017)) was used. The project addressed both an improvement of the understanding of aviation-influenced atmospheric processes and an assessment of different mitigation options. An essential output of the project was a new set of emission inventories for global aviation (Grewe, V et al., 2017). The network of flight trajectories was developed following a four-layer approach implemented in the AIRCAST method (Gosh et al., 2016), starting from an origin-destination passenger demand network that was built-up from exogenous socio-economic scenarios, via the passenger routes network (sequence of flight segments, a passenger actually travelled from origin to destination) to an aircraft movements network, which assigns aircraft categories to the resulting flight routes and provides flight frequency information. The final step is a simulation of trajectories based on the aircraft movements obtained from the aircraft movements network layer, using the Global Air Traffic Emissions Distribution Laboratory (GRIDLAB) developed by DLR (Linke, 2016). Each mission, defined by departure and arrival cities, aircraft type, and load factor, was simulated under typical operational conditions, resulting in a network of flight trajectories. For this purpose, DLR's Trajectory Calculation Module (Lührs et al., 2014) is used, that applies simplified equations of motion known as the Total Energy Model. Based on the aircraft's engine state (e.g. thrust, fuel flow), the engine emission distribution of NO_x, CO and HC species along the trajectory was determined applying the Boeing Fuel Flow Method 2 (DuBois & Paynter, 2006). The amount of CO_2 and H_2O was calculated assuming a linear relationship to the fuel burn. The emission distributions of all flights were mapped into a geographical grid resulting in 3D inventories.

These were the essential input for the climate effect assessment tool AirClim (Dahlmann et al., 2016), which determines concentration changes of different radiative forcing agents (CO_2, H_2O, O_3) as well as aviation-induced cloudiness. Based on that, various climate metrics for the given emission scenario were calculated. In WeCare, using the approach mentioned above, emission inventories and the corresponding climate effect were calculated for the years 2015 to 2050 in 5-year steps.

The forecast was based on the reference year 2012. The resulting flight plan of the base year consisted of 47,057 airport pairs and approximately 31 million flights. As it was found that aircraft with more than 100 seats contribute to about 95% of the globally available seat kilometres (ASK), only aircraft larger than 100 seats were covered by the study to reduce complexity and ensure model availability. Therefore, seven different aircraft size categories (based on the number of seats) were considered in the inventories (20-50 seats; 51-100 seats; 101-151 seats; 152-201 seats; 202-251 seats; 252-301 seats; 302-600 seats) and each size category was modelled using one representative aircraft type (plus one backup aircraft type. Respective engine emission characteristics were taken from the Aircraft Engine Emissions Databank of the International Civil Aviation Organization (ICAO).

A.3 Derivation of fuel functions and NO_x functions

Using a selection of all flights of a given seat category from the database of all flights, we derived regression formulas which approximate the burnt fuel (BF) and the emission index of NO_x ($EINO_x$) for a given flight distance *d*. Fuel functions obey the pattern:

$$BF = a_0 + a_1 \cdot d + a_2 \cdot d^2$$

The derived $EINO_x$ regression formulas vary for distances smaller and larger than 2,000 km and are described by:

$$\mathrm{EINOx} = \begin{cases} a_0 + a_1 \cdot \ln(d) & if\ d < 2000\ km \\ a_0 + a_1 \cdot d + a_2 \cdot d^2 + a_3 \cdot a^3 & if\ d \geq 2000\ km \end{cases}$$

A.4 Clustering of flights by climate effects using K-means and derivation of climate effect functions

Due to the large variety of importance of the different climate effect components among different flights, it is challenging to find a single set of equations that would reasonably predict the climate effect under most circumstances. Therefore, in the first step, we apply a K-Means clustering algorithm to separate the flights into several clusters. This clustering is based solely on the share of the six aforementioned components of the climate effect in the total climate effect:

$$\frac{ATR100_{CO2}}{ATR100_{tot}}, \frac{ATR100_{H2O}}{ATR100_{tot}}, \frac{ATR100_{CiC}}{ATR100_{tot}}, \frac{ATR100_{O3}}{ATR100_{tot}}, \frac{ATR100_{PMO}}{ATR100_{tot}}, \frac{ATR100_{CH4}}{ATR100_{tot}}$$

This ensures that flights in a given cluster have similar climate effect characteristics. The clustering is not directly dependent on proxy quantities to the climate effect, such as the emissions and the emission location. We use an implementation by scikit learn (Pedregosa et al., 2011) and scale the input quantities to the standard normal distribution before clustering. For seat categories greater than 100 seats we find a partition into three clusters to be most useful, as larger numbers of clusters lead to some clusters, whose distinctions do not have a clear physical interpretation.

For each of the simplified clusters, a regression formula is derived, which approximates the climate effect for a given flight. The usage of clusters enables us to find regression formulas that follow the data more closely. Following (Dahlmann et al., 2021), the regression formulas obey the pattern:

$$ATR100_{tot} = c_{CO2} \cdot f + c_{NOx}(d, \overline{\varphi}) \cdot e + c_{H2O}(d, \overline{\varphi}) \cdot f + c_{CiC}(d, \overline{\varphi}) \cdot d,$$

where f is the fuel use, e are the NO_x emissions, d is the flown distance, $\overline{\varphi}$ is the mean latitude, c_{CO2}, c_{NOx}, c_{H2O}, and c_{CiC} are cluster-dependent regression formulas.

A.5 Rough estimation of the climate impact of next generation aircraft

In order to project the future climate impact of next generation aircraft, we use assumptions about the expected annual savings of fuel (%) and NO_x (%) for future technology classes from the Aeolus model or from the ICAO global environmental trends (A41-WP/93 EX/45 Rev.1). Future block fuel and future NO_x emissions will be reduced accordingly, while keeping the same climate impact regression formulas in use (no saturation effects; no variations of growth rates, etc.):

$$Future\ BF = BF(d) \cdot (1 - \text{annual fuel savings})^{\text{target year} - \text{reference year}},$$
$$Future\ NOx = EINOx(d) \cdot BF(d) \cdot (1 - \text{annual NOx savings})^{\text{target year} - \text{reference year}}$$

For the sake of simplicity, it is assumed that the CO_2e of contrail cirrus is constant over time.

A.6 Disclaimer

This model has been produced by DLR to provide the German Environment Agency (Umweltbundesamt) with a simplified (latitude-dependent) calculation methodology for estimating the total ecological footprint (CO_2 and non-CO_2 effects) of a flight.
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“Latitude-dependent CO_2e estimates should not be used for a monitoring, reporting and verification (MRV) scheme of non-CO_2 effects as they
- further increase the focus on CO_2 reduction;
- might create false incentives (incentive to fly higher rather than lower);
- “penalize” climate-cost-efficient routings (due to the increased fuel burn of an alternative routing)."

The development of the simplified CO_2eEstimator model belongs to the field of scientific research and development, this is why the DLR cannot give any warranty that the expectations associated with the assigned tasks will be fulfilled in the course of the scientific work as regards the work results to be obtained. This means that the DLR does not warrant that this result can be exploited or used in economic respect.

DLR accepts no liability for the content of this tool, in particular for the external data that are encoded by users into the tool and over which it has no control, neither does it assume any liability for the accuracy, completeness or usefulness of this information or consequences of this use.

B Overview zones in Aeolus

Table 11 displays the zones of the Aeolus model. The table is extracted from the current versions of the Aeolus Documentation (Aeolus Documentatie 1.1) which can be requested by Rijkswaterstaat.

Table 11 - Zones in the Aeolus model

Nr	Passagierszone	Achter-land	Beschrijving (COROP / regio / land)
1	Amsterdam	√	Groot-Amsterdam, uitgezonderd Schiphol
2	Schiphol regio	√	
3	Hilversum regio	√	Gooi en Vechtstreek
4	Haarlem regio	√	Agglomeratie Haarlem
5	Noord-Holland overig	√	Kop van Noord-Holland, Alkmaar en omgeving, IJmond, Zaanstreek
6	Den Haag regio	√	Agglomeratie 's-Gravenhage
7	Rotterdam regio	√	Groot Rijnmond
8	Gouda regio	√	Oost-Zuid-Holland
9	Zuid-Holland overig	√	Delft en Westland, Agglomeratie. Leiden en Bollenstreek, Zuidoost-Zuid-Holland
10	Utrecht provincie	√	Utrecht
11	Zeeland provincie	√	Zeeuws-Vlaanderen, Overig Zeeland
12	Eindhoven regio	√	Zuidoost-Noord-Brabant
13	Noord-Brabant overig	√	West-Noord-Brabant, Midden-Noord-Brabant, Noordoost-Noord-Brabant
14	Arnhem regio	√	Arnhem / Nijmegen
15	Gelderland overig	√	Zuidwest-Gelderland, Achterhoek, Veluwe
16	Maastricht overig	√	Zuid-Limburg
17	Limburg overig	√	Noord-Limburg, Midden-Limburg
18	Overijssel provincie	√	Noord-Overijssel, Zuidwest-Overijssel, Twente
19	Drenthe provincie	√	Noord-Drenthe, Zuidoost-Drenthe, Zuidwest-Drenthe
20	Groningen provincie	√	Oost-Groningen, Delfzijl en omgeving, Overig Groningen

Nr	Passagierszone	Achter-land	Beschrijving (COROP / regio / land)
21	Friesland provincie	√	Noord-Friesland, Zuidwest-Friesland, Zuidoost-Friesland
22	Flevoland provincie	√	Flevoland
23	België	√	
24	Luxemburg	√	
25	Düsseldorf/Keulen	√	NR Westfalen
26	Frankfurt e.o.	√	Hessen, Rheinland Pfalz, Saarland
27	Parijs e.o.	√	Ile-de-France, Picardie, Haute Normandie, Nord pas de Calais, Champagne Ardennes, Lorraine
28	Hannover/Bremen		Bremen, Niedersachsen
29	Hamburg		Hamburg, Sleswig Holstein
30	Zuid Duitsland		Baden Wurttemberg, Bayern
31	Oost-Duitsland		Berlin, Mecklenburg Vorpommern, Sachsen Anhalt, Brandenburg, Thuringen, Sachsen
32	Londen		Groot Londen
33	Groot-Brittannië overig		Rest UK, Ierland
34	Frankrijk Zuid		Poitou Char'te, Aquitaine, Limousin, Auvergne, Languedoc R'on, Rhone Alpes, Provence Cd'Azur, Corse
35	Frankrijk overig		Rest Frankrijk
36	Denemarken		Denemarken
37	Scandinavië		Noorwegen, Zweden, Finland, IJsland
38	Zwitserland/Oostenrijk		Zwitserland/Oostenrijk
39	Spanje		Inclusief Canarische eilanden
40	Portugal		Inclusief Azoren
41	Italië/Malta		Italië, Malta
42	Griekenland		Griekenland, Cyprus
43	Zuidoost-Europa		Slovenië, Kroatië, Servië, Montenegro, Kosovo, Albanië, Macedonië, Bosnië, Roemenië, Bulgarije, Turkije
44	Oost-Europa		Polen, Tsjechië, Slowakije, Hongarije, Baltische landen, Europese Rusland, Wit-Rusland, Oekraïne, Moldavië, Kaukasus (Armenië, Azerbeidzjan, Georgië)
45	VS Noordoost		District of Columbia (DC), Delaware (DE), Maryland (MD), Connecticut (CT), Massachusetts (MA), New Hampshire (NH), Rhode Island (RI), Vermont (VT), New Jersey (NJ), New York (NY), Pennsylvania (PA), Virginia (VA)
46	VS Zuid		Florida (FL), Georgia (GA), North Carolina (NC), South Carolina (SC), Alabama (AL), Mississippi (MS), Tennessee (TN), Arkansas (AR), Louisiana (LA), Oklahoma (OK), Texas (TX), New Mexico (NM)
47	VS Midwest		Illinois (IL), Indiana (IN), Michigan (MI), Ohio (OH), Wisconsin (WI), Kentucky (KY), Iowa (IA), Kansas (KS), Minnesota (MN), Missouri (MO), Nebraska (NE), North Dakota (ND), South Dakota (SD)
48	VS West		Alaska (AK), Hawaii (HI), Arizona (AZ), Colorado (CO), Idaho (ID), Montana (MT), Nevada (NV), Utah (UT), Wyoming (WY), California (CA), Oregon (OR), Washington (WA)
49	Canada		Canada
50	Centraal Amerika		Inclusief Mexico en de Caraïben

Nr	Passagierszone	Achter-land	Beschrijving (COROP / regio / land)
51	Zuid-Amerika		Alle landen in Zuid-Amerika
52	Afrika		Alle landen in Afrika
53	Midden-Oosten		Bahrein, Iran, Irak, Israël, Jordanië, Koeweit, Libanon, Oman, Qatar, Saoedi-Arabië, Syrië, Verenigde Arabische Emiraten, Jemen, Afghanistan, Kazachstan, Kirgizië, Tadzjikistan, Turkmenistan, Oezbekistan
54	Australië/ Nieuw Zeeland		Ook Oceanië
55	Zuidoost-Azië		China, Taiwan, Japan, Korea, Myanmar, Thailand en rest ZO Azië (Mongolië, Indonesië, Filippijnen, Bangladesh, Brunei, Cambodja, Laos, Maldiven, Vietnam, Singapore, Maleisië)
56	Azië overig		Aziatisch Rusland, Centraal-Azië, India, Pakistan, Nepal