CLIMATE CHANGE
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Final Report

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On behalf of the German Environment Agency

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Abstract: Testing of a monitoring and reporting scheme for integrating non-CO_2 aviation effects into EU ETS

In order to achieve a reduction in non-CO_2 effects, the European Parliament (EP) voted on June 8, 2022 to expand the scope of the EU Emissions Trading System (EU ETS) (EP, 2022). In December 2022 the European Council, the European Commission (EC) and the EP reached an agreement on the revision of the EU ETS. According to the agreement, non-CO_2 effects can no longer be ignored and the EC should set up a monitoring, reporting and verification (MRV) scheme for non-CO_2 aviation emissions from 2025, as a first step for the full integration of non-CO_2 effects into the EU ETS. This project focuses on the development and testing of such an MRV system. For this purpose, non-CO_2 effects are integrated according to the principle of equivalent CO_2 emissions (CO2e). Since several CO2e calculation methods are in principle available, the selection process involves a trade-off between the level of atmospheric uncertainties, the level of climate mitigation incentives, and the resulting effort of MRV activities (see Section 1.2).

In the present report we take over the perspective of an aircraft operator and analyze all necessary tasks for monitoring and reporting of location-dependent CO_2 equivalents. For this purpose, we use flight monitoring data from 400 intra-European flights, which were provided by the European Air Transportation Leipzig (EAT) (see Section 2). To keep the MRV effort as low as possible, most monitoring and reporting steps are automated via a software tool that might be provided or approved for the users by the EC (see Section 3). In the case of location-dependent CO_2 equivalents, the standardized CO2e software includes the emission calculation (CO_2, H_2O, NO_x) along the flight route (see Section 3.1) as well as the estimation of the CO2e factor of the flight (see Section 3.2). Exemplary results are discussed in Section 4. We show some possible steps forward for integrating non-CO_2 effects into the EU ETS and formulate recommendations for an MRV scheme of non-CO_2 effects.

Kurzbeschreibung: Erprobung eines Überwachungs- und Berichterstattungssystems zur Integration von Nicht-CO_2-Effekten des Luftverkehrs ins EU ETS

Mit dem Ziel die Klimawirkung des Luftverkehrs zu reduzieren, votierte das Europäische Parlament (EP) am 8. Juni 2022 dafür, das EU-Emissionshandelssystem (EU ETS) um Nicht-CO_2-Effekte zu erweitern (EP, 2022). Im Dezember 2022 einigten sich der Europäische Rat, die Europäische Kommission (KOM) und das EP auf eine entsprechende Änderung des EU ETS. Gemäß des Gesetzesänderungsbeschlusses dürfen Nicht-CO_2-Effekte nicht länger ignoriert werden und sollen, als erster Schritt zur vollständigen Integration in das EU-ETS, ab 2025 durch ein von der KOM entworfenes Überwachungs-, Berichterstattungs- und Verifizierungssystem (MRV) erfasst werden. Dieses Projekt behandelt die Entwicklung und Erprobung eines solchen Systems. Die Nicht-CO_2-Effekte werden dabei nach dem Prinzip der CO_2-Äquivalente (CO2e) erfasst. Da verschiedene Ansätze zur Berechnung von CO2e zur Verfügung stehen, muss bei der Wahl der Berechnungsmethode eine Abwägung zwischen möglichst geringen atmosphärischen Unsicherheiten, möglichst hohen Klimaschutzanreizen und möglichst geringem Aufwand für MRV-Aktivitäten gefunden werden (siehe Abschnitt 1.2).

In diesem Bericht analysieren wir aus der Perspektive eines Flugzeugbetreibers alle notwendigen Aufgaben zur Überwachung und Berichterstattung von ortsabhängigen CO_2-Äquivalenten. Grundlage hierfür sind Flugmonitordaten von 400 innereuropäischen Flügen, die von der Fluggesellschaft European Air Transportation Leipzig (EAT) zur Verfügung gestellt wurden (siehe Abschnitt 2). Um den MRV-Aufwand so gering wie möglich zu halten, werden die meisten Überwachungs- und Berichterstattungsschritte mithilfe eines Softwareprogramms automatisiert, welches von der KOM bereitgestellt oder zugelassen werden könnte (siehe Abschnitt 3). Dies beinhaltet die Emissionsberechnung (CO_2, H_2O, NO_x) entlang der Flugstrecke (siehe Abschnitt 3.1) sowie die Abschätzung des CO2e-Faktors des Fluges (siehe Abschnitt 3.2). Beispielhafte Ergebnisse werden in Abschnitt 4 diskutiert. Wir zeigen einige mögliche Schritte

zur Integration von Nicht-CO_2-Effekten in das EU-ETS auf und formulieren Empfehlungen für ein MRV-System für Nicht-CO_2-Effekte.

Table of content

List of figures

List of tables

List of abbreviations

ATR	Averaged Temperature Response
BFFM	Boeing Fuel Flow Method
CiC	Contrail Induced Cloudiness
CH_4	Methane
CO_2	Carbon Dioxide
CO2e	Carbon Dioxide Equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
EAT	European Air Transportation Leipzig
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
EDB	ICAO Engine Exhaust Emissions Database
EI	Emission Index (Mass of emission per mass of fuel)
EMP	Emission Monitoring Plan
ERF	Effective Radiative Forcing
EU-ETS	EU Emissions Trading Scheme
ETS SF	ETS Support Facility
GTP	Global Temperature Potential
GWP	Global Warming Potential
H_2O	Water Vapor
ICAO	International Civil Aviation Organization
ISSR	Ice-SuperSaturated Region
MBM	Market-Based Measure
MRV	Monitoring, Reporting and Verification
MTOW	Maximum Take-Off Weight
NO_x	Nitrogen Oxides
O_3	Ozone
OEM	Original Equipment Manufacturer
PMO	Primary Mode Ozone
RF	Radiative Forcing
SAC	Schmidt-Appleman Criterion
SAF	Sustainable Aviation Fuel
TAS	True Air Speed

1 Introduction

1.1 Short overview of climate effects of aviation and possible mitigation approaches

The climate change gets more and more noticeable. Since 1980, global aviation has doubled all 15 years in terms of revenue passenger kilometers with an average growth rate of about 5% per year and is expected to grow significantly in the next decades (e.g., ICAO, 2013). 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).

Beside CO_2 emissions, also non-CO_2 emissions contribute to aviation induced climate change. Especially the impact of contrail cirrus and the effect of NO_x emissions on the concentration of ozone increases the climate impact of aviation. The impact of non-CO_2 effects of the historical emissions of aviation caused about two third of the total aviation impact in 2020 (Lee et al., 2021). However, due to strong non-linearities coupled with these effects, their impact on individual flights varies over a wide range.

There are different options to mitigate the climate impact of aviation. Besides reducing the number of flights, the climate impact can also be reduced by technical measures, alternative fuels or operational measures. Technical measures include reduction of specific fuel consumption, reduced weight and optimized aerodynamics. In addition, optimized aircraft design for flying at lower altitudes or in a broader altitude band could reduce offsets of flying climate optimized. The climate impact can also be reduced by using alternative fuels like sustainable aviation fuel (SAF) or liquid hydrogen. This does not only reduce the impact of CO_2 (as it is climate neutral if the fuel is produced with renewable energy), but has also an impact on non-CO_2 effects, e.g. contrails. Efficient flight guidance can reduce the fuel consumption and the impact on climate. As the climate impact of non-CO_2 emissions depends not only on the amount, but also on the location and time of emission, it is possible to reduce their climate impact if climate sensitive atmospheric regions are avoided (climate optimized flights).

Measures to reduce the climate impact of non-CO_2 effects often come along with an increase of cash operating costs. As operators of aircraft have little motivation to pay these additional costs voluntarily, incentives for reducing the climate impact of non-CO_2 effects can support the introduction of such measures. Including also non-CO_2 effects in emission trading schemes or marked based measures (MBM) could be a significant incentive and therefore contribution to the agreed climate goals of Paris.

1.2 Options for integrating non-CO_2 effects of aviation into EU ETS and under CORSIA

Carbon dioxide equivalents (CO2e or CO2eq or CO2-e) are a common metric for unitizing the climate impact of various climate agents. Since the climate impact of CO_2 is well understood due to its independence of emission source and location, it is reasonable to express the impacts of non-CO_2 effects in relation to the impacts of CO_2. For a given type and amount of a climate agent *i*, resulting CO2e cause the same climate response (e.g. RF or ΔT) over a specific time horizon (e.g. 20, 50 or 100 years) as CO_2:

$$\mathrm{CO2e}_{\mathrm{agent}\ i} = \frac{\mathrm{Climate\ Impact}_{\mathrm{agent}\ i}}{\mathrm{Climate\ Impact}_{1\ \mathrm{kg\ CO2}}}$$

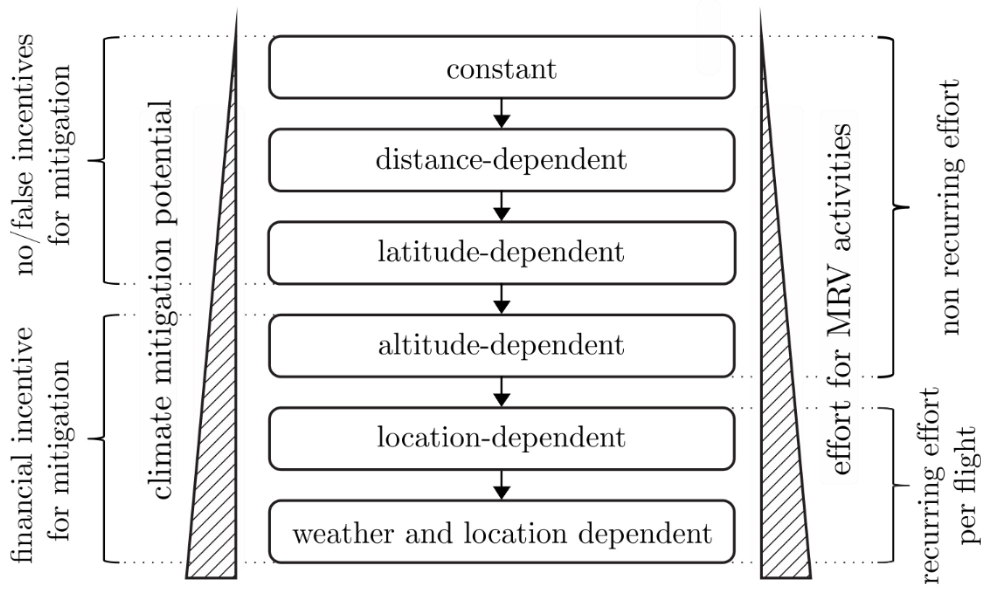
$$CO2e_{total} = CO_2 + \sum_i CO2e_{agent\,i}$$

In principle, there are several CO2e calculation methods available (see Figure 1) that are designed for different applications and differ, among other things, in the accuracy of the climate assessment. As a general rule, CO_2 equivalents should be easily calculable, predictable and transparent. The higher the accuracy of relevant atmospheric processes, the greater the incentives for climate mitigation. But, however, more accurate CO2e approaches will also require a higher amount of data for monitoring, reporting and verification. The selection of a CO2e calculation method is therefore a trade-off between high climate mitigation incentives and low efforts for MRV activities:

Key criteria for choosing a CO2e method:

- CO2e factors must provide incentives for actually reducing non-CO_2 effects (not simply adding costs, but providing the possibility to reduce climate impact and cost of operation)
- CO2e factors should be easily calculable, predictable and transparent

Figure 1: Mitigation benefit and effort for monitoring, reporting and verification (MRV) activities of different CO2e calculation methods



© Niklaß et al., 2020, p. 43 (adapted)

If only a constant factor is used, this increases the focus on CO_2 emissions as CO_2 emissions simply get more expensive. As the climate impact of non-CO_2 effects is not only dependent on the total emission amount, but also on the emission location (longitude, latitude and altitude) this might create false incentives. As an example, flying in higher altitudes decreases fuel consumption due to reduced drag, but increases the total climate impact as especially the impact of contrail cirrus and NO_x induced ozone changes increases (Matthes et al., 2021). Flying climate optimized would therefore in this case be penalized instead of rewarded with a constant CO2e factor.

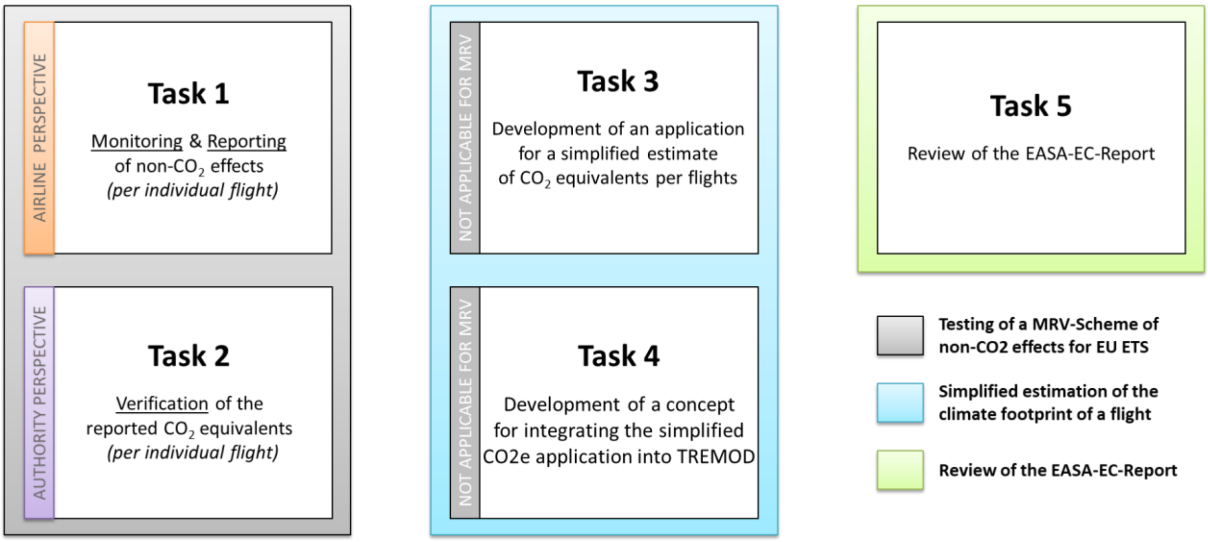
In order to avoid these misguiding incentives, at least the altitude dependency of non-CO_2 effects has to be considered in the CO2e calculation method (Faber et al., 2008; Niklaß et al., 2020; Scheelhaase et al., 2016). This requires at least detailed information about the flown trajectory (altitude profile) of each flight.

Using location dependent or even weather and location dependent CO2e factors opens up greater climate mitigation potential. In this study we analyze the feasibility of using location dependent CO2e factors. For this type of factors, it is still possible to apply simplified tools to estimate the climate impact of non-CO_2 effects as a first validation or to calculate the CO2e if the airlines are not able to provide the required data. However, these CO2e estimation methods must be conservative (i.e. should not underestimate the climate impact) to ensure that the airlines benefit from providing the data required for the more accurate calculation procedure.

1.3 Integration into the project

In this project on behalf of the German Environment Agency (UBA), three out of five tasks focus on the calculation of non-CO_2 climate effects (see Figure 2). The present report addresses Task 1, in which we take over the perspective of an aircraft operator and analyze all necessary steps for monitoring and reporting of CO_2 equivalents.

Figure 2: Overview of current project activities



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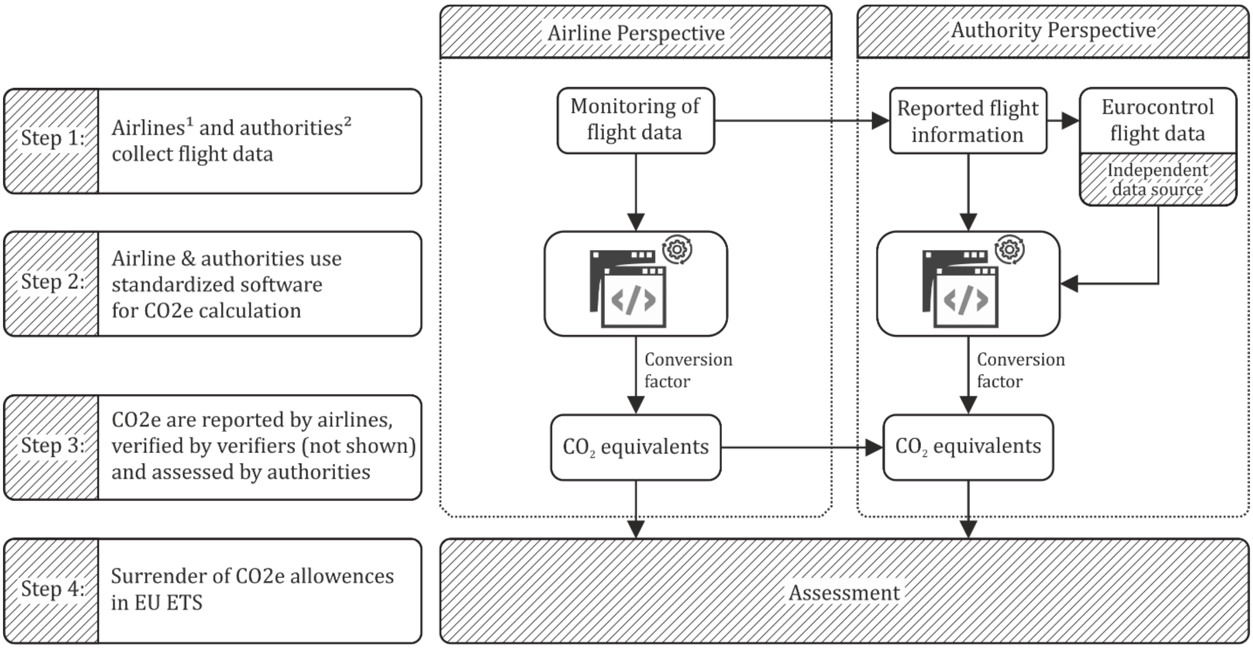
In the case of location-dependent CO_2 equivalents, the relevant emissions must be reported for each flight individually, as the CO2e level varies with the flown 3D flight path. This implementation requires monitoring additional data as well as enhanced reporting. For reducing the MRV effort, we suggest to use a standardized CO2e software (see step 2 in Figure 3 and Section 3), which might be provided or approved by the European commission (EC) for airlines (monitoring and reporting) as well as verifiers and authorities (verification and assessment). In this regard, the current EU ETS system serves as a blueprint, for which Eurocontrol provides a web application called ETS Support Facility (ETS SF) for operators and agencies (Eurocontrol, 2022). The standardized CO2e software could automatically perform all necessary calculations to determine the CO2e. For aircraft operators, this includes the emission calculation (CO_2, H_2O, NO_x) along the flight path (see Section 3.1) as well as the estimation of the resulting CO2e "factor" of the flight under consideration (see Section 3.2).

In Task 2, we take over the authority perspective and test all steps to verify the CO_2 equivalents reported by the airlines (see Niklaß et al., 2023). In Task 3 we provide a simplified tool to calculate CO2 equivalents without detailed information about a flight (see Dahlmann et al., 2022). For this tool we use a latitude dependent CO2e factor, as only information about origin and destination airport as well as the flown distance are known. This data cannot be used for EU ETS directly, but could serve for plausibility checks or as a backup, if airlines are not able to provide the needed data. Calculated CO2e values for all three approaches are compared in Task 2 (see Niklaß et al., 2023).

Figure 3: Monitoring and reporting steps for integrating non-CO2 aviation effects into EU ETS (Niklaß et al., 2022, p. 13)



[1] Airlines collect flight data for all flights
[2] Authorities collect/request flight data for reported flights that should be assessed

© Niklaß et al., 2022, p. 13

2 Airline Data

The integration of non-CO_2 aviation effects into EU ETS will involve significant adjustments to the monitoring and reporting procedures currently in place. For location-dependent CO_2 equivalents, emissions must be declared separately for each flight as the CO2e level varies with the flown 3D flight path. This implementation requires additional monitoring data as well as enhanced reporting.

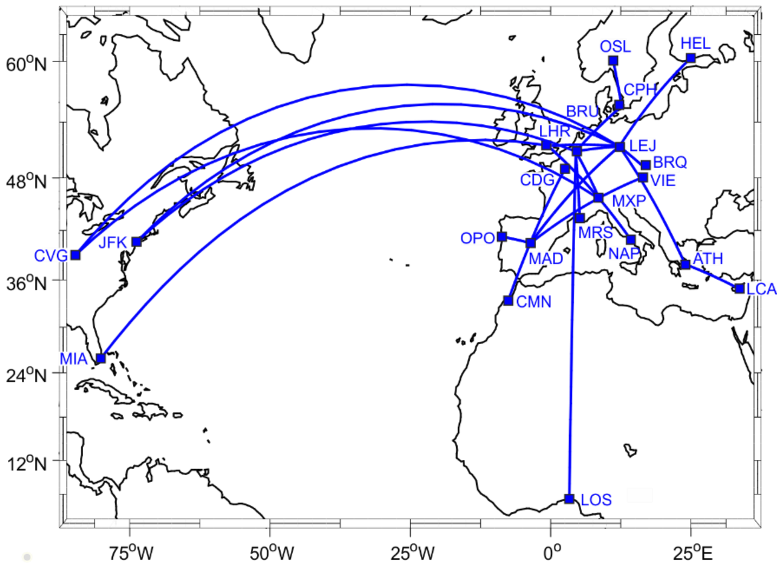
2.1 Flight and fuel data used for the project

For the purpose of monitoring and, if necessary, checking up on any irregularities, commercial airliners are recording a range of data during their flights. These datasets are usually collected by the operating airline and deleted after a certain time. These data records could be used to evaluate the non-CO_2 climate effects of individual flights more accurate. Part of this work was to evaluate what data would be available and how it needs to be processed to estimate the non-CO_2 climate effects of a flight.

The German cargo airline European Air Transport Leipzig GmbH (EAT) has agreed to support this project with data records from selected short and medium/long haul flights, most of them within Europe. A pre-selection of relevant routes from the EAT route network for the estimation of non-CO_2 climate effects has been done. Selected routes cover large parts of the European airspace controlled by Eurocontrol and represent typical flight distances within Europe.

These selected routes are shown in Figure 4. In total, EAT provided data records from 449 flights on routes between 24 city pairs, covering 3 weeks in 2021 and 4 weeks in 2022. These flights were performed by 35 different aircraft identified by their individual registration. These aircraft were 21 Airbus A300-600s, 3 Airbus A330-200, 2 Airbus A330-300s and 9 Boeing B757-200s. The 418 intra-European flights have been supplemented by 31 intercontinental flights to the east coast of north America
(Cincinnati/Northern Kentucky International Airport (CVG), Kentucky, USA; John F. Kennedy International Airport (JFK), New York, USA; Miami International Airport (MIA), Florida, USA) and to Lagos, Nigeria (Murtala Muhammed International Airport, LOS), which have been selected as examples for comparative purposes.

Figure 4: Analyzed route Network of work package 1 and 2



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The data required for the calculation of non-CO_2 climate effects of individual flights include flight altitude and true air speed (TAS), ambient air temperature and engine fuel flow, as well as the current aircraft position coordinates. It was considered sufficient for the purpose of this work to provide the data with a time interval of one minute, however in the EAT datasets a time interval of 4 seconds was provided.

In addition to the recorded data, the exact engine type, ideally by UID number from the ICAO Engine Exhaust Emissions Database (EDB) [ICAO, 2021], is required for the estimation of NO_x emissions as described in Section 3.1.3 of this report. This information is not included in the data records and was provided by EAT as supplemental information. Additionally, it was decided to include the current aircraft gross mass in the datasets for consistency checks and to be able to estimate the required data in case of data gaps.

2.2 Minimum data set to be monitored during flight

During the flight all data should be monitored and recorded that are needed to calculate the non-CO_2 climate effects from the individual flight. These include the current flight altitude and TAS, the ambient air temperature and the fuel flow per engine, as well as the current aircraft position coordinates. These data need to be recorded in time intervals that allow for a sufficiently accurate modelling of the flight's non-CO_2 climate effects. For the purpose of this work, a time interval of one minute was considered appropriate.

EAT's fleet includes older aircraft like the Airbus A300 or the Boeing B757, and also more modern types like the A330. While the older aircraft record only a more limited number of parameters, compared to newer types, the data records from all aircraft under consideration were sufficient to provide the required parameters and time resolution. As an example, an extract from a data record of a Boeing B757 flight is shown in Figure 5.

Figure 5: Sample data record of an EAT B757 flight from Brussels to Barcelona (Extract)

Time	FLIGHT_PHASE	FLIGHT_NO2	ORIGIN	DESTINATION	LATPC	LONPC	ALT_QNH	ALT_STDC	BARO1	GSC	TAS	SAT	FF1C	FF2C	GW_C
					deg	deg	feet	feet	inHg	knot	knot	deg C	lb/h	lb/h	lb
02:28:01	ENG. STOP	8048	BRU	BCN	50.90464	4.4649	-27788.8	-117	30.17	0	0	17.0	0	0	0
02:29:05	TAXI OUT	8048	BRU	BCN	50.90464	4.4649	115.65	-118	30.17	0	0	16.8	896	0	184953
02:30:09	TAXI OUT	8048	BRU	BCN	50.90464	4.4649	115.65	-118	30.17	0	0	17.0	928	0	184936
02:31:13	TAXI OUT	8048	BRU	BCN	50.90464	4.4649	115.65	-118	30.17	0	0	16.8	928	0	184920
02:32:17	TAXI OUT	8048	BRU	BCN	50.90464	4.4649	115.65	-118	30.17	0	0	17.0	928	0	184903
02:33:25	TAXI OUT	8048	BRU	BCN	50.90464	4.4649	116.65	-117	30.17	0	0	16.8	928	0	184887
02:34:29	TAXI OUT	8048	BRU	BCN	50.90395	4.4651	118.65	-115	30.17	3	3	16.8	928	0	184870
02:35:33	TAXI OUT	8048	BRU	BCN	50.90361	4.4642	119.65	-114	30.17	0	0	17.3	928	0	184854
02:36:37	TAXI OUT	8048	BRU	BCN	50.90361	4.4642	118.65	-115	30.17	0	0	16.8	1536	0	184835
02:37:41	TAXI OUT	8048	BRU	BCN	50.90361	4.4642	118.65	-115	30.17	0	0	17.0	1536	640	184804
02:38:45	TAXI OUT	8048	BRU	BCN	50.90361	4.4642	118.65	-115	30.17	0	0	17.0	928	1024	184766
02:39:49	TAXI OUT	8048	BRU	BCN	50.90361	4.4642	118.65	-115	30.17	0	0	17.0	928	1024	184731
02:40:53	TAXI OUT	8048	BRU	BCN	50.90258	4.4687	120.65	-113	30.17	21	21	16.3	896	992	184682
02:41:57	TAXI OUT	8048	BRU	BCN	50.90309	4.4766	121.65	-112	30.17	20	21	16.3	1568	1408	184647
02:43:01	TAXI OUT	8048	BRU	BCN	50.90618	4.4872	120.65	-113	30.17	27	27	16.0	928	1024	184610
02:44:05	TAXI OUT	8048	BRU	BCN	50.90893	4.4975	118.65	-115	30.17	15	15	15.5	928	1024	184575
02:45:09	TAXI OUT	8048	BRU	BCN	50.90704	4.5030	119.65	-114	30.17	15	15	15.5	928	1024	184541
02:46:13	TAXI OUT	8048	BRU	BCN	50.91185	4.5049	108.65	-125	30.17	20	20	15.3	928	1024	184506
02:47:17	2 SEGMENT	8048	BRU	BCN	50.90343	4.4711	428.65	195	30.17	163	160	16.3	10112	10496	184270
02:48:28	INIT CLIMB	8048	BRU	BCN	50.90755	4.3841	3526.65	3293	30.17	177	180	13.5	9152	9312	183922
02:49:36	CLIMB	8048	BRU	BCN	50.88593	4.2804	5041.00	5041	29.91	274	270	11.8	9024	9248	183597
02:50:40	CLIMB	8048	BRU	BCN	50.82516	4.1892	8262.00	8262	29.91	290	284	6.3	8416	8512	183284
02:51:44	CLIMB	8048	BRU	BCN	50.75872	4.0960	10890.00	10890	29.91	322	320	1.0	7872	8032	182993
02:52:48	CLIMB	8048	BRU	BCN	50.67358	4.0035	12732.00	12732	29.91	368	370	-3.0	7648	7936	182712
02:53:52	CLIMB	8048	BRU	BCN	50.57951	3.9110	15327.00	15327	29.91	379	386	-6.3	7328	7424	182442
02:54:56	CLIMB	8048	BRU	BCN	50.47771	3.8265	17471.00	17471	29.91	397	406	-10.8	6912	7008	182188
02:56:00	CLIMB	8048	BRU	BCN	50.36991	3.7475	19541.00	19541	29.91	409	416	-15.3	6560	6688	181946
02:57:04	CLIMB	8048	BRU	BCN	50.25799	3.6657	21346.00	21346	29.91	423	428	-19.5	6304	6400	181715
02:58:08	CLIMB	8048	BRU	BCN	50.14297	3.5815	23047.00	23047	29.91	434	440	-23.5	6048	6144	181494

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2.3 Minimum data set to be reported to the authority per flight

After monitoring, the CO_2 equivalents have to be reported to the authority. The minimum data to be reported to the authority in the EU-ETS are strongly depending on the chosen CO2e calculation method (see Figure 1). The higher the accuracy of modelling the relevant atmospheric processes, the greater climate impact mitigation is achievable. However, more accurate CO2e approaches will also require a higher amount of data for monitoring, reporting and verification (see Table 1).

Table 1: Overview of the properties of various CO2e calculation methods (Niklaß et al., 2022, p. 14), gray text indicates data/ information that is identical to simpler calculation methodologies

CO2e calculation method	Data to be monitored	Data to be reported	Additional MRV effort	Accuracy in climate assessment	Mitigation incentive	Possible applications
Constant	Fuel consumption	Origin-Destination Frequency Fuel consumption CO_2 equivalents	To be neglected	very low	non	ecological footprint assessments
Distance-dependent	Fuel consumption	Origin-Destination Frequency Fuel consumption CO_2 equivalents	To be neglected	Low	non	ecological footprint assessments
Latitude-dependent	Fuel consumption	Origin-Destination Frequency Fuel consumption CO_2 equivalents	Standardized software needed	realistic representation on a yearly basis	non	compensation market
Altitude-dependent	Fuel consumption 3-D position Fuel flow Aircraft mass (optional) Ambient temperature	Origin-Destination Aircraft & Engine type Flight number Fuel consumption CO_2 equivalents Take-off mass (opt.)	Standardized software needed	realistic representation on a yearly basis	Low to medium	compensation market, emission trading
Location-dependent	Fuel consumption Aircraft mass (optional) 3-D position Fuel flow Ambient temperature Ambient humidity (opt.)	Origin-Destination Aircraft & Engine type Flight number Fuel consumption CO_2 equivalents Take-off mass (opt.)	Standardized software needed	Best estimate on a seasonal or yearly basis	Medium	emission trading

CO2e calculation method	Data to be monitored	Data to be reported	Additional MRV effort	Accuracy in climate assessment	Mitigation incentive	Possible applications
Location- & weather-dependent	Fuel consumption 4-D position Fuel flow Aircraft mass (optional) Ambient temperature Weather forecast data	Origin-Destination Aircraft & Engine type Flight number Fuel consumption CO_2 equivalents Take-off mass (opt.)	Standardized software needed	Best estimate on a daily basis	High	emission trading

As a good compromise between high mitigation effects of non-CO_2 impacts and reduced MRV effort (no ECMWF data required), we selected a location-dependent CO2e factor within this work. For integrating location-dependent CO2e factors into the EU ETS, the minimum data to be reported to the authority are the flight date and flight number, the origin and destination airports as well as the fuel consumption (CO_2) per flight (see Table 2). For considering non-CO_2 climate effects, additional to this data the exact aircraft and engine type as well as the CO_2 equivalents due to the non-CO_2 climate effects of the flight need to be reported. The latter can be calculated by the airline based on the data described in the previous section, using the methods described in section 3. Optionally, the take-off mass should be reported to allow e.g. for consistency checks. Highly sensitive airline data, like the exact fuel flow over time, should be excluded from the reporting process, if possible.

Table 2: Possible EU ETS report of non-CO_2 effects per flights

Airline	Flight Date	Flight Number	Origin-Destination	AC & Eng. Type	Fuel Type	CO_2 [t]	CO2e(Total) [t]

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2.4 Handling of data gaps

The flight data provided by EAT was high-quality and did not include gaps or inconsistencies except in one case, which will be described later in this section. Nevertheless, from earlier experience with recorded flight data, gaps and inconsistencies are known that include incomplete data for longer time periods (up to the whole flight) and erroneous position data, resulting in sudden changes of the flight path.

Most of these errors can be easily detected by simple plausibility checks like average flight speed comparisons and aircraft weight estimates based on the take-off mass and the duration of the flight.

In the case mentioned above, the error was not easily detected, despite having a quite significant impact on the calculation of non-CO_2 climate effects. In this particular case, one of the EAT datasets contained fuel flow data that did not change after a certain point in the initial climb phase of the flight. Instead, the same value was copied to all subsequent data points until close to the end of the flight's cruise phase. All other parameters appeared unaffected, except the recorded gross weight data. This parameter cannot be measured during the flight and is therefore calculated from the initial gross weight, entered by the pilot into the flight management system, and the fuel consumed in each time step. As a result, the recorded gross weight is calculated with the erroneous fuel flow data, and at the end of the mission its value is quite low, but still greater than the operating empty weight of the aircraft [Airbus, 2017].

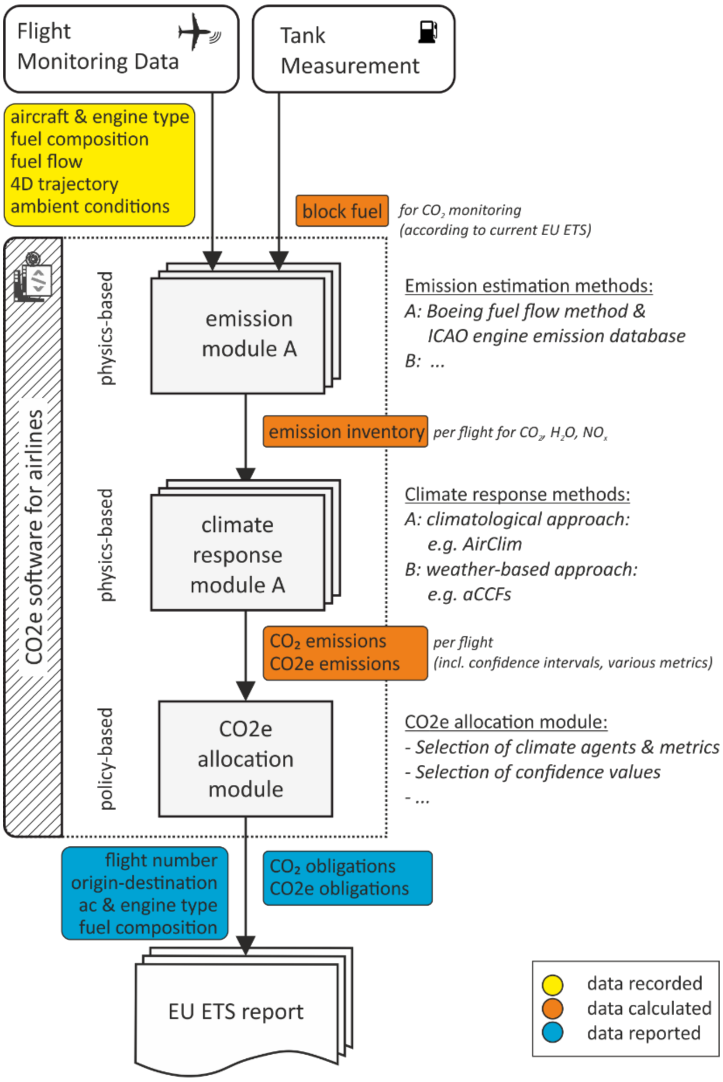
It is therefore difficult to detect errors like this. In this case, average EI NO_x values have been calculated with the total fuel recorded and the calculated NO_x emitted (by the procedure described in Section 3.1.2). In this case, this average EI NO_x was higher than the maximum (Take-off) value for this engine in the ICAO EDB, which is clearly implausible and almost 3 times the correct value for this flight. As a result, a too high climate effect would be calculated when using the data without appropriate corrections.

However, if the erroneous recording had lasted only for a shorter time period, it would probably not been noticed. Therefore, it appears appropriate to check for variations of the parameters between two adjacent data points. Identical values recorded for several subsequent points should be considered as a warning that the recording might contain irregularities. Smaller errors may be corrected by simple linear interpolation of data for erroneous recording periods, larger errors would probably require discarding the complete recorded data and applying appropriate estimation methods. These could be similar methods as applied for the validation of the reported data Task 2 (see Niklaß et al., 2023) or the simplified estimates as developed in Task 3 (see Dahlmann et al., 2022).

3 Standardized software for CO2e calculations per flight

Based on the recorded flight data (see step 1 in Figure 3), CO_2 equivalents per flight have to be calculated as a second step. In order to reduce the additional MRV effort to a minimum, all necessary CO2e calculation steps should automatically be performed by a standardized CO2e software (see step 2 in Figure 3 and Figure 6), possibly provided directly by the EC or by an approved organization.

Figure 6: Possible structure of the required software for CO2e calculations per flight



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For aircraft operators, the standardized software for CO2e calculations should include two physics-based simulation steps:

1. the calculation of emission inventories along the flight path for CO_2, H_2O and NO_x (see emission module in Section 3.1) and
2. the CO2e estimation for the flight for H_2O, NO_x, CiC under consideration of uncertainties (e.g. 5% percentile, 50% percentile, 95% percentile) for different climate indicators (e.g. ATR, GWP) and time horizons (e.g. 20, 50, 100 years) (see climate response module in Section 3.2).

Analogous to the CO_2 monitoring in EU ETS and under CORSIA, different calculation methods can be made available for these physical-based modules (e.g. climatological and weather-based approach for climate response simulations). The selection of the calculation methods used by an individual aircraft operator should be specified in the airline specific Emission Monitoring Plan (EMP) and submitted to the competent authority for approval.

Following the physical-based modules, the EU decision is implemented in a policy-based module in order to set the level of CO2e obligations (e.g., depending on the confidence levels of each climate agent):

3. Allocation of CO2e obligations (policy-based module, not part of this project)

To better understand the impact of uncertainties on the calculation of non-CO_2 effects and thereby on the potential of setting wrong incentives, risk assessments are required for selected climate agents. First, the climate mitigation potentials of specific strategies have to be verified.[1] Second, reported CO2e values have to represent estimated climate impact of aviation on average.[2] This requires a solid data base, including flight information, fuel consumption as well as CO_2 equivalents from numerous flights. Necessary data could be collected in the pilot non-CO_2 MRV scheme of the EU ETS starting in 2025, in which non-CO2 effects are already monitored and reported, but are not yet subject to monetary internalization.

3.1 Emission module: Evaluation of non-CO_2 emissions per flight

3.1.1 Evaluation of CO_2 and H_2O Emissions

Due to the high combustion efficiencies achieved in gas turbine engine combustors (greater than 99.9% for all high power operating conditions, not less than 98.8% at low power [Liu et al, 2017]), the emission indices of the main combustion products of hydrocarbon fuels, Carbon Dioxide (CO_2) and Water (H_2O), can be assumed to be constant for all relevant operating conditions (for local air quality assessments, more detailed models may be required for engine start-up and idle).

The ratio of CO_2 and H_2O emissions is then only dependent on the composition of the jet fuel. For a mean chemical sum formula for Jet A-1 kerosene of $C_{19}H_{23}$ (Rachner, 1998), the emission indices for CO_2 and H_2O for complete combustion are:

$$EI\ CO_2 = 3157.3\ g/kg\ Fuel$$

$$EI\ H_2O = 1237.2\ g/kg\ Fuel$$

These values can be applied to directly calculate CO_2 and H_2O emissions from the recorded fuel flow.

3.1.2 Evaluation of NO_x Emissions

In contrast, emissions of Nitrous Oxides (NO_x) are not a direct combustion product, but a by-product caused by oxidation of Nitrogen, contained in the air, under high combustion

1 Here, the risk assessment clarifies that at a high probability (e.g. >95%) any mitigation measure leads on average to a climate impact reduction of CO_2 and non-CO_2 effects, but may allow for individual cases adverse effects. This kind of risk assessment may include Monte Carlo simulation or similar tools that consider uncertainties and propagate them for various climate mitigation options to uncertainties in gained reductions of CO_2 equivalents.

2 Here, the risk assessment clarifies that at a high probability (e.g. >95%) the simplified methodologies for CO2e calculations sufficiently describes on average aviation's climate impact on the basis of higher fidelity models and measurements.

temperatures. As such, the NO_x production rate is strongly dependent on the combustion temperature and the residence time in the combustor (Lefebvre et al., 2010). Fortunately, in an existing gas turbine engine, all parameters affecting these values are interconnected. Therefore, it is possible to characterize an operating condition of a turbofan engine only by the ambient condition (given by air pressure, temperature and flight speed) and the fuel flow, which is the only parameter varied to control the engine thrust. As a consequence, a correlation exists between the flight condition, fuel flow and NO_x production. Several methodologies have been proposed to make use of this correlation to estimate the NO_x emission of an aircraft during flight, based on measured and certified sea level static engine emissions data as published in ICAO's EDB for each engine type in service.

For the purpose of this project the so-called Boeing Fuel Flow Method (BFFM) has been selected to estimate the NO_x emissions along the flight path of the individual flights considered. The method is described in detail in [Dubois and Paynter, 2007] and is recommended in ICAO's Environmental Technical Manual [ICAO, 2020] for the purpose of calculating NO_x emissions of individual flights. The required input data are engine fuel flow, ambient pressure and temperature as well as the flight Mach number, which can be calculated from ambient pressure, temperature and flight speed, if not available in the recorded flight data. Additionally, fuel flow and EI NO_x data for the exact engine type from the EDB are needed. The methodology comprises a standardized step-by-step application procedure and is therefore well suited for automated application, e.g. as component of a software tool.

The methodology consists of the following 4 steps:

Step 1. Correct the current (measured/reported) fuel flow to ground reference conditions by

$$W_{ff} = \frac{W_f}{\delta_{amb}} \cdot \theta_{amb}^{3.8} \cdot e^{0.2 \cdot M^2} \qquad \text{where } \theta_{amb} = \frac{T_{amb}}{288.15K} \text{ and } \delta_{amb} = \frac{p_{amb}}{101325Pa}$$

Step 2. Correct step 1 fuel flow for installation effects:

$$W_{ff,ref} = W_{ff,db} \cdot r$$

	Take-off	Climb-out	Approach	Idle
Thrust setting [% F_{00}]	100%	85%	30%	7%
Correction factor r [-]	1.010	1.013	1.020	1.100

Step 3. Interpolate ground reference EI NO_x ($REINO_x$) in the EDB data by linear interpolation in log-log scale for the corrected fuel flow from step 2

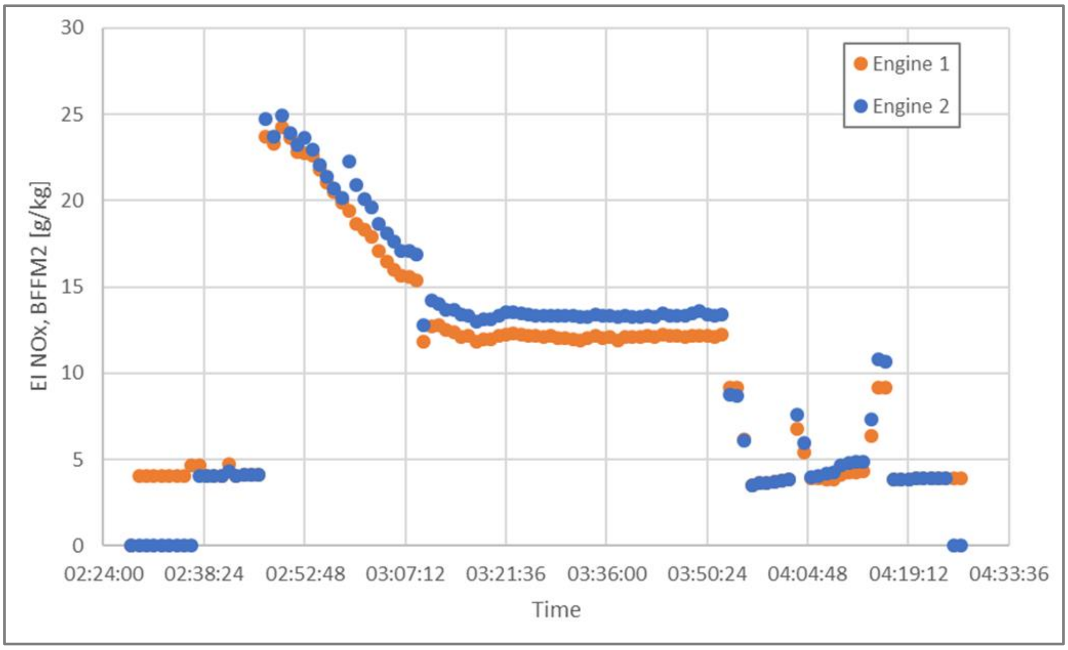
Step 4. Re-correct $REINO_x$ for ambient conditions at the current flight condition by

$$EINO_X = REINO_X \cdot \sqrt{\frac{\delta_{amb}^{1.02}}{\theta_{amb}^{3.3}}} \cdot e^H$$

The term e^H in step 4 is a correction factor for ambient humidity. Since measured data of the current ambient humidity under flight conditions is mostly not available, usually a standardized, altitude-dependent correction is applied here.

An example of the application of this method to an EAT flight data recording is given in Figure 7:

Figure 7: Example of EI NO_x data calculated for a flight data recording with the Boeing fuel flow method



In this example, the initial low EI NO_x values are attributable to the Idle/Taxi operations before take-off. The Take-off run is easily identified by the sharp rise in EI NO_x, with is subsequently decreasing with the decreasing ambient pressure during the Climb phase. The Cruise phase is characterized by a lower, mainly constant EI NO_x value. The Descent phase shows mostly NO_x emissions in the Idle range (<5g/kg), sometimes interrupted by higher values supposedly caused by corrections to the descent path.

The noticeable difference between the two engines is probably caused by different maintenance conditions. During a longer period of operation, the performance of an aircraft engine will slowly degrade due to wear and abrasion, as well as deposition on the aerodynamic surfaces, resulting in lower efficiency and therefore more fuel required to provide the same thrust. The initial performance can usually be restored by a maintenance procedure.

3.1.3 Uncertainties of NO_x prediction

A comparison of several NO_x correlation methods and an estimate of their accuracy, when compared with (undisclosed) OEM data, was provided in the final technical report of the EC-project NEPAir (Norman et al., 2003). In this report, an accuracy of ±10% is given for NO_x predictions by the BFFM for conventional RQL combustors. Methods with better accuracy are described in the project, but those require knowledge of internal engine temperatures and pressures which are usually only available to the engine OEM.

A procedure for application of the BFFM to advanced low NO_x combustors, featuring staged, lean-burn technology is under development by ICAO CAEP’s Working Group 3. Due to additional (usually unknown) parameters determining the combustion staging, it is expected that this method will be unable to achieve the same accuracy as for conventional combustors.

Further sources of uncertainties can arise from the required reference data for application of the BFFM. Although emissions and fuel flow data for every engine in service is available through the

ICAO EDB, the engine designation is not always unambiguous. There are engine variants with the same engine designation in the database featuring different combustion systems with sometimes very different NO_x emission behaviour. If an airline doesn't know the exact UID of the ICAO EDB entry of their engines, it is not possible to accurately estimate the NO_x emissions of a flight. In this case it is recommended to use averaged EI NO_x data from all engine variants with the same designation. While this would still result in higher uncertainties for an individual flight, the uncertainties will likely balance out for a larger number of flights with several aircraft propelled by the engine types in question.

3.2 Climate-response module: Evaluation of CO_2 equivalents per flight

To calculate the CO2e for the provided routes we use the climate response model *AirClim* (Dahlmann et al., 2016; Grewe & Stenke, 2008). *AirClim* is a non-linear climate response model, which combines aircraft emission data (longitude, latitude and altitude) with a set of previously calculated atmospheric responses to calculate the temporal development of the global near-surface temperature change.

For deriving the atmospheric responses for H_2O and NO_x-induced changes in O_3 and CH_4, 85 steady-state simulations for the year 2000 were performed 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 contrail induced cloudiness (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 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.

AirClim is a very efficient response tool and is able to calculate the climate impact of a single route in less than one minute on a standard PC. Therefore, it is possible to automate the CO2e calculations.

As a metric we use here the ATR100, which is the average near surface temperature response over 100 years. As an emission development we assume increasing emissions in the future according to Grewe et al., 2021. One could also use pulse emissions (emissions only in one year) to calculate the CO2e, but here we use increasing emissions to compare the results to work package 3.

AirClim is a DLR tool without free access at the moment. But we are developing an open Version of *AirClim* which should be available by end of 2024. This version will be designed for research purpose with a lot of parameters which can be freely chosen. For MRV purposes we assume that a kind of Blackbox version would be suitable, with fixed parameters and exactly defined input and output. Such a version could be developed quite fast.

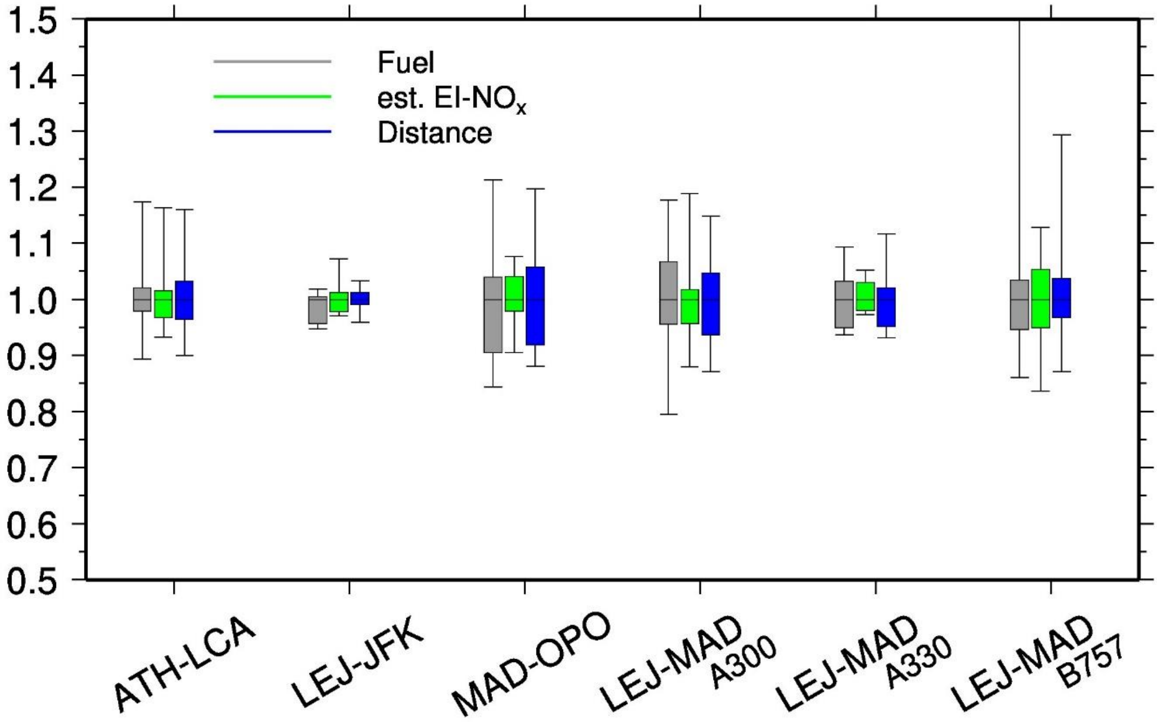
Beside *AirClim*, other climate-response models are available that consider the temporal development of the climate impact (Lim et al., 2006) or the altitude dependency (Köhler et al., 2008; Rädel and Shine, 2008). For location-dependent CO_2 equivalents, the climate response simulation however must at least take latitude and altitude dependency into account.

4 Results

4.1 Emissions from individual flights

Within this study, emission calculations have been performed for data records of 449 EAT flights covering 3 weeks in 2021 and 4 weeks in 2022 (see Figure 4). Monitored flight distances, monitored fuel consumptions and estimated EI NO_x values scatter for different flights on the same origin and destination pair. Most deviations in routing are most likely weather or capacity related, resulting in different flight planning or mid-flight re-routing. For four different flight connections, exemplary, distributions are plotted in Figure 8 relative to the median values of each route. Absolute values of the median are presented in Table 3.

Figure 8: Distribution of fuel consumption, estimated emission index of NO_x and flown distances for some of the analyzed routes relative to the median value of each route. Boxes indicate the 25 and 75 percentile and the whiskers indicate the 2.5 and 97.5 percentiles



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As the Leipzig (LEJ) – Madrid (MAD) route was served by three different types of aircraft (A300, A330, B757), the LEJ-MAD distributions are plotted on an aircraft-specific basis. With the exception of the LEJ-MAD B757 fuel distribution, emissions and flown distances vary between 20% around the Median. For the flight LEJ-MAD with a B757, the fuel consumption of one single flight is about 57% larger than the Median value, while the distance increases only by 29%. We therefore assume an incorrect recording in this case.

Table 3: Great circle distance (GCD) + 95 km and absolute values of the median of fuel consumption, estimated emission index of NOx and flown distances and number of analysed flights

Route	AC Type	GCD + 95km [km]	Median (Distance) [km]	Median (Fuel) [kg]	Median (EI NO_x) [g/kg]	Number of flights
ATH-LCA	A300	*1025*	927	6620	16.0	23
LEJ-JFK	A330	*6448*	7324	49254	13.7	9
MAD-OPO	B757	*533*	517	2463	13.8	16
LEJ-MAD	A300	*1811*	1823	12285	15.5	34
LEJ-MAD	A330	*1811*	1816	11698	13.0	7
LEJ-MAD	B757	*1811*	1860	7142	12.4	54

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The absolute values of the median fuel consumption are significantly lower on the LEJ-MAD route for the B757 than for the A300 and the A330, due to its lower transport capacity (measured by maximum take-off weight, MTOW). The median fuel flow of the more modern A330 is slightly lower than that of the older A300, although its MTOW is about 40% more than that of the A300.

Table 4 shows MTOW data of the different aircraft types considered in this study.

Table 4: Maximum Take-off Weights (MTOW) of aircraft types considered in this study

Aircraft Type	MTOW [kg]
Airbus A300-600	170500
Airbus A330-200	233000
Airbus A330-300	242000
Boeing B757-200	115660

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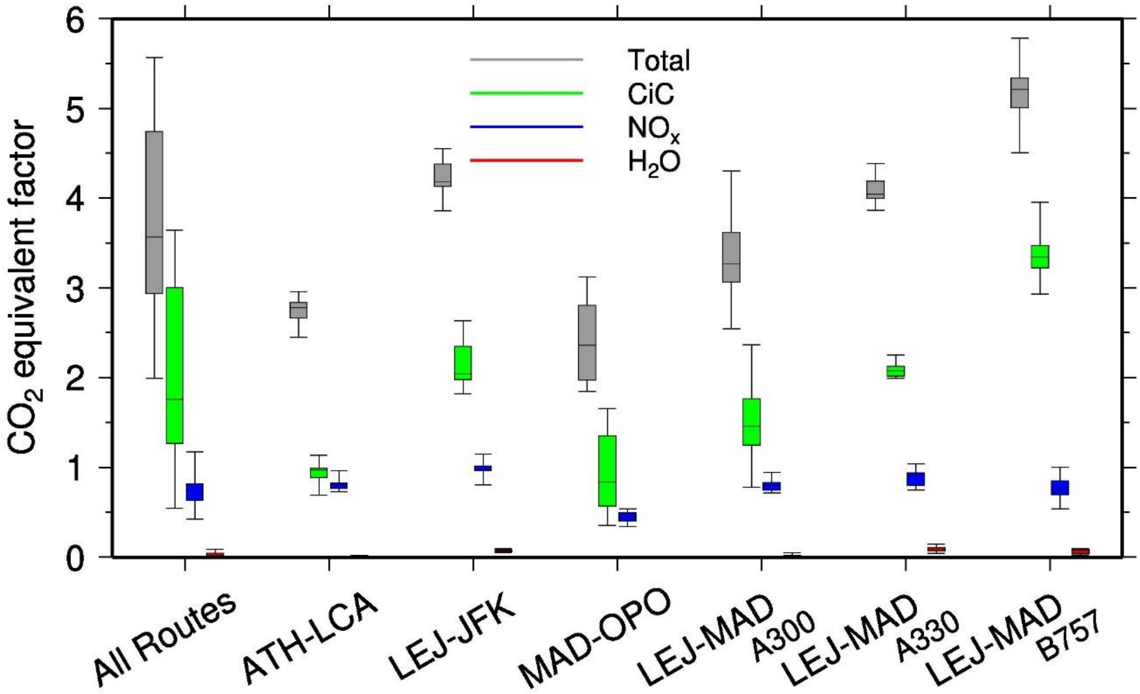
4.2 CO2e from individual flights

For all 449 EAT flights individual CO_2 equivalents have been calculated. Distributions of CO2e values of each species are shown first for the analyzed route network in the climate metric ATR_{100} without specifying areas of uncertainty. For individual city pairs (routes), the shown flight-specific CO2e scatter is caused by different flight trajectories, fuel consumptions and emissions (see Figure 8). In a second step, uncertainty-related CO2e scattering is shown for a single flight for different climate agents and climate metrics. To make the results of the different flights more comparable, we focus on CO_2 equivalent factors (fraction of ATR_{spec} and ATR_{CO2}) within this study. CO_2 equivalent factors have to be multiplied with total CO_2 emissions of the flight in order to receive CO2e.

Resulting CO_2 equivalent factors of the total climate impact as well as the individual shares of CiC, NO_x and H_2O are shown in Figure 9 over all routes and for four exemplarily selected connections, with the LEJ-MAD data again plotted aircraft-specific.

Figure 9: Distribution of CO_2 equivalent factors of the total impact and the impact of CiC, NO_x and H_2O for some of the analyzed routes relative to the median of each route (CO_2 is not shown but would by definition be 1). Boxes indicate the 25 and 75 percentile and the whiskers indicate the 2.5 and 97.5 percentiles



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Due to the different flown trajectories of different flights on the same connection which can be seen by the scatter of flight distance, fuel consumption and EI NO_x values (see Figure 8), there is also a variability in the resulting CO_2 equivalent factors of individual flights. For all 449 flights on the 24 city pairs (and 3 aircraft types), the magnitude of variance is between 2 and almost 6 with a median of about 3.5. CiC contributes the most to the climate impact with a CO2e factor of about 2 and a spread between 0.5 and 3.5. By definition, the contribution of CO_2 is 1. NO_x contributes between 0.5 and 1.3 with a median of 0.7. For the analysed routes, the contribution of H_2O is less than 0.1

The level of the CO2e factor strongly dependents on the level of the CO_2 reference. Since EU ETS is designed to estimate the climate impact of present and future flights, we do 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 relation between non-CO_2 effects and CO_2 is higher than the known factor from the literature for non-CO_2 effects of 2-3, which is based on the total CO_2 level from preindustrial times (e.g. from 1940 to 2018 for Lee et al., 2021).

By plotting the CO2e factor for each route, it can be seen that the magnitude of the factors is strongly location (route) dependent. From Madrid, Spain (MAD) to Porto, Portugal (OPO), for example, the median CO2e factor of an B757 is less than 2.5, while the median of CO2e factor of all B757 flights on the route Leipzig, Germany (LEJ) to Madrid, Spain (MAD) is larger than 5, which is mainly caused by high CO2e values of CiC.

A comparison of the CO2e factors of the different aircraft types on the LEJ-MAD route reveals differences in the total factors as well in shares of CiC and NO_x. In contrast to LEJ-MAD B757, where the calculated total CO2e factor is between 4.5 and 6.5 for the individual flights, the factor for LEJ-MAD A300 is just between 2.5 and 4.5. Main reason for the different factors is that they are relative to the emitted CO_2 amount of the flight. The fuel consumption and CO_2 emission of an aircraft is dependent on its transport capacity (measured e.g. by MTOW) and fuel efficiency. Both lower transport capacity and higher fuel efficiency result in decreasing fuel consumption and hence CO_2 emission. If, for instance, non-CO_2 effects do not change, the CO2e factor would increase as the denominator (CO_2) decreases. Therefore, it is important to look at the total value of CO2e instead of CO2e factors.

Median values of CO2e are presented in Table 5 for the different routes. From the relative presentation in Figure 8 and Figure 9, the total climate impact of the LEJ-MAD route might appear to be higher for an B757 aircraft than for an A300 and an A330. However, in absolute values the B757 has a lower impact, as fuel consumption and CO_2 emissions are significantly smaller (see Table 3). Again, this has to be weighted with the different transport capacities of the aircraft and the flown distance (see last column of Table 5).

Table 5: Averaged CO_2 emissions and averaged median CO2e emissions for the different species and routes

Route	aircraft	CO_2 [kg]	CO2e(CiC) [kg]	CO2e(NO_x) [kg]	CO2e(H_2O) [kg]	CO2e(Total) [kg]	CO2e(Total) per MTOW & Distance [kg/(t km)]
ATH-LCA	A300	20079	19533	16083	321	55264	0.35
LEJ-JFK	A330	160622	327216	156025	11549	678822	0.40
MAD-OPO	B757	7437	6425	3521	58	18084	0.30
LEJ-MAD	A300	38830	59617	30831	653	128295	0.41
LEJ-MAD	A330	36919	79120	33465	3492	156216	0.36
LEJ-MAD	B757	22680	76389	17,519	1718	117479	0.55

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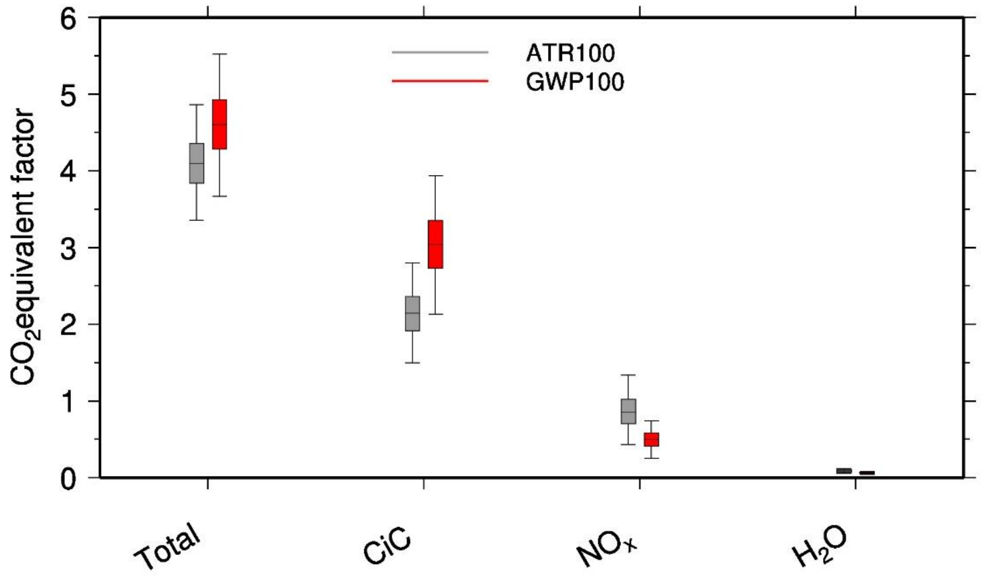
What can be seen already from these examples is, that it is important to analyze the climate impact on a single flight basis, as the CO2e differ for the individual flights, although we use a climatology approach in this study.

For one single flight on the route LEJ-MAD with an A330, uncertainty-related CO2e scattering is shown in Figure 10 for different climate agents (Total, H_2O, NO_x, CiC) and climate metrics (ATR_{100}, GWP_{100}). All uncertainty ranges are taken form Dahlmann et al., 2016. The largest uncertainties come from CiC and NO_x. The difference in the CO2e factor between the analyzed climate metrics are mainly due to the efficacy (climate sensitivity factor of a species relative to that of CO_2) which is larger for NO_x and lower for CiC. Since GWP does not include the efficacy, this leads to a larger impact of CiC and a lower impact of NO_x compared to ATR_{100}.

Figure 10: Uncertainty range for a single flight from LEJ to MAD with a A330 for the different climate species and two different climate metrics (ATR100 and GWP100)



The final level of CO2e obligations to be set for a flight is a political decision, which could be based, for example, depending on the confidence levels of individual climate agents. Risk assessments are required to better understand the impact of uncertainties on the calculation of non-CO_2 effects and thereby on the potential of setting wrong incentives.

5 Summary

In the present report we took over the perspective of an aircraft operator and demonstrated that it is possible to calculate the climate impact in terms of CO_2 for real flights. For this purpose, we analyzed all necessary tasks for monitoring and reporting of location-dependent CO_2 equivalents. Our demonstration is based on flight monitoring data from 449 mainly intra-European flights of four different aircraft types (A300, A330-200, A330-300, B757), which were provided by the European Air Transportation Leipzig (EAT) cargo airline. These datasets are usually collected by the aircraft operators and deleted after a certain time. While the older aircraft (here: A300, B757) record only a more limited number of parameters, compared to newer types, the data records from all aircraft under consideration were sufficient to provide the required parameters and time resolution. For location-dependent CO_2 equivalents, the minimum data set to be monitored during flight includes the current flight altitude and true air speed (TAS), the ambient air temperature and the fuel flow per engine, as well as the current aircraft position coordinates. The provision of this data should not cause any problems for aircraft operators, as this data is already being recorded.

Based on the recorded airline data, the aircraft operator has to calculate location-dependent CO_2 equivalents of the flight as a second step. Here, we follow the idea, that the effort of the airline should be as small as possible. The CO2e calculation should therefore be carried out automatically by a software, which might be provided or approved by the EC.

For aircraft operators, the standardized software for CO2e calculations per flight should include two physics-based simulations:

1. the calculation of emission inventories along the flight path for H_2O, NO_x, and CiC (emission module) and
2. the CO2e estimation for the flight for H_2O, NO_x, and CiC under consideration of uncertainties (e.g. 5% percentile, 50% percentile, 95% percentile) for different climate indicators (e.g. ATR, GWP) and time horizons (e.g. 20, 50, 100 years) (climate response module)

Analogous to the CO_2 monitoring in EU ETS and under CORSIA, different calculation methods can be made available for these physical-based modules (e.g. climatological and weather-based approach for climate response simulations). The selection of the calculation methods used by an individual aircraft operator should be specified in the airline specific Emission Monitoring Plan (EMP) and submitted to the competent authority for approval.

For both physics-based modules, a possible calculation method was tested andautomated in this project, but the data was exchanged manually.

For the automated calculation of NO_x emissions, the Boeing Fuel Flow Method (BFFM) was implemented into a software tool which applies this method on the basis of engine-specific, certified sea level static emissions data from the ICAO EDB for every data point in the recorded data for each flight. The tool was then applied to calculate the NO_x emissions data of all recorded flights in a single step and write the results back into the individual data files. Subsequently, the data files were manually transferred for the CO2e calculations.

For the automatic calculation of CO2e of individual flights, it is necessary to develop a unified software that contains both steps with automatic processing and transfer of data. The evaluation of CO2e per flight has been carried out with the DLR's climate response model *AirClim*. However, there is no public version of *AirClim* available at the moment but an open source version is currently under development, which should be available by end of 2024. The open *AirClim* version is developed for research purposes with many parameters that can be freely changed. For MRV purpose, a user friendly “black box” version would be more suitable, with fixed parameters and well-defined input and output parameters. Such an *AirClim* version could be developed in a shorter time. Beside *AirClim*, other climate-response models are available that consider the temporal development of the climate impact or the altitude dependency. For location-dependent CO_2 equivalents, the climate response simulation however must at least take latitude and altitude dependency into account.

The analyzed 449 flights show a spread in fuel, estimated EI NO_x and distance of about 20% due to different trajectories for the same route caused by weather or capacity reasons. The resulting CO2e factors strongly differs for individual route, but also show a larger spread for individual flights on the same route. Therefore, it is important to analyze the climate impact on a single flight basis, as the CO2e differ for the individual flights, although we use a climatology approach in this study.

The level of the CO2e factor 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, we do 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 relation between non-CO_2 effects and CO_2 is higher than the known factor from the literature for non-CO_2 effects of 2-3, 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 to the two physically-based modules, the proposed CO2e software should also include a policy-based module (see Figure 6), that set the level of CO2e obligations (e.g., depending on the confidence levels of each climate agent) in accordance with the EU decision.

3. Allocation of CO2e obligations (policy-based module, not part of this project)

To better understand the impact of uncertainties on the calculation of non-CO2 effects and thereby on the potential of setting wrong incentives, risk assessments are required for selected climate agents. This requires a solid data bases, that could be collected in the pilot non-CO2 MRV scheme of the EU ETS starting in 2025. In addition, the actual cost implications for airlines and the resulting impact on competition must be analyzed before implementing CO2e obligations either to surrender allowances or to buy offsets.

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