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# Integration of Non-CO2 Effects of Aviation in the EU ETS and under CORSIA

## Final Report

For our Environment

Umwelt Bundesamt

CLIMATE CHANGE 20/2020

Environmental Research of the Federal Ministry
for the Environment, Nature Conservation
and Nuclear Safety

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# Integration of Non-$CO_2$ Effects of Aviation in the EU ETS and under CORSIA

Final report

by

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### Abstract: Integration of Non-$CO_2$ Effects of Aviation in the EU ETS and under CORSIA

In addition to carbon dioxide, air traffic operation affects the climate through other emissions and atmospheric processes, such as the formation of ozone and contrail cirrus. The climate impact of these non-$CO_2$ effects is strongly dependent on the emission location (in particular cruise altitude) and emission time (e.g. weather conditions) and, thus, highly non-linear to the fuel consumption. Although non-$CO_2$ effects are responsible for about 2/3 of the climate impact of aviation, they are not yet taken into account in existing and currently planned emissions trading systems (e.g. EU ETS) or market-based measures (MBM, e.g. CORSIA [1]).

This research project focuses on the development of concepts for the integration of non-$CO_2$ effects of air traffic into the EU ETS and under CORSIA. For this purpose, suitable climate metrics for assessing the relationship between non-$CO_2$ and $CO_2$ climate impacts are analyzed first (Part A). For selected non-$CO_2$ calculation methodologies, the availability of the necessary data is examined and estimation procedures for non-existent data are investigated (Part B). Afterwards, the current practice in voluntary carbon markets for estimating $CO_2$ and non-CO2 effects of aviation is presented (Part C). The additional administrative burden to verify reporting on aviation's non-$CO_2$ is examined in Part D. In the final step, key design parameters for the integration of non-$CO_2$ consequences of aviation in the EU ETS and CORSIA are evaluated (Part E).

The inclusion of non-$CO_2$ effects in the EU ETS and CORSIA is highly recommended for climate-logical reasons and technically feasible, but involves an additional administrative burden for authorities and aircraft operators. The level of the resulting mitigation incentive as well as the additional effort is strongly depending on the calculation methodology of the $CO_2$ equivalents. For this choice, a trade-off must be made between a simple operational feasibility and a high incentive level to modify flight routing and to reduce the $NO_x$ emission indices. False mitigation incentives, which can arise from to the non-linearity between non-$CO_2$ climate effects and fuel consumption, must be prevented.



### Kurzbeschreibung: Integration von Nicht-$CO_2$ Effekte der Luftfahrt in EU ETS und unter CORSIA

Der Luftverkehr verursacht neben Kohlendioxid ($CO_2$) weitere Emissionen und atmosphärische Prozesse, wie z. B. die Ozon- und Kondensstreifenzirrenbildung, deren Klimawirkung stark vom Emissionsort (insbesondere Reiseflughöhe) und –zeitpunkt (u.a. Wetterbedingungen) abhängt und somit hochgradig nicht linear zum Kraftstoffverbrauch ist. Obwohl Nicht-$CO_2$-Effekte ca. 2/3 der Klimawirkung der Luftfahrt induzieren, werden sie in bestehenden und aktuell geplanten Emissionshandelssystemen (z.B. EU ETS) bzw. marktbasierten Maßnahmen (MBM, z.B. CORSIA) zur Regulierung von klimawirksamen Luftverkehrsemissionen noch nicht berücksichtigt.

Gegenstand dieses Forschungsprojekts ist die Erarbeitung von Konzepten zur Integration dieser Nicht-$CO_2$-Effekte in das EU ETS bzw. CORSIA. Zu diesem Zweck werden zunächst geeignete Klimametriken zur Beurteilung des Zusammenhangs zwischen Nicht-$CO_2$- und $CO_2$-Klimawirkungen analysiert (Teil A). Es wird untersucht, welche Daten Luftfahrzeugbetreiber dafür erfassen müssen und wie nicht vorhandene Daten ggf. durch Schätzdaten ersetzt werden können (Teil B). Anschließend wird die derzeitige Praxis auf den freiwilligen Kohlenstoffmärkten zur Abschätzung der $CO_2$- und Nicht-$CO_2$-Effekte des Luftverkehrs dargestellt (Teil C). Der zusätzliche Verwaltungsaufwand zur Überprüfung der Berichterstattung der Nicht-$CO_2$-Effekte wird in Teil D untersucht. Im letzten Schritt werden wesentliche Fragestellungen zur Einbindung von Nicht-$CO_2$-Effekten in das EU ETS bzw. in CORSIA adressiert (Teil E).


[1] Carbon Offsetting and Reduction Scheme for International Aviation

Die Einbeziehung von Nicht-$CO_2$-Effekten ins EU ETS und CORSIA ist aus klimatologischen Gründen empfehlenswert und (Daten-)technisch möglich, aber mit einem zusätzlichen Verwaltungsaufwand für Behörden und Flugzeugbetreiber verbunden. Die Höhe des resultierenden Mitigationsanreizes sowie des entstehenden Mehraufwands ist dabei stark von der Berechnungsmethodik der $CO_2$-Äquivalente abhängig. So gilt es bei der Wahl des $CO_2$-Äquivalentansatzes zwischen einer einfachen Operationalisierbarkeit und einer hohen Anreizwirkung zur Veränderung der Flugroutenführung und zur Reduzierung der $NO_x$-Emissionsindizes abzuwägen und Fehlanreize, die aufgrund der Nichtlinearität zwischen Nicht-$CO_2$-Effekten und Kraftstoffverbrauch entstehen können, zu vermeiden.

## Project Overview

CLIMATE CHANGE 20/2020

Environmental Research of the Federal Ministry
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Project No. (FKZ) 3717 42 509 0

Report No. (UBA-FB) FB000270/ENG

# Part A: Suitable climate metrics for assessing the relation of non-$CO_2$ and $CO_2$ climate effects

Final report

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## Abstract

The final report of work package 1 is separated in five sections: Introduction, Climate impact, Climate metrics, Calculation methods and Alternatives. After the introduction (Section 1) aviation emissions and the impact on climate are presented. The different atmospheric processes and lifetimes of the different emissions are shown in Section 2, as well as the different climate sensitivities and the dependency from emission location. At the end of this section the level of scientific understanding of the different climate agents are presented. The third section is focussing on climate metrics. We provide a definition of climate metrics and show why they are necessary and which requirements should be met by a suitable climate metric. Afterwards, most common climate metrics (emissions, RF, GWP, GTP and ATR) are presented and advantages as well as disadvantages are discussed individually. In addition, it is shown that also the choice of time horizon and emission development play a crucial role for assessing the relation of non-$CO_2$ and $CO_2$ climate effects. According to the previous we recommend the ATR with a time horizon of 100 years as a suitable climate metric for emission trading or CORSIA. The fourth section is dealing with the calculation of $CO_2$ equivalents. Three different calculation methods are presented in detail which are further investigated in the subsequent work packages: First, a simple but potentially misguiding distance dependent factor is introduced. Afterwards a (2) latitude-height-dependent factor and a (3) complex but accurate weather and spatial dependent factor are presented. By taken more atmospheric processes into account, more benefits for climate mitigation can be created. But however, also the amount of necessary data and the effort to calculate the equivalent $CO_2$ emissions increases. In the last section, two alternative concepts are presented which try to create a financial incentive (price-based approach) or a need (regulative approach) for operator of aircraft to reduce non-$CO_2$ effects by charging or closing highly climate-sensitive airspaces.

### Kurzbeschreibung

Der Abschlussbericht zum Arbeitspaket 1 ist in fünf Kapitel aufgeteilt: Einleitung, Klimawirkung des Luftverkehrs, Klimametriken, Berechnungsmethoden und Alternative Ansätze. Im Themenbereich Klimawirkung des Luftverkehrs werden zunächst die verschiedenen Luftverkehrsemissionsarten vorgestellt und aufgezeigt welche atmosphärischen Prozesse mit welchen Lebenszeiten stattfinden. Anschließend wird dargestellt wie sich die Zusammensetzung der Atmosphäre infolge dieser Luftverkehrsemissionen ändert und welchen Beitrag dies zur Strahlungsbilanz der Atmosphäre hat. Außerdem wird in diesem Kapitel auf die Klimasensitivität und regionale Effekte eingegangen und aufgezeigt welche Bereiche der Klimawirkung des Luftverkehrs gut verstanden sind und wo noch Lücken bestehen. Im Themenbereich "Klimametriken" wird zunächst der Begriff „Metrik" genauer definiert und erörtert weshalb eine Metrik zur Bewertung der Klimawirkung notwendig ist und welche Voraussetzungen eine solche erfüllen sollte. Anschließend werden verschiedene gängige Metriken dargestellt und ihre Vor- und Nachteile diskutiert. Zudem wird gezeigt, dass neben der Art der Metrik (z.B. RF, ATR) auch die Wahl des Zeithorizontes und der Verlauf der Emissionen eine wichtige Rolle für die Analyse des Verhältnisses von Nicht-$CO_2$ und $CO_2$ Effekten spielen. Anhand des vorher gezeigten wird empfohlen die Metrik Average Temperature Response mit einem Zeithorizont von 100 Jahren für die Einbindung von nicht-$CO_2$-Effekten in den Emissionshandel oder CORSIA zu verwenden. Im vierten Kapitel werden drei verschiedene Methoden zur Berechnung der Klimawirkung von Einzelflügen dargestellt, die in den

nachfolgenden Arbeitspaketen weiter bearbeitet werden. Einerseits eine sehr einfache, aber unter Umständen fehlleitende Methode bei der die Klimawirkung von nicht-$CO_2$-Effekten über einen einfachen distanzabhängigen Faktor abgeschätzt wird. Andererseits eine genaue aber auch schwer zu berechnende Methode, bei der die Klimawirkung vom Wetter als auch dem Emissionsort (geografische Höhe und Breite) abhängt. Zusätzlich wird eine Art Kompromiss dargestellt, bei dem die Klimawirkung vom Emissionsort abhängt, aber nicht vom aktuellen Wetter. Im letzten Themenbereich werden zwei Alternativen zum Emissionshandel bzw. CORSIA dargestellt, die eine Notwendigkeit (restriktiver Ansatz) bzw. einen finanziellen Anreiz (preisbasierter Ansatz) für Luftverkehrsgesellschaften generieren, ihre Flüge um Regionen mit besonders hoher Klimasensitivität gezielt herumzuführen. Dazu werden in diesen Konzepten Durchflugverbotszonen (sog. „Klimasperrgebiete“) bzw. Durchfluggebührengebiete (sog. „Klimamautgebiete“) eingeführt, wenn die Klimawirksamkeit in einer Region eine bestimmte Höhe übersteigt.

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| | |
|---|---|
| **aCCF** | Algorithmic Climate Change Function |
| **AGTP** | Absolute Global Temperature Potential |
| **AGWP** | Absolute Global Warming Potential |
| **ATR** | Average Temperature Response |
| **CCA** | Climate-Charged Area |
| **CCF** | Climate Change Function |
| **CiC** | Contrail Induced Cloudiness |
| **COC** | Cash Operating Costs |
| **CRA** | Climate-Restricted Area |
| **GTP** | Global Temperature Potential |
| **GWP** | Global Warming Potential |
| **ISSR** | Ice Super-Saturated Region |
| **LOSU** | Level of Scientific Understanding |
| **MBM** | Marked Based Measures |
| **PMO** | Primary Mode Ozone |
| **RF** | Radiative Forcing |

## Summary

The final report of work package 1 of ‘Suitable climate metrics for assessing the relation of non-$CO_2$ und $CO_2$ climate effects’ is separated in five sections: Introduction, Climate impact, Climate metrics, Calculation methods and Alternatives.

After the introduction aviation emissions and the impact on climate are presented. The different atmospheric processes and lifetimes of the different emissions are shown. Large differences exist between various climate species. While carbon dioxide ($CO_2$) and water vapour ($H_2O$) have a direct impact on the radiative balance of the atmosphere, nitrogen oxide ($NO_x$) and aerosol emission indirectly influence the atmosphere by increasing ozone ($O_3$) production and forming particles and contrails. Resulting lifetimes vary widely: while contrails, for example, disperse after few hours, $CO_2$ emissions partly remain in the atmosphere for several thousand years. The lifetime of water vapour depends on the emission altitude and lies between hours at the ground and months in the stratosphere. The emission of $NO_x$ leads to increasing $O_3$ concentrations and decreasing methane ($CH_4$) concentrations. The lifetime of ozone perturbations is in the order of weeks while the methane perturbation has a lifetime of about 12 years. The resulting decline of the methane concentration induces a decrease in ozone concentration with a lifetime equal methane lifetime. The emission of water vapour and particles in wet and cold air leads to formation of contrails and contrail cirrus with lifetimes of minutes to hours. Aerosols have a direct effect on radiation trough absorption and scattering as well as an indirect radiation effect through influencing clouds with a lifetime of days to weeks.

In contrast to the climate impact of water vapour, which increases linearly with the quantity of $H_2O$ emissions (for the same emission location), the impact of $CO_2$, $O_3$, $CH_4$ and CiC show nonlinearities. The saturation effect of $CO_2$ is due to the fact that for higher background $CO_2$ concentration less radiation is apparent to be absorbed by the additional $CO_2$ molecules. For $O_3$, the saturation effect is caused by chemical reaction rates of the $NO_x$-$HO_x$ cycle. Reaction rates increase linear for small $NO_x$ background concentrations, saturate for increasing ones and decrease again, if a certain background concentration has been exceeded. The concentration with maximum ozone production efficiency depends on the background concentration of CO and VOC. The saturation effect of CiC has two main reasons: (1) The available water content is limited and (2) additional clouds above or beyond existing ones have only smaller impact on the radiation balance. In contrast to $CO_2$ and CiC, greater $CH_4$ background concentrations result in stronger effects as the lifetime reduction influence a larger amount of $CH_4$.

Besides $CO_2$ especially $O_3$ and CiC contributes to the aviation radiative forcing in 2005. The RF of $CO_2$ emissions until 2005 is about 28mW/m$^2$ (Lee et al., 2009). The net RF of NOx emissions is about 15mW/m$^2$, as the warming effect of ozone increase (26mW/m$^2$) is partly compensated by the cooling effect of decreasing methane concentration (-12mW/m$^2$) and decreasing longtime ozone concentration (not stated in Lee et al., 2009). The warming effect of CiC was only given as estimate of 30mW/m$^2$ in Lee et al., 2009. Newer studies give values between 30 and 50mW/m$^2$, but for different emission years. The warming effect of $H_2O$ and the direct effect of soot are relatively small with 2.8 and 3.4 mW/m$^2$. The direct effect of sulfur aerosols is negative with -4.8mW/m$^2$. The

indirect aerosol effect on clouds has large uncertainties, but first sensitivity analyses indicate negative RF.

There is a linear relation between RF and global near surface temperature change via the climate sensitivity parameter λ. This climate sensitivity parameter depends on feedback mechanism which differ in-between climate agents. The climate sensitivity of $CO_2$, for example, is smaller than λ of $O_3$ but larger as λ of CiC.

Beside the amount of emissions, the climate impact of an agent is also influenced by other factors, e.g. atmospheric lifetime or background conditions (e.g. temperature, humidity). Some of these factors are strongly dependent on actual weather conditions; some of them are dominated by the emission location. For example, the impact of $H_2O$ strongly increases with increasing altitude as a lack of degradation mechanism in the stratosphere result in clearly longer lifetimes than in the lower troposphere. Due to relatively long $CH_4$ lifetimes, the impact of $CH_4$ is less dependent from the emission location. The formation of contrails and CiC, significantly depend on the surrounding temperature and humidity. Environmental conditions near the tropopause (cold and humid) are particular favorable. At the end of this section the levels of scientific understanding for the different climate agents are presented.

In the third section climate metrics are presented. We show that climate metrics are necessary to compare highly varying impacts of the different emissions. A climate metric is a kind of shortcut from the emission to the impact that is analysed (e.g. temperature change). A suitable climate metric has to fulfil several requirements. Most important, a climate metric has to fit to the question that should be answered. Metrics should also be useful for comparing the climate impact of different species, for assessing mitigation strategies as well as for comparing the impact of different sector. On the one hand, climate metrics should be easily understandable and simply usable, but nevertheless scientific well-grounded on the other hand. Additionally, a climate metric has to provide qualitative the same result for pulse and sustained emissions, as sustained emissions can be seen as a chain of pulse emissions. Afterwards common climate metrics are presented and advantages as well as disadvantages are discussed. The introduced climate metrics are Emissions, Radiative Forcing (RF), Global Warming Potential (GWP), Global Temperature Potential (GTP) and Average Temperature Response (ATR). Besides the kind of the climate metric (e.g. RF, ATR) also the choice of time horizon and emission development plays a crucial role. For pulse emissions, for example, a short time horizon puts more emphasize on short-lived climate agents like $O_3$ or CiC, while a long-time horizon emphasizes the long-lived $CO_2$ effect.

According to the previously mentioned metrics, we recommend ATR with a time horizon of 100 years as a suitable climate metric for emission trading or CORSIA. ATR includes the different climate sensitivities, the different lifetimes and the thermal inertia of the atmosphere. Compared with the more abstract concept of integrated Radiative Forcing, ATR is further down the cause- and effect chain from emissions to the climate impact and might be more easily comprehensible (direct relation to temperature change unlike RF and GWP). Due to the averaging over time, ATR is less dependent on the time horizon than GTP. It also provides qualitatively the same results for pulse and constant emissions. A suitable time horizon for including non-$CO_2$ effects in an emission trading scheme or market-based measure is 100 years; a time horizon known from the Kyoto protocol.

100 years are long enough that long-lived species like $CO_2$ are properly considered, but short enough that people have the feeling that it is a time horizon which is imaginable and relevant for them self. However, ATR is not commonly used and the introduction of a new climate metric may lead to fewer acceptances than using a well-known metric like GWP. Therefore, a comparison of AGWP and ATR as well as a method to convert ATR into AGWP or vice versa is provided within this study, which depends on the climate species, the emission development and the analysed time horizon. Even though GWP and ATR place emphasise on the impact of different climate species due to the different lifetimes and climate sensitivities, the relation of non-$CO_2$ and $CO_2$ effects are very similar. The relation of non-$CO_2$ and $CO_2$ effects is more strongly affected by changes in the emission development than by the choice of the metric.

As it is difficult to trade units of climate metrics, the climate impact of non-$CO_2$ climate species is calculated as $CO_2$ equivalents. $CO_2$ equivalents represents the amount of $CO_2$ which cause the same climate impact than a non-$CO_2$ emission over a specific time horizon and a given emission development. Three different calculation methods for $CO_2$ equivalents for individual flights are presented in Section four, which are further investigated in the subsequent work packages of this project.

A constant $CO_2$ equivalent factor is one of the easiest ways to approximate the climate impact of non-$CO_2$ effects as it requires just a simple multiplication with the $CO_2$ emissions, which are known from the fuel consumption. However, constant $CO_2$ equivalent factors are highly inaccurate since there are strong interdependencies between climate impact and emission location as well as between flight altitude and flight distance. For this reason, it is meaningful to use at least a factor depending on the flight distance, which uses implicit different flight altitudes. The simple distance dependent factor better represents the total individual climate impact but depends implicitly on used emission indices, emission inventories, flight altitude, and weather situation. But nevertheless, using a distance dependent factor for emission trading or MBMs does not provide incentives for airliners to reduce climate impact of non-$CO_2$ effects. As the calculated equivalent $CO_2$ emissions only depends on the $CO_2$ emissions, airlines might even stronger focus on $CO_2$ emission reduction only. Although a reduction in $CO_2$ leads to a reduced climate impact of $CO_2$, a potential increase in non-$CO_2$ effects could overcompensate this benefit. Therefore, simple distance dependent $CO_2$ equivalent factors can just be used for public to see an estimate of the total climate impact of aviation, e.g. for compensation market or personal $CO_2$ footprint. Nevertheless, it is not suitable for a use in emissions trading or MBMs as it cannot produce incentives for airlines to reduce the non-$CO_2$ climate impact.

To gain incentives to reduce the climate impact of non-$CO_2$ effects, at least some altitude and latitude dependencies have to be taken into consideration. The latitude and altitude dependency of the climate impact of non-$CO_2$ can be accounted by using a climate response model. This requires additional information about the emission location (longitude, latitude, altitude) and the amount of emission in each region (Fuel consumption, $NO_x$ emission and flown distances). However, an altitude height dependent climate response model can only be based on climatological mean data and does not include different weather situations explicitly. The non-consideration of current weather conditions might produce false incentives for specific days: if, for example, airlines accept detours to avoid regions in which contrails often occur, although no contrails can form on this special day. In this case, the increase of fuel consumption might cause additional warming. But however, if the same strategic trajectory modification is performed every day, the additional warming of $CO_2$ will be surpassed by the reduction of non-$CO_2$ climate effects on an annual average. Therefore, altitude height dependent $CO_2$ equivalent factors provide right incentives for airliners to reduce the climate impact of non-$CO_2$ effects on an annual mean.

To avoid misguiding incentives on single days, a weather and special dependent $CO_2$ equivalent calculation method is presented as a third option which is both more complex and more accurate. To estimate the climate change contribution due to an individual emission as function of emission location, altitude and time in a specific weather situation, four-dimensional response surfaces are used, which are called climate change functions (CCF). Beside the detailed information about emissions and location also information about the actual weather situation and their development are necessary.

Besides integrating non-$CO_2$ climate effects into emission trading or MBMs, alternative environmental policy options exist that focuses on the location and time dependency of non-$CO_2$ climate effects. To mitigate the climate impact of aviation, these concepts try to create either a financial incentive (price-based approach) or a need (regulative approach) for operator of aircraft to reduce emissions and flight time in highly climate-sensitive airspaces. In analogy to military exclusion zones, one opportunity is to close highly climate sensitive airspaces for a certain period of time (i.e., for several hours or a day) and affected flight trajectories are rerouted cost optimally around them. In this matter, climate mitigation is achieved without integrating complex climate change algorithms into the flight planning software of an airline. Nevertheless, this method could lead to bottlenecks as less airspace is available. A second option is to replace these hard restrictions with a system of incentives. Climate-sensitive regions can also be levied with climate charges for operators of aircraft that fly through these areas. Thus, cost-minimizing airlines are expected to reroute their flights to reduce both climate charges and cash operating costs: climate-friendly operation is getting economically attractive.

## Zusammenfassung

Der Abschlussbericht zum Arbeitspaket 1 des Projektes „Möglichkeiten der Einbindung von Nicht-$CO_2$-Treibhausgas-Effekten im Luftverkehr am Beispiel von EU ETS und CORSIA" ist in 5 Kapitel aufgeteilt: Einleitung, Klimawirkung des Luftverkehrs, Klimametriken, Berechnungs-methoden und Alternative Ansätze.

Im Themenbereich Klimawirkung des Luftverkehrs werden zunächst die Emissionen aufgezeigt und dargestellt welche atmosphärischen Prozesse mit welchen Lebenszeiten stattfinden. Dabei zeigen sich schon die ersten großen Unterschiede der einzelnen Emissionen. Während $CO_2$ und $H_2O$ einen direkten Einfluss auf die Strahlung haben, führen die Emissionen von $NO_x$ und Aerosolen nur indirekt durch die Bildung von $O_3$, $CH_4$, Partikeln und Kondensstreifen-Zirren (Contrail induced cloudiness, CiC) zu einer Beeinflussung des Strahlungshaushaltes. Große Unterschiede zeigen sich auch bei den Lebenszeiten. $CO_2$ hat eine sehr lange Lebenszeit, wobei die Angabe einer einzigen Zahl durch unterschiedliche Abbauprozesse erschwert ist. Während etwa die Hälfte des $CO_2$ innerhalb von 20 Jahren abgebaut wird, verbleiben etwa 20% mehrere Jahrtausende in der Atmosphäre. Die Lebenszeit von $H_2O$ liegt je nach Emissionsort im Bereich von Stunden bis Wochen. Die Emission von $NO_x$ führt zunächst zu einer Erhöhung der Ozon-konzentration und einem Abbau der Methankonzentration. Die Lebenszeit von $O_3$ liegt im Bereich von Wochen, während CH4 eine Lebenszeit von etwa 12 Jahren hat. Die Verringerung der $CH_4$ Konzentration führt wiederum zu einer Verringerung der Ozonproduktion mit einer Lebenszeit entsprechend der von $CH_4$. Die Emission von Partikeln und $H_2O$ führt in kalter und feuchter Luft zur Bildung von Kondensstreifen und Kondensstreifen-Zirren mit einer Lebenszeit von Minuten bis zu mehreren Stunden. Aerosole haben sowohl einen direkten Strahlungseffekt durch Streuung und Reflexion als auch einen indirekten Einfluss auf Wolken und eine Lebenszeit von Tagen bis Wochen.

Während für $H_2O$ die Wirkung mit steigenden Emissionen proportional ansteigt, zeigen $CO_2$, $O_3$, CiC und $CH_4$ nicht lineare Änderungen. Bei $CO_2$ entsteht ein Sättigungseffekt dadurch, dass bei höherer $CO_2$ Konzentration weniger Strahlung ankommt, die zusätzlich absorbiert werden kann. Bei $O_3$ hingegen sind die Sättigungseffekte auf die chemische Reaktionsfreudigkeit zurück zu führen. Bei geringer Hintergrundkonzentration steigt die Ozonproduktionsrate zunächst linear an, wird dann geringer und sinkt ab einer gewissen Hintergrundkonzentration schließlich wieder ab. Die Konzentration mit der höchsten Ozonproduktion hängt von der Hintergrund-konzentration von CO und VOC ab. CiC zeigt ebenfalls einen Sättigungseffekt. Dies liegt daran, dass in Regionen in denen bereits viel Luftverkehr stattfindet, bei geeigneten atmosphärischen Bedingungen bereits Wolken gebildet haben und zusätzlicher Luftverkehr keine Wolken mehr bilden kann oder die Wirkung geringer ist, weil dich darüber oder darunter bereits Wolken befinden. Im Gegensatz zu $CO_2$ und CiC führt bei $CH_4$ eine höhere Hintergrundkonzentration zu einer größeren Wirkung von $CH_4$. Dies liegt daran, dass sich die Lebenszeitänderung durch OH auf eine größere Gesamtmenge $CH_4$ auswirkt.

Neben $CO_2$ tragen vor allem $O_3$ und CiC zum Strahlungsantrieb der Luftverkehrsemissionen bis 2005 bei. Der Strahlungsantrieb für $CO_2$ wird mit etwa $28 mW/m^2$ angegeben. Die Emission von $NO_x$ führt insgesamt zu einem positiven RF von etwa 15 $mW/m^2$, wobei der positive Beitrag von $O_3$ (26 $mW/m^2$) teilweise von dem negativen Beitrag der $CH_4$ Reduktion ($-12mW/m^2$) und langlebigen $O_3$ -Abbau kompensiert wird. Die wärmende Wirkung von CiC wurde in Lee et al. (2009) nur als

Schätzung mit etwa 30 mW/m² abgegeben. Neuere Studien zeigen Werte zwischen 30 und 50 mW/m², allerdings für unterschiedliche Emissionsjahre. Die wärmende Wirkung von $H_2O$ und der direkte Ruß-Effekt sind mit 2.8 bzw. 3.4 mW/m² nur gering. Der direkte Effekt von Sulfat-Aerosolen wirkt kühlend mit etwa -4.8 mW/m². Die Wirkung des indirekten Aerosoleffekt ist noch sehr unsicher. Erste Sensitivitätsstudien deuten auf einen kühlenden Effekt hin.

Der Strahlungsantrieb ist durch den Klimasensitivitätsparameter λ linear mit der Änderung der globalen bodennahen Temperatur verknüpft. Der Klimasensitivitätsparameter λ hängt aller-dings von verschiedenen Rückkopplungsmechanismen ab und unterscheidet sich dadurch für verschiedene Emissionsarten. So ist λ zum Beispiel für $O_3$ höher als der von $CO_2$ und für CiC geringer.

Neben der Emissionsstärke der einzelnen Klimaspezies hängt deren Wirkung auch von einigen anderen Faktoren ab, wie zum Beispiel atmosphärische Lebenszeit oder Hintergrundbedingungen (z.B. Temperatur, Feuchte, Hintergrundkonzentration und Sonnenstand). Während einige dieser Einflussfaktoren stark vom aktuellen Wetter beeinflusst werden, hängen andere hauptsächlich vom Emissionsort ab. So nimmt die Wirkung der $H_2O$ Emission stark mit der Höhe zu, da die Lebenszeit in der Stratosphäre deutlich größer ist als in der Troposphäre. Auch steigt die Wirkung von $O_3$ stark mit zunehmender Höhe. Die Wirkung von $CH_4$ zeigt durch die längere Lebenszeit eine geringe Abhängigkeit vom Emissionsort. Die Wirkung von Kondensstreifen und Kondensstreifen-Zirren hängt wesentlich von der umgebenden Feuchte und Temperatur ab und ist besonders im Bereich der Tropopause groß. Neben der unterschiedlichen Wirkung aufgrund des Emissionsorts, hängt die Wirkung auch vom aktuellen Wetter und der Tageszeit der Emission ab.

Kapitel 3 beschäftigt sich mit Klimametriken. Dabei wird zunächst aufgezeigt, dass eine Klima-metrik nötig ist um die sehr unterschiedlichen Wirkungen zu vergleichen. Eine Klimametrik stellt dabei den direkten Zusammenhang zwischen Emission und der zu untersuchenden Wirkung da (z.B. Temperaturänderung). Je weiter man in der Ursache-Wirkung-Kette von den Emissionen zu den Schäden geht, desto relevanter wird die Metrik, aber auch umso unsicherer. Eine geeignete Klimametrik muss eine Reihe von Voraussetzungen erfüllen. Die wichtigste Voraussetzung ist dabei, dass die Metrik zur Fragestellung passt. Je genauer eine Frage formuliert wird, desto weniger Metriken kommen in Frage. Zudem sollte eine Metrik vielseitig einsetzbar sein, wissenschaftlich fundiert und dennoch einfach zu verwenden. Eine weitere wichtige Eigenschaft ist, dass eine Metrik für Pulsemission und Emissionen über einen längeren Zeitraum das gleiche Szenario als klimafreundlich bewerten soll, da eine anhaltende Emission nur eine Summe von Pulsemissionen ist.

Anschließend werden verschiedene gängige Metriken dargestellt und ihre Vor- und Nachteile aufgezeigt. Zu den vorgestellten Metriken gehören Emissionen, Radiative Forcing (RF), Global Warming Potential (GWP), Global Temperature Potential (GTP) und Average Temperature Response (ATR). Neben der Art der Metrik (z.B. RF, ATR) spielen auch die Wahl des Zeithorizontes und der Verlauf der Emissionen eine wichtige Rolle. Wird zum Beispiel bei Pulsemissionen ein kurzer Zeithorizont gewählt liegt die Wichtung mehr auf kurzlebigen Spezies, während bei langen Zeithorizonten die Wichtung hauptsächlich bei dem langlebigen Effekt der $CO_2$-Emissionen liegt.

Anhand des vorher gezeigten wird für die Einbeziehung von Nicht-$CO_2$-Effekten in den Emissionshandel oder Market-Based-Measures das Average Temperature Response mit einem Zeithorizont von 100 Jahren empfohlen. ATR berücksichtigt neben den unterschiedlichen Lebenszeiten auch die unterschiedlichen Klimasensitivitäten und die Trägheit des Klimasystems. ATR ist im Vergleich zum viel verwendeten GWP in der Ursache-Wirkungskette weiter unten und leichter verständlich als das GWP, das einem integrierten RF entspricht und keinen direkten Bezug zur Temperaturänderung hat. Zudem ist das ATR weniger stark vom Zeithorizont abhängig und Pulse und anhaltende Emissionen liefern ein qualitativ gleiches Ergebnis. Dennoch ist ATR nicht weit verbreitet und die Einführung einer neuen Metrik könnte zu einer geringeren Akzeptanz der Maßnahme führen als bei Verwendung des weit verbreiteten GWP. Aus diesem Grund zeigen wir einen Vergleich der beiden Metriken und eine Methode zur Umrechnung der beiden Metriken ineinander. Dabei zeigt sich, dass das Verhältnis von $CO_2$ zu Nicht-$CO_2$-Wirkung stärker von der Wahl des Emissionsszenarios abhängt, als von der Wahl der Metrik. Eine Umrechnung von GWP zu ATR ist möglich, es muss aber beachtet werden, dass der Umrechnungsfaktor für jede Spezies unterschiedlich ist und dass diese Umrechnungsfaktoren von der Wahl des Emissionsverlaufs und des Zeithorizontes abhängt.

Im dritten Themenschwerpunkt werden drei verschiedene Methoden zur Berechnung der Klimawirkung von Einzelflügen dargestellt, die in den nachfolgenden Arbeitspaketen weiter bearbeitet werden. Da Einheiten von Klimawirkung schlecht gehandelt werden können, wird die Klimawirkung oft in $CO_2$-Äquivalente umgerechnet. Ein $CO_2$-Äquivalent repräsentiert die Klimawirkung die ein kg $CO_2$ über den gegebenen Zeitraum hätte.

Eine sehr einfache, aber unter Umständen fehlleitende Methode ist, die Klimawirkung über einen einfachen distanzabhängigen Faktor zu berechnen. Da Flüge mit geringerer Distanz in geringeren Höhen fliegen und die Klimawirkung stark von der Höhe in der emittiert wird abhängt, zeigt die Klimawirkung eine starke Abhängigkeit von der Flugdistanz. Dieser einfache distanzabhängige Faktor zeigt eine deutlich bessere Repräsentation der tatsächlichen Klimawirkung, hängt aber implizit von den Emissionsindizes, des gewählten Flottennetz, der Flughöhe und des Wetters ab. Da ein Luftfahrzeugbetreiber nur über die Reduzierung der $CO_2$-Emission einen Einfluss auf die berechneten $CO_2$-Equivalente hat, wird er versuchen diese zu reduzieren. Da eine reduzierte $CO_2$-Wirkung durch höhere Nicht-$CO_2$-Effekte überkompensiert werden kann, könnte dies zu einer Vergrößerung des Klimaeinflusses führen. Es besteht für den Luftfahrzeugbetreiber kein Anreiz die Klimawirkung durch Reduzierung der $NO_x$-Emissionsindizes oder geänderte Routenführung zu reduzieren. Solch ein distanzabhängiger Faktor könnte aber für die Öffentlichkeit verwendet werden, um eine Abschätzung der gesamten Klimawirkung einzelner Flüge zu bieten.

Eine andere Möglichkeit die Klimawirkung des Luftverkehrs zu berechnen, ist ein klimatologischer Breiten-Höhenabhängiger Faktor. Dabei wird die Klimawirkung in Abhängigkeit vom Emissionsort und aktuellen Emissionen mit Hilfe eines Response-Modells berechnet. Dadurch entsteht für Luftfahrzeugbetreiber eine Möglichkeit und ein Anreiz die tatsächliche Klimawirkung zu reduzieren, da sich sowohl geringe $NO_x$-Emissionen als auch geänderte Flughöhen auf die Berechnung der $CO_2$-Equivalente auswirken. Diese Berechnungsmethode ist verhältnismäßig einfach, benötigt aber im Vergleich zum einfachen distanzabhängigen Faktor genaue Informationen über Emissionsort und –menge. Da allerdings die einzelnen Wetter-situationen nicht explizit berücksichtigt werden, sondern klimatologische Mittelwerte betrachtet werden, kann dies dazu führen, dass an einzelnen Tagen falsche Anreize gesetzt werden, wenn zum Beispiel Umwege in Kauf genommen werden um CiC zu reduzieren, obwohl an diesem Tag keine CiC zu erwarten wären. Der dabei steigende Kraftstoffverbrauch führt stattdessen zu einer zusätzlichen Erwärmung. Wird jedoch die Flugroutenmodifikation an jedem Tag des Jahres durchgeführt, wird die zusätzliche $CO_2$-Erwärmung im Jahresdurchschnitt durch die Reduzierung von nicht $CO_2$-bedingten Klimaeffekten übertroffen.

Um auch diese möglichen falschen Anreize zu vermeiden, wird eine dritte Methode vorgestellt, bei der die Klimawirkung in Abhängigkeit vom Emissionsort und aktueller Wettersituation berechnet wird. Die Berechnung der Klimawirkung erfolgt über die Verwendung von sogenannten Klimaänderungsfunktionen, die die Klimawirkung einer normieren Emission an einem bestimmten Ort und in einer bestimmten Wetterlage berechnen. Dazu sind neben detaillierten Informationen über den Emissionsort und Emissionsmenge auch genaue Informationen über die aktuelle Wettersituation und deren Entwicklung nötig.

Im letzten Themenbereich werden zwei Alternativen zum Emissionshandel oder MBMs dargestellt. Eine Möglichkeit die Klimawirkung des Luftverkehrs ohne MBM oder Emissions-handel zu reduzieren ist, Gebiete in denen die Klimawirkung einen gewissen Schwellenwert übersteigt zu sperren (regulativer Ansatz). Airlines müssen diese Gebiete dann umfliegen und reduzieren dadurch die Klimawirkung. Vorteil dieses Konzeptes ist, dass der Aufwand relativ gering bleibt und die Maßnahme sofort eingeführt werden kann, da das Umfliegen von gesperrtem Luftraum bereits jetzt in den Flugplanungstools enthalten ist und keine komplexen Klimawirkungsalgorithmen integriert werden müssen. Ein Nachteil dieses Konzept ist, dass der Luftraum dadurch stark begrenzt wird und es zu Engpässen kommen könnte. Anstelle von Sperrungen von klimasensitiven Gebieten kann auch eine Gebühr für das Durchfliegen dieser Gebiete erhoben werden (preisbasierter Ansatz). Ein Luftfahrzeugbetreiber hat dann die Wahl das Gebiet zu Umfliegen um Abgaben zu sparen oder die Abgaben in Kauf zu nehmen um die schnellste Route zu fliegen. Der in der Luftfahrt bestehende Zielkonflikt zwischen Ökologie und Ökonomie wird aufgelöst: klimafreundliches Fliegen wird wirtschaftlich.

# 1 Introduction

The increasing demand of mobility in a globalized world means a social challenge to an environmental compatible air transportation system. Global aviation increased between 2000 and 2013 by 61% in terms of revenue passenger kilometres and is expected to grow significantly in the next decades (e.g., ICAO, 2013a). Although technical improvements increased the fuel efficiency in the past and are expected to increase by 1-2% per year in the next decades, the increasing demand will lead to increasing emissions in the next decades.

While international aviation's carbon dioxide emissions have been regulated in several countries in the recent years, this is not the case for most of aviation's non-$CO_2$ climate effects (Scheelhaase et al., 2016), although they contribute to about two-thirds of the total aviation-induced global warming. As some effects only occur in higher altitudes (e.g. contrails), the non-$CO_2$ effects are especially important for aviation emissions. Reducing the climate impact of non-$CO_2$ effects often come along with an increase of cash operating costs. As operators of aircraft have little incentives to bear these additional costs voluntarily, incentives for reducing climate impact of non-$CO_2$ effects are necessary. Therefore, including also non-$CO_2$ effects in emission trading schemes or marked based measures (MBM) could be a significant contribution to the agreed climate goals of Paris.

Climate impact depends beside the emission strength also on emission location and time of emission. Including only $CO_2$ effects could lead to false incentives as $CO_2$ reduction might lead to increasing non-$CO_2$ effects: increasing flight altitude leads to reduced fuel consumption due to reduced friction, but increases the climate impact of $O_3$, $H_2O$ and probably contrails and contrail induced cloudiness (CiC). Therefore, increasing flight altitude may lead to increasing climate impact, despite reduced $CO_2$ emissions (Frömming et al., 2012).

The crucial question is how to create a monetary incentive for airlines to minimize their climate footprint and which climate metric could be used therefore. However, this question cannot be answered without quantifying and assessing the relation of non-$CO_2$ and $CO_2$ climate effects. Therefore, we first present the climate impact of $CO_2$ and non-$CO_2$ effects from aviation's emission and how they depend on emission location and time. In Section 3 we give an overview of different climate metrics which can be used to compare the very different climate effects in a meaningful way. Therefore, we list some requirements a climate metric should fulfil and show how the climate metrics depend on time horizon and the chosen emission scenario. According to this information we identify a suitable climate metric for an emission trading system or MBMs. To calculate the climate impact of aircraft emissions we present different methods to calculate equivalent $CO_2$ emissions, from simple factors to complex calculation methods. In the last section we present two alternative concepts, which could allow generating incentives to reduce the total aviation climate impact without including aviation to emissions trading or MBMs.

# 2 Climate impact of $CO_2$ and non-$CO_2$ effects from aviation

## 2.1 Emissions

Combustion of hydrocarbon containing jet-fuel is an oxidation process consuming oxygen from the air and producing $CO_2$ and $H_2O$. With the combustion of 1 kg of jet-fuel 3.16 kg of carbon dioxide ($CO_2$) and 1.26 kg of water vapour ($H_2O$) are emitted. Additionally, about 10-14 g of nitrogen oxides[2] ($NO_x$=NO+$NO_2$) per kilogram of jet fuel are emitted through oxidation of atmospheric nitrogen and oxygen. The emission of $NO_x$ depends on engine temperature and pressure (e. g. Ruijgrok and Van Paassen, 2006). Dependent on the amount of sulphur in the jet-fuel, the combustion of 1kg fuel leads to an emission of about 1 g sulphur dioxide ($SO_2$). The imperfect combustion leads to the additional emission of about 1-10 g carbon monoxide (CO) and less than 1g hydrocarbons and soot.

Revenue passenger kilometre increases by about 5% per year and is expected to grow further over the next decades. Although the fuel efficiency increased by 70% over the last 40 years (IATA, 2017), the increasing demand overcompensates this effect and the share of aviation in global $CO_2$ emissions can rise to 22% in 2050 (Cames et al., 2015).

## 2.2 Atmospheric processes and lifetime

### 2.2.1 Carbon Dioxide ($CO_2$)

Emitted $CO_2$ shows only a low chemical reactivity and therefore a long perturbation lifetime. Natural sinks of CO2 are uptake in natural reservoirs, including ocean, terrestrial biosphere, rocks and fossil fuels. About 18% of the emitted $CO_2$ is bonded to natural sinks and removed from the atmosphere after around 1 year, while additional 34% is bonded after about 20 years (IPCC, 2007). Additional 26% are removed over the next 170 years, while about 22% remain for several 1000 years in the atmosphere. Due to its very long lifetime CO2 disperse homogenous in the atmosphere. Its impact on climate is therefore almost independent from emission location (IPCC, 1999).

### 2.2.2 Water Vapour ($H_2O$)

$H_2O$ is the most important greenhouse gas in the atmosphere and contributes to about two third of the natural greenhouse effect. Nevertheless, the impact of aviation $H_2O$ in the troposphere is small as the lifetime is very short due to the hydrological cycle. Emitted water vapour condensates in clouds and is removed from the atmosphere through rainfall. The lifetime of $H_2O$ depends on emission location and is between some hours at the surface, some weeks in the troposphere and up to some month in the stratosphere (Grewe and Stenke, 2008). Therefore, the impact of supersonic aviation, which takes place in the stratosphere, has a significant climate impact.

[2] Emissions of nitrogen oxides are given in g of $NO_2$ including a conversion of NO to $NO_2$ to avoid ambiguities in the share between NO and $NO_2$.

### 2.2.3 Nitrogen Oxide ($NO_x$)

The atmospheric residence time of $NO_x$ is very small and its impact on radiation is insignificant. Therefore, the direct climate impact of $NO_x$ can be neglected. However, $NO_x$ is very reactive and influences climate through increasing ozone ($O_3$) production and decreasing methane ($CH_4$) production.

$NO_x$ emissions in the upper troposphere and lower stratosphere shift the $HO_x$ (=OH+$HO_2$) balance from $HO_2$ to OH, which increases the oxidation of CO and $CH_4$ and the catalytic ozone production via NO via

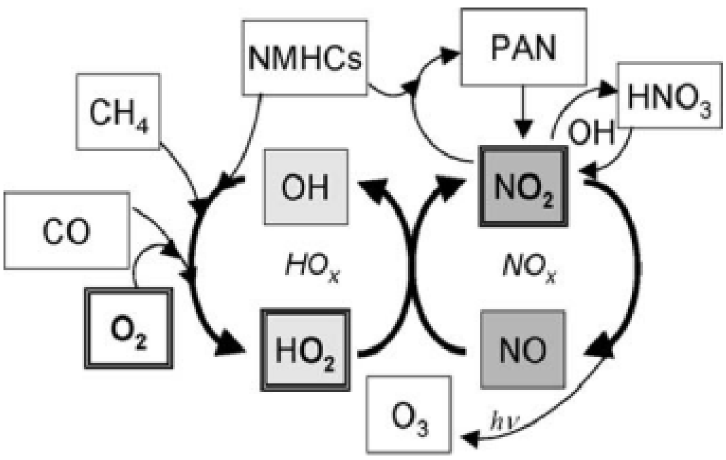
$$CO + 2O_2 + h\nu \overset{NO}{\rightarrow} CO_2 + O_3 \qquad (1)$$

$$CH_4 + 4O_2 + h\nu \overset{NO}{\rightarrow} CH_2O + H_2O + 2O_3 \qquad (2)$$

(e.g. Fishman und Crutzen, 1978; Grooß et al., 1998; see also Figure 1). This increases the short-lived ozone production and reduces the $CH_4$ lifetime. The reduced $CH_4$ concentration leads to a shift of $HO_x$ balance towards $HO_2$, which reduces the ozone production coupled with the $CH_4$ lifetime. This effect is called primary mode ozone (PMO) or long-lived ozone.

The lifetime of the ozone perturbation is in the order of weeks, while the lifetime of a $CH_4$ and PMO perturbation is about 12 years. Therefore, the climate impact of $O_3$ is more dependent of the emission location than the impact of $CH_4$.

**Figure 1: Schema of $NO_x$ photochemistry**

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### 2.2.4 Contrails and Contrail Cirrus

Under special atmospheric condition contrails can form when the hot and humid exhaust from aircraft engines mixes with the cold and dry ambient air. This mixing increases the relative humidity and water droplets are formed, if 100% relative humidity is reached. The droplets freeze if the temperature is cold enough (< -38°C) and the contrail persists if the ambient air is ice-supersaturated. Whether droplets form depends on the Schmidt-Appleman criterion, which defines a threshold temperature $T_c$ and droplets form whenever the ambient temperature is lower than this threshold temperature $T_c$. $T_c$ depends on the ambient pressure, temperature and humidity as well as on aircraft and fuel parameters (Schumann, 1996). For aircraft with modern engines and higher overall efficiency, $T_c$ is higher, that means that contrails can form over a larger range of cruise altitudes (Schumann, 2000).

If the ambient air is ice supersaturated contrails can persist over a longer time period otherwise they disappear within minutes. Long persisting contrails might change shape due to wind shear until they can no longer be visually distinguished from natural clouds. Accordingly, they are called contrail cirrus or contrail induced cloudiness (CiC).

The lifetime of contrails and contrail cirrus is between minutes for non-persisting contrails up to several hours for long persisting contrail cirrus.

### 2.2.5 Aerosols

Aerosols (e.g., soot particles) and aerosol precursor (e.g. sulphur dioxide) have the potential to serve as condensation nuclei. If more ice condensation nuclii exist more, but smaller cloud droplets are formed. This increases the cloud albedo as well as the lifetime of clouds. However, it is currently unclear whether aircraft emitted soot is a good ice nuclei and whether it influences cirrus clouds. The lifetime of atmospheric aerosol is in the order of one day to two weeks in the troposphere, and about one year in the stratosphere (IPCC, 2013).

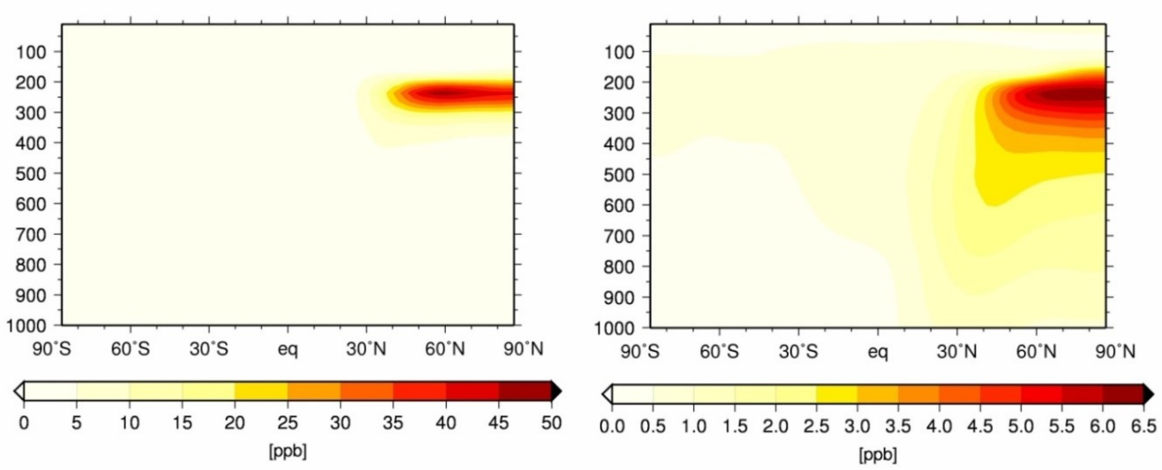
## 2.3 Composition changes

### 2.3.1 Composition

The spatial distribution of aviation's emissions within the atmosphere is crucially influenced by their atmospheric lifetimes. Due to the long lifetime of $CO_2$ it is homogenous distributed in the atmosphere. The global concentration of $CO_2$ has increased from about 280 $ppm_v$ in the preindustrial time to about 400 $ppm_v$ in 2016. The global aviation contributes to about 1.6% to this concentration change. The long lifetime of $CH_4$ leads to an almost homogenously distribution. The 2006 global aviation emissions (REACT4C emission inventory, Owen et al., 2011, Søvde et al., 2014) lead to a mean global $CH_4$ concentration reduction of 20 ppbv (calculated with AirClim by Dahlmann et al., 2016b).

In contrast to $CO_2$ and $CH_4$, the lifetime of $H_2O$ and $O_3$ is only in the order of weeks. Therefore, the concentration change is not homogenous distributed in the atmosphere. In Figure 2 the concentration change due to global aviation emissions in 2006 is presented for $O_3$ and $H_2O$, respectively. As the global air traffic has its maximum in the northern mid-latitudes in altitudes of about 10 km (about 250hPa) the largest concentration change took place there.

**Figure 2: Change in $H_2O$ (left) and $O_3$ (right) concentration due to global aviation emissions in the year 2006 (REACT4C emission inventory) analysed with AirClim.**

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Over central Europe the contrail coverage can be up to 10%, while it is only up to 6% in the US (Burkhardt and Kärcher, 2011). This is due to the fact that many contrails are advected from the North Altantic to Europe. In global average contrail cirrus coverage is about 0.61% (Burkhardt and Kärcher, 2011).

Aircraft emissions cause significant increases of the $SO_4$ and soot burden and number concentrations in the upper troposphere (Righi et al., 2013). Soot and $SO_4$ contributes to about 3-5% in main cruise altitudes (Righi et al., 2013).

### 2.3.2 Saturation effects

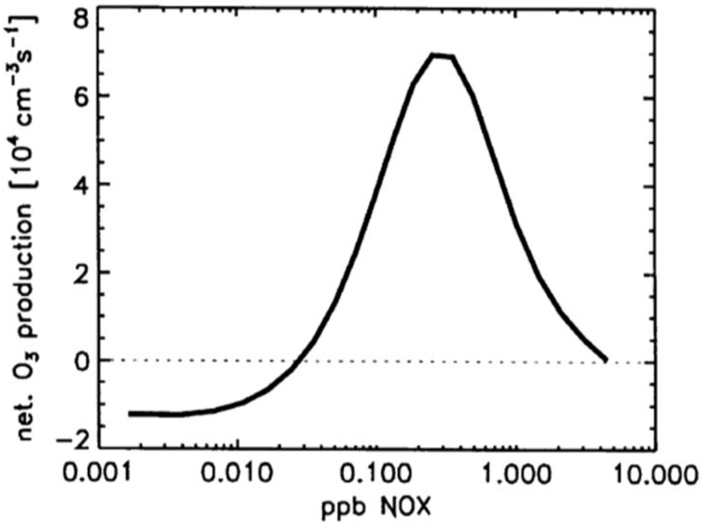
In a first order increasing emissions lead to increasing climate impact, but for some climate species, like, e.g., $CO_2$, $CH_4$, $O_3$ and CiC, saturation effects occur. For $CO_2$, for example, the impact of a concentration change is lower the larger the background concentration is. The reason therefore is that if more $CO_2$ is in the atmosphere the probability decreases that the radiation hits an additional $CO_2$ molecule. This is the same for $CH_4$. Nevertheless, the impact of a $CH_4$ concentration change increases with increasing background concentration as the decreasing lifetime change effect a larger amount of $CH_4$.

$O_3$ strongly depends on the background concentration of $NO_x$, but also CO and $HO_x$. For very low background $NO_x$ ozone is reduced via $O_3+HO_2 \rightarrow OH + 2O_2$. Increasing background concentrations lead to increasing ozone production (e.g. Jaegle et al., 1998; Grooß et al., 1998; Figure 3). Very large background concentrations lead to $HO_x$ losses and decreases ozone production (Grooß et al., 1998; Lin et al., 1988). The shape of the ozone production curve also depends on the background concentration of CO and $HO_x$. Air traffic occurs in regions in which the system is quite linear. Dahlmann et al. (2011) showed that this saturation effect decreased the ozone production efficiency from 1990 to 2010 by less than 3%. In addition to the chemical saturation effect, $O_3$

shows a saturation of longwave spectral range similar to $CO_2$ and $CH_4$. Dahlmann et al. (2011) showed that this effect is about 1% for $O_3$.

Saturation effects also exist for CiC. In region were already CiC exist additional air traffic has a lower impact. One reason therefore is the limited water content. If already cloud exists there is not enough humidity for additional contrails. Additionally, the coverage does not increase if already contrails exist in different altitudes. In regions with dense air traffic this saturation effect already takes place. A doubling of air traffic results only in a 1.6-time larger impact of CiC.

**Figure 3: Net $O_3$-production rate as a function of $NO_x$ mixing ratio**

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## 2.4 Radiative Forcing

Radiative forcing is defined as the net change in the energy balance of the Earth system that is caused by any perturbation (e.g. concentration change) and is expressed in watts per square meter (see Section 1.3.2). A positive RF is associated with a warming while a negative RF is associated with a cooling of the earth's surface.

Aviation induced concentration changes of trace gases and clouds are influencing the radiation budget by absorbing and reflecting the solar radiation or outgoing longwave radiation.

$CO_2$ is a greenhouse gas, which absorbs mainly in long wave range and leads to a warming. Figure 4 presents RF of aviation's emission up to 2005 of several climate agents analysed by Lee et al. (2009) together with newer findings. Aviation's $CO_2$ emission up to 2005 leads to a $RF_{CO2}$ of 28 $mW/m^2$.

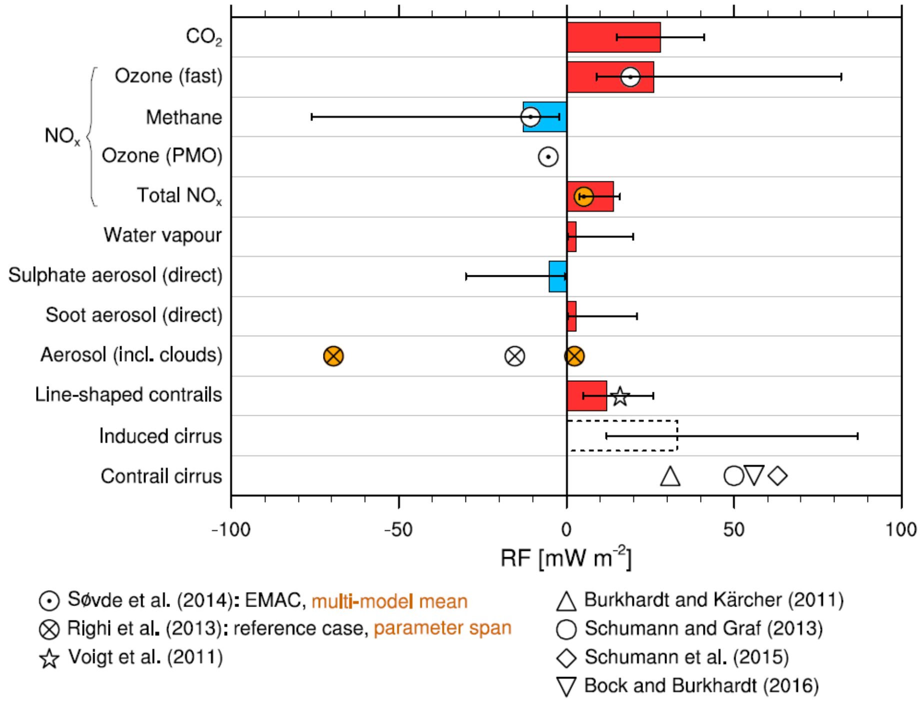
Aviation's $NO_x$ emissions result in an increasing ozone concentration and a decreasing methane concentration. $CH_4$ is – similar to $CO_2$ – a greenhouse gas which absorbs longwave radiation. As a declining atmospheric $CH_4$ concentration leads to a negative Radiative Forcing, aviation induced a $CH_4$ cooling of approximately -12$mW/m^2$ in 2005. As $O_3$ absorbs both long- and short-wave radiation, ozone has a cooling as well as a warming effect. In total the warming effect dominates (especially in the Troposphere), which leads to positive $RF_{O3}$ of 26mW/m$^2$ in 2005. In contrast, the long-lived ozone decrease associated with decreasing methane concentration shows a negative RF. No approximation of this effect was given in Lee et al. (2009); Søvde et al. (2014) calculated a value of -3.4mW/m$^2$ for a multi-model mean for emissions in 2006.

The climate impact of $H_2O$ emissions (without contrail formation) is increasing strongly with altitude. $H_2O$ emissions released in the troposphere trigger a comparatively small $RF_{H2O}$ (2.8mW/m$^2$). However, if the emission takes place in higher altitudes, which is the case, e.g., for supersonic aviation, $H_2O$ emissions can have a significant impact on climate.

The RF of aerosols is differing strongly for various climate agents. While sulphate aerosols reflect short wave radiation and cause a cooling of about -4.8 mW/m$^2$, soot absorbs shortwave radiation and leads to warming of 3.4 mW/m$^2$. While these direct effects (absorption and reflection of solar radiation) can be assessed with uncertainties, the indirect aerosol effect is very uncertain that even the sign is still discussed. Lee et al. (2009) did not assess a value for indirect aerosol effects, but newer results from Righi et al. (2013) show a wide range of results, dependent of parameter range.

Contrails and CiC have cooling effects (due to the reflection of solar radiation) and warming effects (due to the absorption of longwave radiation). The question of which effect is predominant, is affected by the optical thickness in the short wave (scattering of sunlight), the water content (infrared absorption), the ice particle number (small ice particles: low water vapour, but large optical thickness at shortwave), the solar zenith angle (time of day) and the surface albedo. In the annual global mean the warming effect dominates and leads to a RF of about 55 mW/m$^2$ (Lee et al., 2009). Newer results from Burkhardt and Kärcher (2011), Schumann and Graf (2013), Schumann et al. (2015) and Bock and Burkhardt (2016) provides results between 30 and 63 mW/m$^2$.

**Figure 4: Aviation-induced RF from different components (bars and uncertainty ranges as reported by Lee et al. (2009) and new findings with symbols).**

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## 2.5 Climate sensitivity

As a result of the perturbation of the atmosphere's radiative balance by aviation emission, the atmosphere tries to reach new radiation equilibrium by changing the surface temperature. The surface temperature is a driver for atmospheric circulation and responsible for the melting of ice on the polar caps and therefore a good indicator for climate change.

To what extend the atmosphere reacts on a change in RF is given by the climate sensitivity parameter λ in K/(Wm$^{-2}$): $\Delta T = \lambda \cdot RF$. This relation resulted from early model results, which had shown that the Radiative Forcing caused by a given concentration change is approximately related to the steady-state global mean near-surface temperature change ΔT. Hence it relates a change in radiation at a given time to the resulting long-term change in global mean surface temperature assuming that everything else remains constant. It was assumed that the climate sensitivity parameter λ is constant, but newer results showed that λ is only constant for homogenous distributed emissions like $CO_2$. For inhomogeneous emissions the climate sensitivity parameter varies between different climate species (Hansen et al., 1997, 2005; Joshi et al., 2003). Therefore, an equal RF of different climate species results in diverse temperature changes.

Therefore, the simple linear relation $\Delta T = \lambda \cdot RF$ between Radiative Forcing (RF) and global mean surface temperature response (ΔT) is not fulfilled. This hampers the general applicability of the RF concept. To retain its applicability, Hansen et al. (2005) proposed to attribute a specific efficacy parameter for each non-$CO_2$ Radiative Forcing. The efficacy $r_{eff}$ is defined by

$$\Delta T = \lambda_{CO_2} \cdot r_{eff} \cdot RF, \quad (3)$$

with $r_{\text{eff}} = \frac{\lambda}{\lambda_{CO_2}}$. The "standard climate sensitivity" of $CO_2$ is obtained by choosing a $CO_2$-driven simulation as the reference simulation. Current estimations of the climate sensitivity parameter λ and the efficacy for different climate species are shown in Table 1. These climate sensitivity parameters crucially depend on a number of feedbacks, such as the atmospheric temperature, surface albedo, water vapour and cloud feedback (Rieger et al., 2017).

**Table 1: Climate sensitivity λ and efficacy for the different climate species**

| Climate Agent | $CO_2$ | $H_2O$ | $O_3$ | $CH_4$ |
|---|---|---|---|---|
| λ [K/(Wm$^{-2}$)] | 0.73 | 0.83 | 1.00 | 0.86 |
| $r_{eff}$ | 1.00 | 1.14 | 1.37 | 1.18 |

© Ponater et al., 2006

## 2.6 Regional emission effects

Besides the strength of the emission, the climate impact of a species also depends on other factors, like its atmospheric lifetime (or precursor) or the background conditions (e.g. temperature, humidity, composition and solar zenith angle). Some of these conditions strongly depend on the actual weather situation (e.g. cloud coverage, low/high pressure systems), but some only depend on the emission location (e.g. the surface albedo, altitude). Radiative forcing from a uniform emission, e.g., depends on temperature difference between ground and emission layer (Lacis et al., 1990). Increasing altitude therefore increases the climate impact. In the following we present first the difference in climate impact in dependency of the emission location on a climatological base (Section 2.6.1). That means the climate impact is analysed by several model years, which represents a number of different weather situations. Weather dependent emission effects are introduced in Section 2.6.2.

### 2.6.1 Climatological emission effects

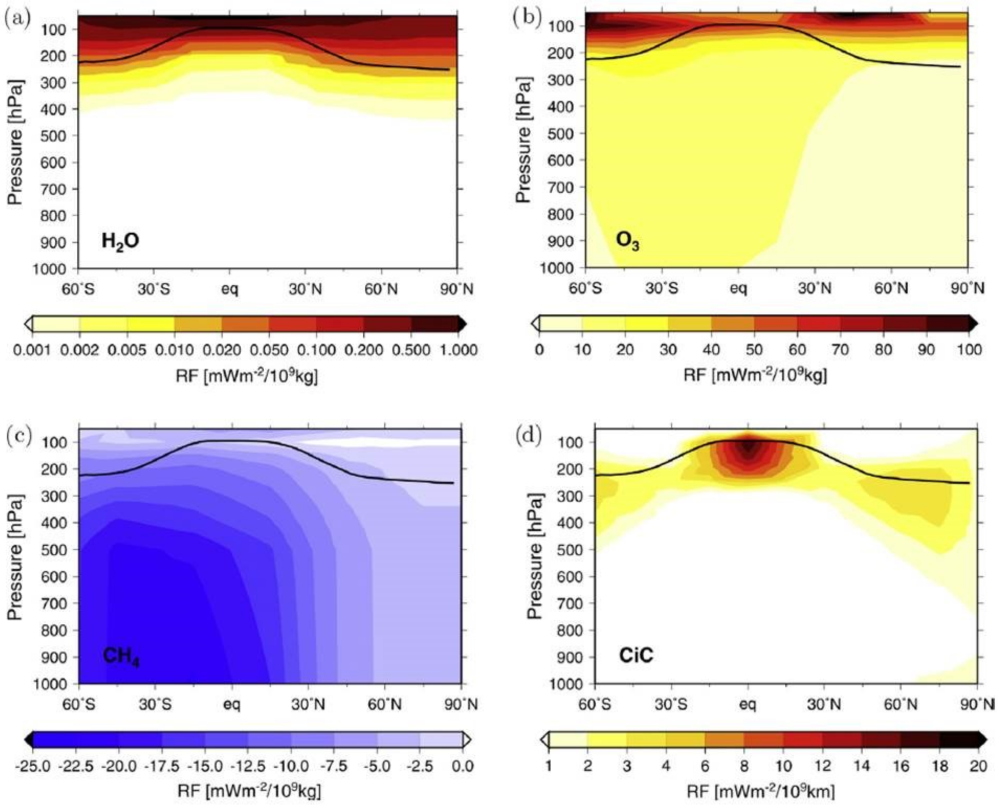
The relative climate impact of $H_2O$ emissions increases with altitude of the emission due to longer lifetime and lower background concentrations (Figure 5; Grewe and Stenke, 2008). The lifetime of water vapour is only in the range of hours to days in the troposphere due to rain out, while it increases in the stratosphere up to years (Grewe and Stenke, 2008).

The climate impact of a $NO_x$ emission via of $O_3$ depends on the background concentration of $HO_x$, CO and the ratio between NO and $NO_2$. At higher altitudes ozone production is most effective due to low background $NO_x$ and $HO_x$ and high $NO/NO_2$ ratio. Therefore, the climate impact of a $NO_x$ emission increases from less than 10 $mWm^{-2}/Tg_{fuel}$ at the ground up to 100 $mWm^{-2}/Tg_{fuel}$ at 16 km (about 100hPa) emission altitude.

The climate impact of a $NO_x$ emission via $CH_4$ shows a weak altitude dependency in the northern latitudes and a decreasing climate impact with increasing emission altitude in the southern latitudes. As the impact of $NO_x$ emissions via $O_3$ is very small at low altitudes, the total $NO_x$ impact can be negative in the tropics.

The climate impact of contrails and CiC depends on both, the emission altitude and on the latitude of emission. For contrail formation the air has to be cold and humid enough. This is especially the case in the upper troposphere. As the altitude of the tropopause is lower in higher latitudes, the altitude in which contrails can form decreases with increasing latitude (Figure 5).

**Figure 5: Global and annual mean Radiative Forcing of $H_2O$, $O_3$, $CH_4$ and CiC as a function of emission location.**

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### 2.6.2 Weather dependent emission effects

The climate impact of non-$CO_2$ aviation emissions depends on both, the location and the time of emission (e.g. day or night). Hence, it depends on the prevailing weather situation (e.g. high- or low-pressure system). For example, nitrogen oxides emitted by an aircraft might either (i) be converted to $HNO_3$ and rained out within days, which strongly limits its impact on ozone and methane, or (ii) be transported over long distances for weeks producing ozone and destroying methane. Another example is the climate impact of contrails. Persistent contrails and contrail cirrus are formed in ice–supersaturated regions (ISSR), which are rather thin in the vertical extent (in the order of 500 m; Spichtinger et al., 2003) but might have a lateral expansion of 100 km (Burkhardt und Kärcher, 2011), and are related to the general weather situation. By shifting the temporary cruise altitude one flight level (1000 ft) up or down or avoiding those regions, the climate impact from contrail formation can be avoided totally. Furthermore, the time of the day plays a major role for the climate impact of contrails. If a contrail exists only during night, it only has a longwave warming effect, trapping the outgoing terrestrial radiation. If the same contrail exists during day, the warming effect might be equal, but solar radiation is reflected additionally, which might result in a cooling effect, off-setting the warming. Therefore, the location and time of emission plays an important role for the formation of contrails, the transport pathway of the emitted species, their atmospheric lifetimes and their chemical response.

## 2.7 Knowledge and uncertainties

### 2.7.1 $CO_2$

Basically, the processes determining the atmospheric concentration of $CO_2$ are well established and the climate impact of $CO_2$ has only small uncertainties. The way $CO_2$ influences the radiative balance of the atmosphere and the climate sensitivity is considerably well known. Uncertainties exist in the absolute lifetime. While the relatively fast loss processes are quite well known, the slow processes like soil storage shows larger uncertainties. The behaviour of the ocean uptake with increasing temperature also leads to uncertainties in the lifetime of $CO_2$.

### 2.7.2 $O_3$ and $CH_4$

In principle, the basic transport pathways of aviation $NO_x$ and the atmospheric chemistry involved in forming ozone and destroying methane are well described in literature. In addition, there is an agreement between different chemical regimes in different atmospheric regions (Lee et al., 2010). However, one problem with analysing the climate impact of $NO_x$ emissions is the aviation $NO_x$ emission itself. Information about $NO_x$ emissions in the landing and take-off cycle has been widely studied, but there is only less information about cruise level emissions. The impact of a $NO_x$ emission on ozone strongly depends on the background concentrations of many other species such as $NO_x$, CO, $O_3$, and $HO_x$. Their variations in the atmospheric distribution, uncertainties in the location of $NO_x$ emissions, and inaccuracies in the transport of both the emitted species and precursors, provide a source of uncertainty, which manifest in a large model range in Figure 4. The impact of a $NO_x$ emission on $CH_4$ is controlled by the induced changes of OH. It has been shown that the short-term changes in OH enable a reliable estimate of the steady-state methane change, which largely reduces the required simulation time. However, since changes in methane also change the OH concentration, a feedback factor is applied, which might vary among models and imposes some uncertainty. Although there are large differences in the response of aviation $NO_x$ emissions to the impact on ozone and methane among climate models (see Figure 4), the ratio of RF($O_3$) and RF($CH_4$) show less variability between climate models (Lee et al., 2010; Holmes et al., 2011), as $O_3$ and $CH_4$ processes are coupled through OH. That means a model with larger ozone impact also calculates larger $CH_4$ impact, so that both effects compensate partly and leads to smaller uncertainties in the net impact of $NO_x$ emissions.

### 2.7.3 Contrails and Contrail cirrus

The physics behind the formation of contrails and the criteria when a contrail is formed and may persist is well known since the 1940s. However, the climate impact of contrails and especially contrail cirrus has large uncertainties. One reason is the limited observational data on contrail cirrus coverage, optical properties and radiative effects. This imposes some difficulty on verifying all aspects of contrail cirrus simulation results. Although near global data sets exist, the detection limit of contrails and contrail cirrus is only roughly known. Therefore, a large part of thin contrails is not detected by, e.g. satellite data. Additionally, during the evolution of a line shaped contrail to contrail cirrus it is difficult to distinguish between older contrail-cirrus, which have lost their line-shaped character, and cirrus, as they look very similar. In addition, many assumptions like ice crystal radiative parameters, optical thickness and also engine parameters have to be made. While contrail cirrus leads to a warming of the atmosphere at night time, warming as well as cooling effects occur during daytime. Therefore, uncertainties in the lifetime of contrail cirrus, leads to uncertainties in the net effect of contrails, as the time in which only warming occur may be larger or lower.

### 2.7.4 Aerosols

The principle physical mechanisms, involved in the direct aerosol effect, such as transport of aerosol, aerosol micro physics, sedimentation, and radiative properties are relatively well known in many aspects. However, the large atmospheric variability and required parameterisations to treat these effects in a climate model grid cell are limiting the accuracy of any simulation. Hence, the scientific understanding of climate impact of the direct aerosol effect is rated to be low. Reasons for the uncertainties are the parametrisation of wet deposition, difficulty to measure atmospheric concentrations and the conversion of $SO_2$ to sulphur (IPCC, 2013). Uncertainties exits also in aerosol single-scattering albedo and the vertical profile of aerosol concentration (IPCC, 2013).

Even larger uncertainties exist in the assessment of the climate impact of indirect aerosol effects. One of the uncertainties arises through the unknown size distribution of emitted particles (Righi et al., 2013). The contribution of anthropogenic aerosol which serves as ice nuclii is complicated by our poor understanding of the climatology and lifecycle of aerosol particles that can serve as ice nuclii (IPCC, 2013).

# 3 Climate Metrics for non-$CO_2$ effects

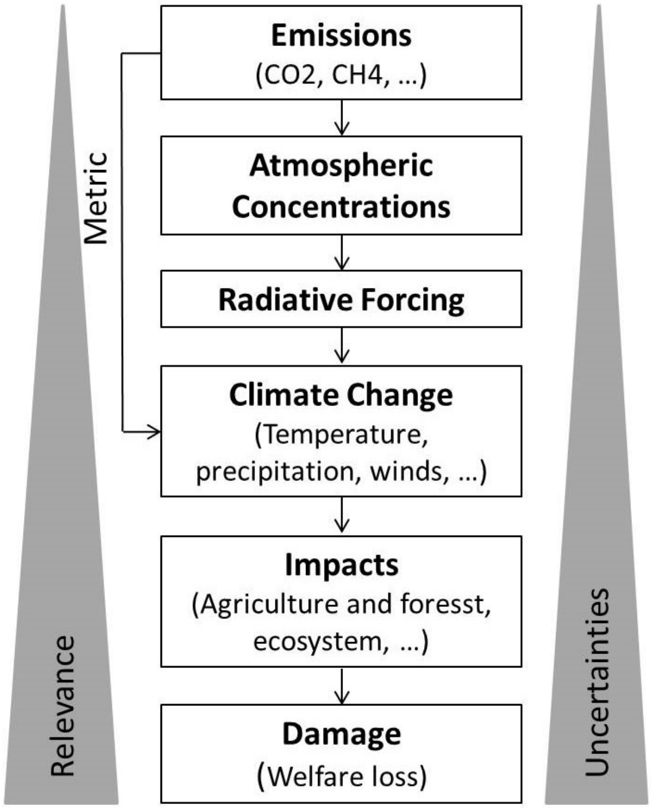
## 1.1 Why climate metrics?

The climate impact of aviation emissions is a combination of different climate effects. These climate effects differ in sign and magnitude and have partly very different life times (see Section 2). Therefore, these effects cannot be easily compared. To assess an option to reduce the climate impact of aviation it is necessary to have a consistent measure, called climate metric. Climate metrics are used to compare the climate impact of several options.

The cause and effect chain from emissions to climate impact is shown in Figure 6 (see also Section 2). Aircraft emissions lead to atmospheric concentration changes, which influence the radiation balance of the atmosphere (Radiative Forcing). The resulting imbalance of the climate system is compensated through changing temperature and precipitation. This has an impact on agriculture and ecosystem, which can cause damage. The climate metric is a direct connection of an emission and the resulting climate impact, which can be expressed, i. a., as Radiative Forcing, temperature change or climatological damage (latter also requires the use of biophysical and socio-economical metrics). As shown in Figure 6 the relevance increases downward the cause and effect chain, but also the uncertainties increase. The public concern about climate impact is not a change in Radiative Forcing but more the fear about possible damages. A relevant metric therefore would be a reduced damage, but the uncertainties in calculating the damages are very large. Calculating the emissions only would be easier and less uncertain, but the conclusions about climate impact are very small. Therefore, the choice of a climate metric is often a compromise between relevance and uncertainty (Figure 6, Fuglestvedt et al., 2003).

For assessing the climate impact we have to differentiate between the measure and the method we use. The measure is the climate metric, which is the combination of climate indicator (such as GWP, ATR; see below), emission scenario and time horizon. The used method is the way we calculate the climate impact, e.g. the model or dependencies which are taken into account. While this section presents the different climate metrics, possible calculation methods are presented in Section 4.

**Figure 6: Cause and effect change from emissions to climate impact and damage.**




Adopted from Fuglestvedt et al. (2003)

## 1.2 Requirements

There are a lot of different possible combinations of climate indicator, time horizon and emission development, which leads to the assumption that climate metrics are ambiguous. A problem is that the term climate change is not well defined. For an exactly defined question the suited climate indicator, time horizon and emission development can be chosen (Grewe and Dahlmann, 2015). Thus, one of the most important requirements for a climate metric is that it has to fit to the question that should be answered.

Climate metrics used for political applications should be multifunctional. They should be useful for comparing the climate impact of different species, for assessing mitigation strategies as well as for comparing the impact of different sector (e.g. IPCC, 2007; Wuebbles et al., 2010).

It should be easy to use and comprehend the climate metric, but nevertheless scientific well grounded. Some parts of aviation's climate impact have still large uncertainties and new insights are expected in future. Therefore, it is important that a climate metric is flexible enough that it can be adopted according to the new insights.

While some metrics analyse the climate impact over a special time horizon, some metrics analyse only the impact of one point in time (see Section 1.4.1). If only one point in time is analysed the chosen time can have a large impact on the results. For $NO_x$ emissions for example the large warming effect of short lived $O_3$ production leads to warming effect in the first years, while the long-lived cooling effect of decreasing methane concentration leads to a cooling about 10 years after the emission. Depending on the choice of the point in time the impact of $NO_x$ can be positive or negative. If a constant $NO_x$ emission instead of pulse emission is assumed, the large positive $O_3$ impact at the beginning will dominate the impact. A constant $NO_x$ emission, which is the same as a series of pulse emission, would thus cause warming although the climate metric would imply a cooling effect. Therefore, it is important that a climate metric provides qualitative the same result for pulse and sustained emissions.

## 1.3 Overview of climate indicators

### 1.3.1 Emission

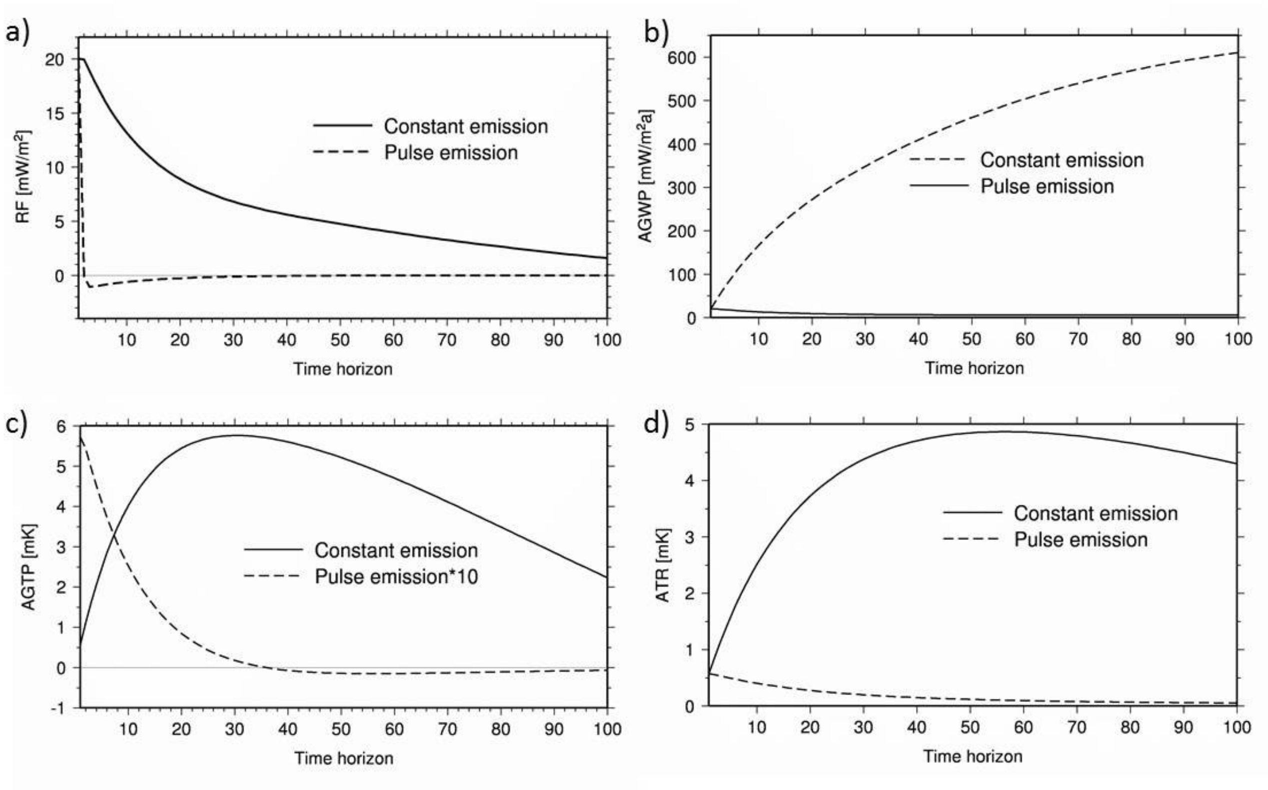
The simplest climate metric is the emitted mass of an individual climate species. While a reduction in $CO_2$ emissions lead to a reduction in the corresponding climate impact, this is not always true for non-$CO_2$ emissions. A reduction in emissions but a simultaneously change in flight altitude can, for example, lead to increasing climate impact as the impact depends on emission location (see Figure 5). In addition, the climate sensitivity of a unit emission differs for the different emission species. The pulse emission of 1 kg $NO_x$, for example, leads to a about 10000-time larger average temperature response over 20 years than an emission of 1 kg $CO_2$ (Scheelhaase et al., 2016). Thus, it is not possible to assess trade-offs for different mitigation scenarios using the amount of emissions as climate metric. An increase in flight altitude, for example, often leads to reduced $CO_2$ emissions, but increasing climate impact through non-$CO_2$ effects (Frömming et al., 2012). Using emissions as climate metric would assess this mitigation option as climate friendly, although the climate impact would increase. Therefore, emissions might serve as a first order indicator for comparing the relative importance of various sources or countries, but not for comparing different species or mitigation strategies.

### 1.3.2 Radiative Forcing

Radiative forcing (RF) is one of the most widely used metrics. It is defined as the net change in the energy balance of the Earth system due to some perturbations (e.g. concentration change), expressed in watts per square meter. Radiative forcing is often presented as the value due to changes between two particular times, such as pre-industrial to present-day, but can also be used as the value due to changes in emissions. There are two different kinds of RF: Instantaneous and stratospheric adjusted RF. The commonly used RF is the stratospheric adjusted RF, which 'is defined as the change in net irradiance at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, while holding surface and tropospheric temperatures and state variables such as water vapour and cloud cover fixed at the unperturbed values' (IPCC, 1990). As shown in Section 2.4 the Radiative Forcing is directly linked to the mean near surface temperature change ($\Delta T$) via the climate sensitivity parameter $\lambda$.

The RF is analysed only at one point in time and does not account for the different lifetimes of the climate species. This makes it strongly dependent on the choice of the time horizon. Figure 7a presents exemplarily the temporal development of the Radiative Forcing of a pulse and constant $NO_x$ emissions, respectively. For pulse emission the RF is positive in the first year due to the warming impact of short-lived ozone production, while it is negative or almost zero in the following years due to the cooling impact of long-lived $CH_4$. For constant emission the large positive impact in the first year dominates over the whole time horizon, which leads to a positive RF. The RF provides qualitatively different results for pulse and constant emissions, which makes is less useful as a climate metric. A summary of climate metric properties can be found in Table 2.

**Figure 7: a) Radiative Forcing, b) Absolute Global Warming Potential, c) Absolute Global Temperature Potential and d) Average Temperature Response for pulse and constant $NO_x$ emissions in dependency of the time horizon.**

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### 1.3.3 Global Warming Potential

The absolute global warming potential (AGWP) is defined as the integral of Radiative Forcing over a chosen time horizon H:

$$AGWP_{spec}(H) = \int_{t_0}^{t_0+H} RF_{spec}(t)dt. \quad (4)$$

The GWP (global warming potential) is the ratio of the AGWP of a species and AGWP of $CO_2$:

$$GWP_{spec}(H) = \frac{AGWP_{spec}(H)}{AGWP_{CO_2}(H)}. \quad (5)$$

The AGWP accounts for the lifetime of long-lived species, but do not take the climate sensitivity into account. Therefore, it is not directly related to a temperature change and relation of the climate impact of different climate species is not correctly represented.

As the RF is integrated over a time horizon, the AGWP is less dependent of the time horizon than RF. In Figure 7b the AGWPs of pulse and constant $NO_x$ emissions in dependency of the time horizon are shown. Independent of the chosen time horizon the AGWPs of a pulse emission and constant emission are positive. A pules emission and a constant emission would so give qualitative the same results. Nevertheless, the temporal development of the temperature change for the same AGWP could be very different, as the thermal inertia of the atmosphere and the climate sensitivity are not taken into account (Boucher und Reddy, 2008).

GWP is widely used, e.g. in the Kyoto protocol. The Kyoto protocol is used for long-lived greenhouse gases, like $CO_2$, $N_2O$ or $CH_4$. The adaptation as a metric for short-lived emissions and aviation effects, in particular, has proved to be controversial (IPCC, 1999). One of the limitations of the GWP concept is that aviation Radiative Forcings do not all rely on emissions alone (e.g., contrails). Additionally, the distribution of the Radiative Forcing is inhomogeneous in the atmosphere due to the very short lifetime of some species. As a result, the IPCC (1999) made strong statements against its use for aviation.

### 1.3.4 Global Temperature Potential

The global temperature potential (GTP) translates the radiation changes caused by a concentration change to a temperature change at a certain point in time. GTP results in a physical quantity, which is directly associated with climate change.

$$GTP_{spec}(H) = \frac{\Delta T_{spec}(H)}{\Delta T_{CO_2}(H)} \qquad (6) \qquad \text{with} \qquad \Delta T_{spec}(H) = \lambda_{spec} \cdot RF_{spec}(H). \qquad (7)$$

As the absolute global temperature potential (AGTP) represents the temperature change at one point in time, it includes the different climate sensitivities and the thermal inertia of the atmosphere. However, the GTP depends strongly on the chosen time horizon. In Figure 7c the temporal development of the AGTP of pulse and constant $NO_x$ emissions is presented. For a time horizon less than 35 years pulse emission show a positive result, while it is negative for larger time horizons. As the positive impact in the earlier years is larger than the negative impact, a constant $NO_x$ emission would lead to positive result (warming) independent of the time horizon. That means GTP provides qualitatively different results for pulse and constant emissions, which makes is less useful as a climate metric.

### 1.3.5 Average Temperature Response

The dependency of the time horizon is largely reduced by using the average temperature response (ATR), which is the mean temperature change over a time horizon H.

$$ATR_{spec}(H) = \frac{1}{H}\int_{t_0}^{t_0+H} \Delta T_{spec}(t)dt. \qquad (8)$$

The ATR combines the advantages of the GWP and GTP. ATR is less dependent of the chosen time horizon and accounts for the lifetime of long-lived climate species as it is averaged over a time period similar to GWP, but includes the different climate sensitivities and the thermal inertia of the atmosphere similar to GTP. The dependency of ATR from the chosen time horizon of a pulse and constant $NO_x$ emission is presented in Figure 7d. ATR provides positive results independent of the chosen time horizon and the chosen emission development (pulse or constant). A disadvantage of using ATR as a metric is the increasing uncertainties resulting from uncertainties of the climate sensitivity parameter.

Although several studies suggest a kind of ATR as a metric (e.g. Marais et al., 2008; Schwartz and Kroo, 2011; Gillett and Matthews, 2010; Dahlmann et al., 2016a), it is not often used for political applications yet. The different studies use slightly different definitions and names for the suggested metric, but all suggest an averaged or integrated temperature change.

**Table 2: Overview of climate metric properties**

| Properties | RF | GWP | GTP | ATR |
|---|---|---|---|---|
| Direct relation to ΔT | - | - | X | X |
| Accounts for lifetime | - | X | X | X |
| Accounts for thermal inertia | - | - | X | X |
| Dependence on time horizon | Strong | Weak | Strong | Weak |
| Σ(Metrik(Pulse))~ Metrik(Σ(Pulse)) | - | X | - | X |

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## 1.4 Dependencies

### 1.4.1 Time horizon

Beside the selection of the climate indicator (e.g. GWP, ATR), the choice of the time horizon is important. As shown in Section 3.3 the choice of the time horizon can have a large impact on the results. Especially for climate metrics, which measure the climate impact in one point in time (e.g. RF, GTP) and pulse emissions the choice of the time horizon is a weighting between short- and long-lived climate species. For short time horizons the impact of short-lived species dominates, while for larger time horizons the impact of long-lived species dominates, as the impact of short-lived species is already gone.

But the choice of the time horizon is not totally based on physical considerations. It strongly depends on the concrete question which should be answered with the climate metric. Asking for reducing the climate change in the near future would imply using short time horizons of e.g. 20 years. While asking for sustainable aviation would imply larger time horizons of, e.g., 100 years. As the atmosphere and the ocean need about 30 years to adjust to the new radiation balance it is useful to use a time horizon of more than 30 years, if a climate metric with temperature change as a basis is used (GTP, ATR). In literature the time horizon has been chosen between 20, 50, 100 and 500 years (e.g. Fuglestvedt et al., 2008, Lund et al., 2017). Also for the Kyoto protocol a time horizon of 100 years was chosen as it is used for long-lived greenhouse gases only.

#### 1.4.2 Emission scenario

Beside the climate indicator and the time horizon, a decision about the temporal development of the emission has to be made, which is used for the calculation of the climate metric. Same as for the climate indicator and the time horizon this strongly depends on the question to be answered. If the impact of a single flight should be measured, pulse emission should be used, while it is useful to use constant emissions for analysing the mitigation potential of new aircraft technologies. Nevertheless, it has to be in mind, that for some climate indicators a pulse emission provides a different qualitative result than a constant emission. That means that if a flight occurs every year, climate indicators, such as RF or GTP, could provide the wrong answers.

As for the time horizon, the emission development can also give a weighting between short- and long-lived climate species. Using pulse emissions with a large time horizon focus on long-lived species, while constant emission with shorter time horizons focus on short-lived species, as the large impact at the beginning dominates.

### 1.5 Identified climate metric

#### 1.5.1 ATR100

GWP is an appropriate climate metric for the Kyoto protocol and often used for political applications. Nevertheless, it is not the best selection for including aviation's non-$CO_2$ effects in an emission trading system like EU ETS or a market-based measure like CORSIA. As shown in Section 3.3 ATR includes the different climate sensitivities, the different lifetimes and the thermal inertia of the atmosphere (Table 2). That means ATR is further down the cause- and effect chain from emissions to the climate impact and may be easier to understand than the more abstract concept of integrated Radiative Forcing (Wuebbles et al., 2010). Additionally, it is less dependent on the time horizon, due to the averaging over time, and pulse and constant emissions provide qualitatively the same results. Nevertheless, ATR is not commonly used and the introduction of a new climate metric may lead to fewer acceptances than using a common metric like GWP. Therefore, we provide in Section 3.5.2 a comparison of AGWP and ATR as well as a method to convert ATR into AGWP or vice versa.

A suitable time horizon for including non-$CO_2$ effects in an emission trading scheme or market-based measure is 100 years. Advantage of using 100 years as time horizon is that it is also used in the Kyoto protocol. Additionally, it is long enough that long-lived species like $CO_2$ are properly considered, but short enough that people have the feeling that it is a time horizon which is imaginable and relevant for them self.

#### 1.5.2 Comparison of ATR and AGWP

As ATR includes the different climate sensitivities it provides a different perspective on the relative importance of emissions of different species compared to AGWP (Wuebbles et al., 2010). To analyse which impact the different climate indicators have on the measured climate impact, we calculated the climate impact of the RECT4C emissions inventory (global aviation emission in 2006; Owen et al., 2011) with both metrics for pulse and constant emissions, respectively. As both metrics provide very different absolute values we present in Table 3 the metric relative to $CO_2$, i.e. GWP and relative ATR, for each species. For both metrics the importance of each species differs. While GWP place more emphasis on CiC, ATR place more emphasis on $O_3$, as the $O_3$ climate sensitivity is larger than that of CiC. Nevertheless, the relation of non-$CO_2$ and $CO_2$ effects are very similar. It can be seen that the impact of different emission developments on the relation of non-$CO_2$ and $CO_2$ effects is larger than the influence of the metric. While for constant emissions the total impact is about 5 times the impact of $CO_2$ emissions alone, the total impact for pulse emissions is only about 3 times the impact of $CO_2$. This is due to the fact, that $CO_2$ has a very long lifetime compared to non-$CO_2$ effects, which increases the relative climate impact of $CO_2$.

**Table 3: Climate impact of REACT4C emission inventory for constant and pulse emissions with a time horizon of 100 years calculated with GWP and ATR (relative to $CO_2$).**

| | | $CO_2$ | $H_2O$ | $O_3$ | $CH_4$+PMO | CiC | Total |
|---|---|---|---|---|---|---|---|
| Constant | GWP | 1.00 | 0.08 | 1.23 | -0.02 | 2.53 | 4.82 |
| | Relative ATR | 1.00 | 0.10 | 1.90 | -0.02 | 1.68 | 4.66 |
| Pulse | GWP | 1.00 | 0.04 | 0.62 | -0.01 | 1.27 | 2.92 |
| | Relative ATR | 1.00 | 0.06 | 1.06 | -0.02 | 0.94 | 3.04 |

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As shown above the relation of GWP and ATR depends on the climate species, as the climate sensitivity and lifetime of the species differ. Additionally, it depends on the emission development and the analysed time horizon.

The above shown relations are only valid for the emission indices of the given emission inventory and are only for giving an impression about the differences between both climate indicators. To convert the results from AGWP to ATR or vice versa it is necessary to calculate a conversion factor for each climate species separately. In this Section we present conversion factors from AGWP to ATR: $f_{spec} = \frac{ATR_{spec}}{AGWP_{spec}}$ for each species and two different emission developments (pulse and constant) for a time horizon of 100 years (see Table 4). These conversion factors account for the different efficacies (see Table 1) as well as for the thermal inertia of the atmosphere. The ATR can be calculated by multiplying the calculated AGWP for each species with the corresponding conversion factor and adding all species specific values together. The larger the conversion factor the larger the weighting of the species for ATR compared to AGWP. While the impact of ozone (0.93) gets 72 % larger compared to $CO_2$ (0.54) the impact of CiC (0.40) gets 26% lower when using ATR instead of AGWP. These conversion factors are only valid for the given climate metric (ATR with a time horizon of 100 years, pulse and constant emissions, respectively).

**Table 4: Conversion factor (x100) for AGWP to ATR for time horizon of 100 years for pulse and constant emission**

| Climate agent | $CO_2$ | $H_2O$ | $O_3$ | $CH_4$ | PMO | CiC |
|---|---|---|---|---|---|---|
| Pulse emission | 0.54 | 0.76 | 0.93 | 0.77 | 0.89 | 0.40 |

| Climate agent | $CO_2$ | $H_2O$ | $O_3$ | $CH_4$ | PMO | CiC |
|---|---|---|---|---|---|---|
| Constant emission | 0.42 | 0.54 | 0.65 | 0.53 | 0.62 | 0.28 |

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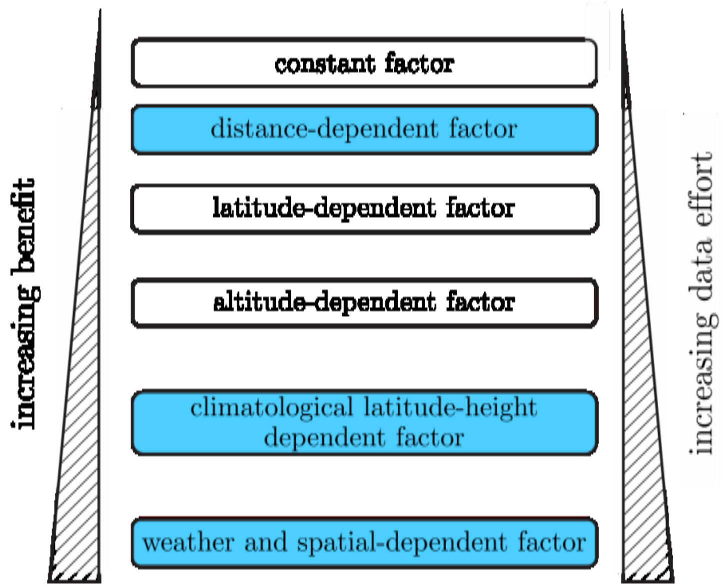
# 4 Method to calculate $CO_2$ equivalents

## 4.1 General concept

The climate impact of $CO_2$ is well understood and commonly known. Additionally, the impact of $CO_2$ is independent of the emission source and location. Therefore, it is reasonable to calculate the impact of non-$CO_2$ climate species relative to the impact of one kg $CO_2$. The resulting $CO_2$ equivalents represents the amount of $CO_2$ which can be emitted to cause the same climate impact over the used time horizon with the given emission development (defined through the used climate metric). Therefore, the results depend strongly on the used climate metric. For calculating $CO_2$ equivalent emissions each of the climate metrics discussed in Section 3 can be used.

Same as for climate metrics, the results are more relevant and have more benefit if more processes are taken into account (going down the chain in Figure 8) but the amount of data and the effort to calculate the equivalent $CO_2$ emissions increases.

**Figure 8: Increasing benefit and data effort for increasing consideration of processes. The calculation methods described in the following section are highlighted in blue.**

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## 4.2 Identified calculation methods

In this section we present three different calculation methods: a simple distance-dependent, a climatological latitude-height dependent and a weather and spatial-dependent factor (see blue boxes in Figure 8).

### 4.2.1 Simple and potentially misguiding: Distance-dependent factor

One of the easiest ways to approximate the climate impact of non-$CO_2$ effects is using a constant factor. This constant factor has only to be multiplied with the $CO_2$ emissions, which are known from the fuel consumption (consumption of 1 kg jet fuel, emits 3.15kg $CO_2$). As the amount of $NO_x$ emissions is often not known this easy constant factor uses a given $NO_x$ emission index.

To show how such a constant factor can be calculated Dahlmann et al. (2018) analysed data from more than 1000 flights with an A330-200 which was calculated by Dahlmann et al. (2016a). In the primary study the climate mitigation potential of changing flight altitudes and speeds was analysed for a world fleet of A330-200 in 2006. Dahlmann et al. (2018) used for each route the flight trajectories with minimal cash operating costs (COC). For assessing the climate impact $ATR_{100}$ was used as climate metric with constant emissions over 32 years, which is the approximated lifetime of a long-haul aircraft, as Dahlmann et al. (2016a) assessed the climate impact of new aircraft designs.

**Table 5: Simple factor for mean climate impact in terms of ATR100 for an emission of 1 kg $CO_2$**

| Climate agent | $CO_2$ | $H_2O$ | $O_3$+$CH_4$+PMO | CiC |
|---|---|---|---|---|
| $CO_2$ equivalents | 1.0 | 0.2 | 1.2 | 1.0 |

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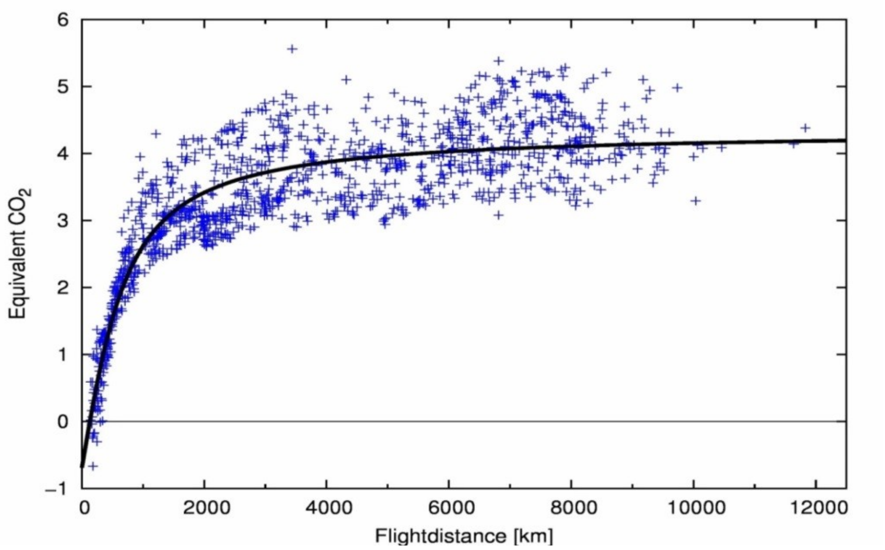
In Table 5 we present simple factors from Dahlmann et al. (2018). Emitting one kg $CO_2$ (or 0.317 kg fuel) results in a mean total climate impact of about 3.2 kg equivalent $CO_2$ emissions for the given climate metric[3]. This is a mean for all flown distances.

As the climate impact strongly depends on the emission location and the flight altitude depends on the flight distance (lower altitude for short distances) it is meaningful to use at least a factor depending on the flight distance, which uses implicit different flight altitudes. In Figure 9 the equivalent $CO_2$ emissions in dependency of flight distance are provided. For distances lower than 500 km the total climate impact can be less than 1, as the impact of $NO_x$ is negative and the impact of CiC and $H_2O$ is very low. The negative climate impact of $NO_x$ is due to low impact of $O_3$ in low altitudes and the larger negative impact of $CH_4$ (see Section 2.6.1). With increasing distances the impact of $H_2O$, CiC and $NO_x$ increases. Fitting these data provides following function: ${}^{eq}CO_2 = (3.20 \cdot arctan(0.00167 \cdot dist) - 0.69) \cdot CO_2$, where *dist* is the flown distance in km and $CO_2$ the amount of emitted $CO_2$ in kg. It can be seen that a purely constant factor does not well represent the results (see Figure 9).

[3] The differences to the value in Section 1.5.2 (4.66 for constant emission) are due to a different emission development (here 32 years constant emission and zero afterwards instead of constant emission) and different aircrafts (here A330-200 instead of global fleet).

**Figure 9: Equivalent $CO_2$ emissions in dependency of the flight distance (blue crosses) and according curve fit (black).**




From Dahlmann et al., 2018

It has to be mentioned that this factor strongly depends on the assumed emission indices (e.g. $NO_x$). If an aircraft with different emission indices or specific fuel consumption, e.g. newer engines, is used the constant factor will differ significantly. This is also possible for aircrafts flying in different regions, e.g. tropics, as for example contrails occur in higher altitudes than for mid-latitudes. General changes in flight altitudes, e.g. new aircrafts optimized for lower altitudes would also result in changing factors.

The simple distance dependent factor depends beside the choice of climate metric (climate indicator, time horizon and emission development) also on following factors:

a) Emission indices
b) Routes/ emission inventories
c) Flight altitude
d) Weather situation

The distance dependent factor, which is presented here, is based on a world fleet of an A330-200 with an average emission index of $NO_x$ of 19 g/kg and a specific fuel consumption of about 6 kg/km. The most emissions take place in mid-latitudes with a mean flight altitude of 11.3kft. Nevertheless, the altitude depends on the flight distance (Dahlmann et al., 2018).

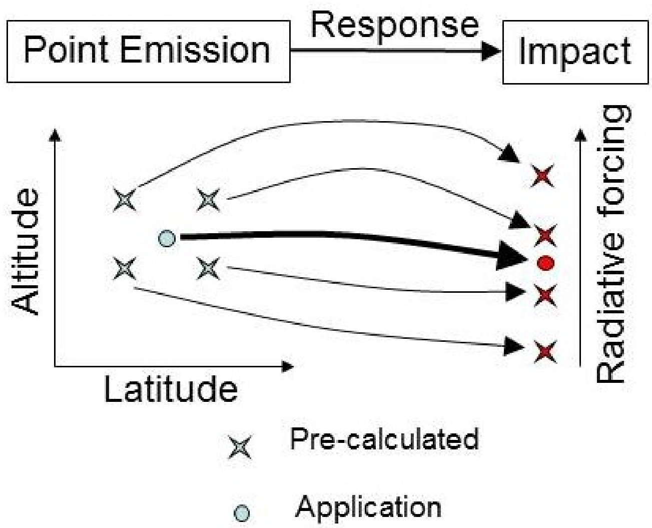
Using a distance dependent factor for emission trading does not give incentives for airliners to reduce climate impact of non-$CO_2$ effects. As the calculated equivalent $CO_2$ emissions only depends on the $CO_2$ emissions and therewith the fuel consumption, airlines will try to reduce only $CO_2$ emissions. Although a reduction in $CO_2$ leads to a reduced climate impact of $CO_2$, a potential increase in non-$CO_2$ effects could overcompensate this benefit. Increasing flight altitudes, for example, can lead to decreasing fuel consumption due to reduced friction, but can increase the impact of CiC, $H_2O$ and $O_3$ (Frömming et al., 2012; Dahlmann et al., 2016a).

Such a simple factor can be used for public to see an estimate of the total climate impact of aviation, e.g. for compensation market or personal $CO_2$ footprint. Nevertheless it is not suitable for a use in emissions trading or MBMs as it cannot produce incentives for airlines to reduce the non-$CO_2$ climate impact, as changes in flight regions or altitude and reduction in $NO_x$ emissions will not lead to reducing $CO_2$ equivalents.

### 4.2.2 Middle ground: climatological latitude-height dependent factor

To gain incentives to reduce the climate impact of non-$CO_2$ effects, at least some altitude dependencies has to be taken into account. As seen in Section 2.6.1 the impact of $H_2O$, $O_3$ and CiC depends strongly on the flight altitude. This altitude dependency also depends on the latitude. CiC for example, forms in mid-latitudes already in altitudes of about 25 kft (350hPa), while it forms in tropics at altitudes of 34 kft (250hPa). A method to account for this latitude and altitude dependent climate impact is using a climate response model like AirClim (Grewe and Stenke, 2008; Dahlmann, 2012; Dahlmann et al., 2016b). AirClim is a response model, i.e. it uses the relation between emissions of $CO_2$, $NO_x$ and $H_2O$ and their impacts on atmospheric composition with respect to carbon dioxide, ozone, methane, water vapour, and contrails. The principle mechanism of AirClim is presented in Figure 10. Any given emission at an arbitrary latitude and altitude (blue circle) can be represented by a linear combination of the predefined emissions (blue crosses). The respective response (red circle) is then the same linear combination of the precalculated responses (red crosses). Benefit of the simplified response model is the very short calculation time. Analysing the climate impact of one trajectory with a response model needs less than one minute on a standard PC, while calculating the impact with a climate-chemistry model would need several weeks on a super computer.

**Figure 10: Principle mechanism of the response model AirClim. Stars indicate precalculated response relations derived with a detailed climate-chemistry model, i.e., the RF caused by an emission at a certain latitude and altitude. Any given emission at an arbitrary latitude and altitude (circle) can be represented by a linear combination of the predefined emissions and the respective response.**




© Grewe et al., 2012

To calculate the climate impact with an altitude-height dependent response model, needs more information than a simple factor needs. The response model needs the information about the emission location (longitude, latitude, altitude) and the amount of emission in each region (Fuel consumption, $NO_x$ emission and flown distances).

A benefit of this calculation method is that it provides incentives for airliners to reduce the climate impact of non-$CO_2$ effects. Dahlmann et al. (2016b) used this response model to analyse the impact of changing flight altitudes and speed. They showed that changing flight altitudes can reduce the climate impact of the global A330-200 fleet by 42% by reducing flight altitude and speed. Nevertheless, this flight altitude change increases COC through longer flight time and increased fuel costs. Including non-$CO_2$ effects in an emission trading scheme or MBM could compensate these additional costs and leading to reduced climate impact of aviation. Additionally, these incentives could lead to introduction of re-designed aircraft, which are optimized for lower climate impact. Dahlmann et al. (2016b) showed that an aircraft designed for lower flight altitudes and speed could reduce the climate impact by 32% without additional COC or by 54% with an increase of COC by 10%.

This calculation method includes different weather situations not explicitly, but only as climatological means. This might produce false incentives for special days: if for example airlines accept detours to avoid regions in which contrails often occur, although no contrails can form on this special day, the impact through additional fuel consumption can increase the climate impact.

But this is only the fact for several days. In an annual mean the incentives are right. The benefit of using climatological latitude-height factors is that flights with same trajectories can be combined reducing the administrational effort.

### 4.2.3 Complex and accurate: weather and spatial dependent factor

The relation between the emission (location and time) and its climate impact is called climate change function (CCF; Matthes et al., 2012; Grewe et al., 2014). The calculation of CCFs is very time consuming and requires detailed calculations with a comprehensive chemistry-climate model. However, algorithmic climate change functions (aCCF) have been developed within the European project ATM4E, aiming at a numerical efficient approximation of the climate change functions (Matthes et al., 2017; Grewe et al., 2017b), based on input data available in numerical weather. This would enable a provision of these aCCFs together with any weather forecast, representing weather and spatial dependent factors.

For each individual flight a planned or executed aircraft trajectory provides a detailed gridded description on the location and time of $CO_2$ and non-$CO_2$ emissions. The multiplication with the CCFs and summation along the trajectory provides a measure of the climate impact from individual components, which directly provides the factors for non-$CO_2$ effects. In this situation, the non-$CO_2$ factors are calculated for each flight separately and will differ from day to day. They represent the spatial variability of the atmosphere and of the atmospheric response to a local emission best among the introduced factors and by this provide an adequate incentive to avoid climate sensitive regions on a flight-by-flight basis.

The concept of climate change functions is new and the calculation methods require a thorough understanding of the atmospheric processes and an acceptable ability to calculate them. Not only flight planning, but also the aCCF calculation largely depends on the quality and reliability of the weather forecast adding an uncertainty to that of the aCCF formulation itself. As a consequence, the factors for non-$CO_2$ effects might vary for different stages of flight planning and for the actual flight execution, which imposes an ambiguity, which has to be resolved or at least addressed if such factors were implemented.

## 4.3 Summary

As shown in Section 4.2, the benefit, but also the amount of necessary data increases from a simple distance dependent factor to weather and spatial dependent factor. A distance dependent factor can be used as a first approximation to get an idea about the magnitude of non-$CO_2$ effects. This can be useful for people to think about their personal $CO_2$ footprint or for the compensation market (e.g. atmosfair). But a distance dependent factor cannot generate incentives for reducing non-$CO_2$ effects. Using newer engines with lower $EINO_x$, for example, would reduce the climate impact of non-$CO_2$ effects but would not be beneficial in an emission trading if a simple distance dependent factor is used.

A weather dependent calculation would be the best from a researcher's point of view. It provides right incentives and is most effective, as only regions with actual high sensitivity for climate change has to be avoided. But the calculation is quite complex and at the moment not operational. In addition each flight has to be analysed separately according to the actual weather situation and time of day.

A middle ground between the complex and the simple factor is a factor dependent on latitude and height. It is still relatively easy to calculate, but generate incentives to reduce non-$CO_2$ effects. This could also be a first step towards a complex method with weather and spatial dependency. If the process of emission trading is accepted and weather dependent calculation can easily be performed a change from altitude-height-dependent factor to the weather dependent factor could easily be made.

# 5 Alternatives

Besides integrating non-$CO_2$ climate effects into emission trading or MBMs, alternative environmental policy options exist, which focus on the location and time dependency of non-$CO_2$ climate effects. To mitigate the climate impact of aviation, these concepts try to create direct incentives for operator of aircraft to reduce emissions and flight time in highly climate-sensitive airspaces. This can either be done regulatory by implementing location- and time-dependent no-fly areas (Niklaß et al., 2017b) or price-based by levying location- and time-dependent climate charges (Niklaß et al., 2016; Niklaß et al., 2018; Niklaß, 2019). Both approaches are briefly presented below.

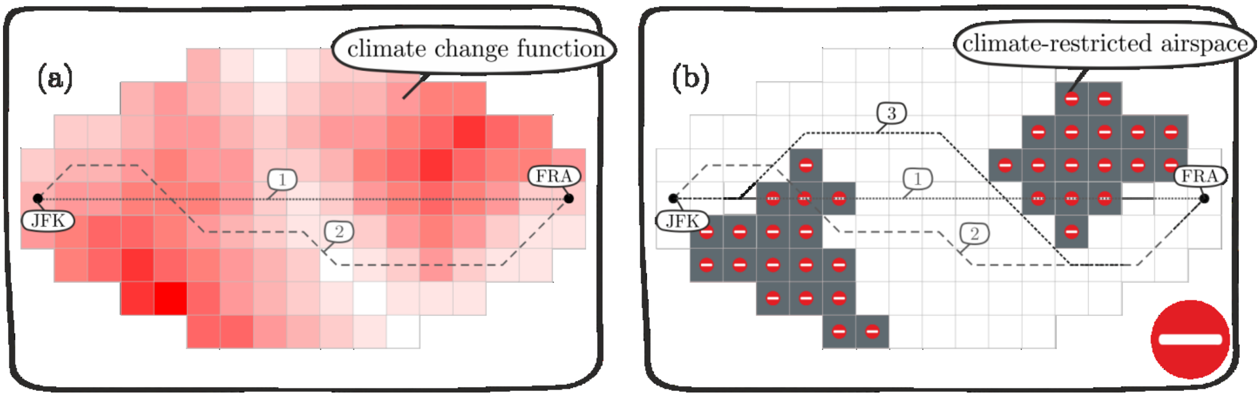
## 5.1 Concept of Climate-Restricted Areas (CRA)

The concept of Climate-Restricted areas is inspired by military exclusion zones. In this concept highly climate sensitive airspaces are restricted for a period of time (hour, day, etc.), if the climate responsibility of an area with respect to aircraft emissions[4] exceeds a specific threshold value $c_{thr}$ :

$$CRA(\boldsymbol{x}) = \begin{cases} 1, & if\ CCF_{tot}(\boldsymbol{x}) \geq c_{thr} \\ 0, & if\ CCF_{tot}(\boldsymbol{x}) < c_{thr} \end{cases} \qquad (9)$$

By re-routing affected flights cost-optimally around CRAs (Figure 11b), non-$CO_2$ climate effects are mitigated without implementation of complex climate algorithms into the flight planning software of the airlines. If a threshold is determined and agreed by policymakers, CRAs can be easily implemented by air traffic control.

**Figure 11: Concept of climate-restricted areas (CRA): highly climate sensitive regions are closed for a period of time and flight trajectories are re-routed cost-optimally around them: (1) Time-optimized trajectory; (2) Climate-optimized trajectory; (3) Cost-optimized trajectory with CRA concept. Different shades of red indicate varying climate impact.**

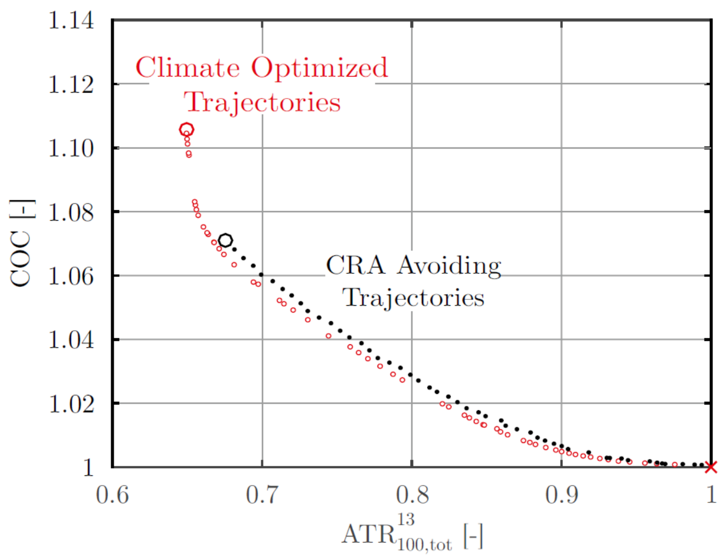



adapted from Grewe et al., 2017a

[4]The climate responsibility of an area is expressed here by total climate change functions ($CCF_{tot}$) characterizing the environmental impact caused by non-$CO_2$ effects of aircraft's emissions at a certain location and time.

The timing of Climate-Restricted Areas – how far can a CRA be scheduled in advance? – as well as its restriction period – hours or days? – are highly depending on non-$CO_2$ climate agents taken into account and the data-set of $CCF_i$ (weather-depended data or climatological mean data?). If, for instance, contrails and contrail cirrus are considered only into the CRA concept, Climate-Restricted Areas could be scheduled three days before departure, as ice supersaturated regions can predicted by specialist services, like the European Centre for Medium-Range Weather Forecasts (ECMWF), with high accuracy (Rädel and Shine, 2010). However, the selection of non- $CO_2$ species can be adapted any time to current level of scientific understanding (LOSU), as $CCF_i$ are calculated individually for each agent *i* before superposing. If CCFs are based on actual weather forecasts, restriction periods of few hours are possible.

**Figure 12: Average temperature response (ATR) and cash operating costs (COC) for climate-optimized trajectories (COT, red) and CRA avoiding trajectories ($U_{cj} \rightarrow \infty$, black) relative to time optimized trajectory**




©Niklaß et al., 2017b

For the CRA-concept a cost-benefit analysis has been conducted for nine North Atlantic routes and monthly varying climate change functions (Niklaß et al., 2017a,b). These studies identified a climate impact mitigation potential of the CRA-concept in the same order of magnitude as for climate-optimal flying (see Figure 12). This demonstrates the effectiveness of focusing on the most ecologically harmful airspaces for climate impact mitigation. For instance, CRA avoiding trajectories can mitigate the climate impact of a single North Atlantic flight by 10% for a cost increase of less than 1%. However, particularly small climate gradients trigger large zones of restrictions, which might reduce the airspace capacity significantly. Instead of closing climate-sensitive regions completely, the hard restrictions of the CRA concept can be replaced by a system of incentives (Niklaß et al., 2017a; Niklaß et al., 2017b).

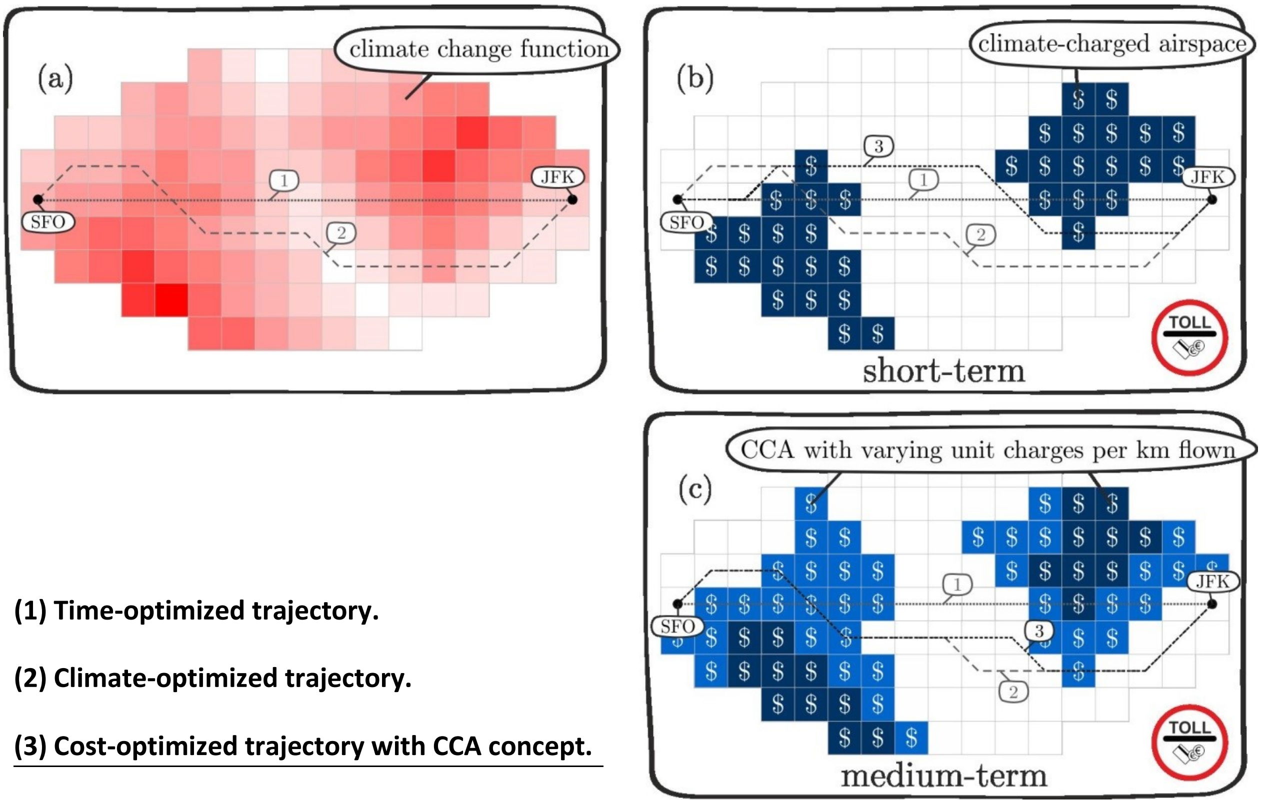
## 5.2 Concept of Climate-Charged Areas (CCA)

Contrary to approaches that propose an environmental charge for non-$CO_2$ emissions, Niklaß et al. (2016, 2018) suggested to impose a location and time-dependent climate charge. In the concept of Climate-Charged Areas (CCA) an airspace area $j$ is levied with an environmental unit charge $U_{cj}$ per kilometre flown ($d_j$), if its climate responsibility with respect to aircraft emissions exceeds a specific threshold value $c_{thr}$:

$$CCA_j(\boldsymbol{x}) = \begin{cases} U_{cj}, & if\ CCF_{tot}(\boldsymbol{x}) \geq c_{thr} \\ 0, & if\ CCF_{tot}(\boldsymbol{x}) < c_{thr} \end{cases} \tag{10}$$

This creates a financial incentive for airlines to minimize flight time and emissions in these areas. Thus, cost-minimizing airlines will re-route their flights to reduce the climate charges and hence their cash operating costs (see Figure 13). In this manner, climate impact mitigation coincides with the cutting of costs. The operator of an aircraft can decide individually for each flight according to individual needs whether to minimize flight time and to pay compensation for higher climate damage (trajectory 1 in Figure 13b) or to minimize costs and, concurrently, reducing the climate impact by total or partial avoidance of CCA (trajectory 3 in Figure 13b).

**Figure 13: Concept of climate-charged airspaces (CCA): creating a financial incentive for airlines to minimize flight time and emissions in highly climate sensitive regions. Different shades of red indicate varying climate impact; different shades of blue indicate CCA with varying unit charges per km flown.**




©Niklaß et al., 2016

The resulting climate charge $C_{cj}$ for a flight through a climate charged area $j$ can be in analogy to en-route and terminal charges:

$$C_{cj} = U_{cj} \cdot \left(\frac{MTOW}{k_1}\right)^{k_2} \cdot I_{AC} \cdot d_j \tag{11}$$

where MTOW is defined as maximum take-off weight of an aircraft and $I_{AC} \in [0,1]$ as incentive factor for climate-friendly technologies:

$$I_{AC} = \begin{cases} 1 & \text{for current aircraft technology standards} \\ \vdots & \text{for more efficient aircraft technology standards} \\ 0 & \text{for zero emission aircraft} \end{cases} \tag{12}$$

By combining climate charge $C_{cj}$ with an incentive factor for more efficient aircraft technologies standards, the profitability of sustainable capital investments – especially of more electric aircraft systems – is increasing. If, for instance, hybrid-electric aircraft switch on the electric-drive while flying through climate-charged areas, no climate charges have to be paid.

By extending the existing charge system of air traffic control with an additional climate charge, adjustment efforts for airlines are minimized: no handling of complex climate-change functions is required within the airline planning processes to reduce non-$CO_2$ climate effects. (Niklaß et al., 2016; Niklaß et al., 2018; Niklaß, 2019)

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# Part B: Determination of Data required for Consideration of non-$CO_2$ Effects of Aviation in EU ETS and under CORSIA

Final report

by

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**Abstract**

This final report summarizes the results of work package 2 and work package 3.1 within six sections. After the introduction (Section 1) direct emissions of the combustion of hydrocarbon fuels are presented (Section 2). Main combustion products are $CO_2$ and $H_2O$, which are directly proportional to the fuel flow. If sulfur is contained in the fuel, all sulfur is oxidized to sulfur dioxide during the combustion. Secondary combustion emissions (Section 3), like nitrogen oxides ($NO_X$) and non-volatile particulate matter (nvPM), are strongly dependent on the type and operating condition of the aircraft engine. Therefore, more complex methods are required to establish the amount of these species, emitted by an aircraft engine. The most commonly used methods for calculating $NO_X$ and nvPM are briefly summarized in this report. In Section 4, potential ways to reduce the amount of data required to estimate the climate impact of non-$CO_2$ emissions are discussed. To quantify the effect of these simplification procedures on the more complex climate metrics proposed for including non-$CO_2$ effects in emission trading systems, more detailed analyses, based on a larger number of actual or modeled flight missions will be needed. Section 5 presents the existing framework conditions for monitoring, reporting and verification (MRV) for aircraft operators for the EU ETS and the newly established CORSIA for compliance purposes. Performing the administrative tasks required – such as collecting data, processing it, or carrying out relevant but non-data related activities – imposes a financial burden on aircraft operators in terms of staff resources allocated but also direct costs paid to third-parties for relevant services delivered. Based on a breakdown of the cyclical MRV process into discrete steps, current practice compliance costs under the EU ETS and anticipated compliance costs under CORSIA are estimated for three aircraft operator size categories: small (<100’000 tCO2), medium (100’000 – 2’000’000 tCO2), large (> 2’000’000 tCO2). The inclusion of non-$CO_2$ climate species into existing climate protecting measures like the EU ETS or CORSIA will lead to additional administrative efforts and costs for aircraft operators (Section 6). The level of these additional expenses will be strongly depending on the method to estimate $CO_2$ equivalents (${}^{eq}CO_2$).

**Kurzbeschreibung**

Dieser Bericht fasst die Ergebnisse des Arbeitspakets 2 und des Arbeitspakets 3.1 in sechs Kapiteln zusammen. Nach der Einführung (Abschnitt 1) werden direkte Flugzeugemissionen, die bei der Verbrennung von Kohlenwasserstoffbrennstoffen ausgestoßen werden, vorgestellt (Abschnitt 2). Die entstehenden Hauptverbrennungsprodukte sind $CO_2$ und $H_2O$, die beide direkt proportional zum Kraftstoffmassenstrom sind. Sind Schwefelrückstände im fossilen Treibstoff enthalten, so werden diese bei der Verbrennung zu Schwefeldioxid oxidiert. Die sekundären Verbrennungsemissionen (Abschnitt 3), wie Stickoxide ($NO_X$) und nichtflüchtige Partikel (nvPM), sind stark von der Art und dem Betriebszustand eines Flugzeugmotors abhängig. Um die Emissionsmenge an $NO_X$ und nvPM bestimmen zu können, sind daher komplexere Methoden erforderlich. Die am häufigsten verwendeten Methoden zur Berechnung von $NO_X$ und nvPM sind in diesem Bericht kurz zusammengefasst. Ansatzmöglichkeiten zur Verringerung der notwendigen Datenmenge zur Abschätzung der Nicht-$CO_2$-Effekte werden in Abschnitt 4 diskutiert. Um die Auswirkungen dieser Vereinfachungen auf die Berechnungs-methoden zur Einbeziehung von Nicht-$CO_2$-Effekten in Emissionshandelssysteme zu quantifizieren sind jedoch detailliertere Analysen erforderlich, die auf einer größeren Anzahl tatsächlicher oder modellierter Flugmissionen basieren. In Abschnitt 5 werden die für das EU ETS und des neu gegründeten CORSIA bestehenden Rahmenbedingungen zur Überwachung, Berichterstattung und Überprüfung («Monitoring, Reporting and Verification» oder MRV) für

Luftfahrzeugbetreiber (LfzB) vorgestellt. Basierend auf einer Aufschlüsselung des zyklischen MRV-Prozesses in einzelne Schritte werden die Einhaltungskosten der gängigen Praxis nach dem EU ETS und die zu erwartenden Einhaltungskosten nach CORSIA für drei Größenkategorien von Flugzeugbetreibern geschätzt: klein (<100'000 tCO2), mittel (100'000 - 2'000'000 tCO2), groß (> 2'000'000 tCO2). In Abschnitt 6 wird der für LfzB entstehende zusätzliche Verwaltungsaufwand durch den Einbezug von Nicht-C02-Effekten in die bestehende umweltökonomische Konzepte (EU ETS, CORSIA) untersucht. Die Höhe dieser zusätzlichen Kosten hängt dabei stark von der Berechnungsmethode der $CO_2$-Äquivalente ab. Je genauer dabei die relevanten atmosphärischen Prozesse berücksichtigt werden, umso größer ist der resultierende Mitigationsnutzen.

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## List of Abbreviations

| | |
|---|---|
| **AFIRS** | Automated Flight Information Reporting System |
| **ANSP** | Air Navigation Service Provider |
| **AER** | Annual Emissions Report |
| **CERT** | $CO_2$ Estimation and Reporting Tool |
| **CORSIA** | Carbon Offsetting and Reduction Scheme for International Aviation |
| **CCD** | Climb cruise descent cycle |
| **CiC** | Contrail-induced cloudiness |
| **Edb** | Emission Database |
| **$EICO_2$** | Emission Index for carbon dioxide |
| **$EIH_2O$** | Emission Index for water vapour |
| **$EINO_x$** | Emission Index for nitrogen oxides |
| **EMP** | Emissions Monitoring Plan |
| **EU ETS** | European Union Emissions Trading System |
| **EUCR** | Emissions Unit Cancellation Report |
| **FAR** | Fuel to air ratio |
| **LTO** | Landing and take-off cycle |
| **MBM** | Marked-based-measures |
| **MRV** | Monitoring, Reporting and Verification |
| **RQL** | Rich – Quench – Lean Combustion System |
| **SET** | Small Emitters Tool |
| **SLS** | Sea Level Static |

## Summary

This final report summarizes the results of work package 2 (Determination of emissions by the aircraft operator) and work package 3.1 (Identification and elimination of existing data gaps) within six sections. After the introduction (Section 1) direct emissions of the combustion of hydrocarbon fuels are presented (Section 2). Main combustion products are $CO_2$ and $H_2O$, which are directly proportional to the fuel flow. If sulfur is contained in the jet fuel all sulfur is oxidized to sulfur dioxide ($SO_2$) during the combustion. The amount of sulfur is depending on the crude oil the fuel was refined from. As sulfur is not needed for the operation of the gas turbine, synthetic fuels do not contain any sulfur. To enable easy comparisons between engines of different sizes, the amount of emissions of a species is quoted in relation to the fuel flow of the engine. This parameter is known as Emission Index (EI) and it is usually given in grams of emissions per kilogram of fuel (g/kg). The emission index of $CO_2$ and $H_2O$ can be approximated as constant; the emission index of $SO_2$ is a function of the fuel sulfur content only.

Contrary to $CO_2$, $H_2O$ and $SO_2$, secondary combustion emissions (Section 3) like nitrogen oxides ($NO_X$) and non-volatile particulate matter (nvPM) are strongly dependent on the type and operating condition of the aircraft engine. Therefore, more complex methods are required to establish the amount of these species, emitted by an aircraft engine. Typically, these prediction methods do not model the physical and chemical processes of emissions formation (although many are derived from simplified models of these processes), but correlate measured emissions data with thermodynamic parameters of the engine, which characterize the operating condition of the combustor. That is why these methods are also known as correlation methods. They divide into two general categories: Direct prediction methods and relative or ratio prediction methods. Direct emission prediction methods are typically developed by engine manufacturers and based on their deep knowledge of engine performance and combustor physical parameters. These methods have the potential to give quite accurate results, but are usually specific to a particular engine or combustor type. Therefore, their application is principally limited to institutions or companies which have access to internal engine or combustor data. The principle of ratio or relative correlation methods is to calculate the amount of emissions of a certain operating condition in relation to a reference condition, for which the emission amount is known. In order to select this reference condition, relative correlation methods make use of a characteristic parameter, which is selected or defined in a way that operating conditions with the same characteristic parameter have similar emission production. For accurate prediction of cruise emissions, usually further correction terms are required to account for the impact of the different ambient conditions in high altitudes. The most commonly used methods for calculating $NO_X$ and nvPM are briefly summarized in this report.

In Section 4, potential ways to reduce the amount of data required to estimate the climate impact of non-$CO_2$ emissions are discussed. Categorization and averaging procedures have been used successfully in the past to simplify the calculation of emission inventories and appear to be also applicable to the calculation of $eqCO_2$ factors. However, to quantify the effect of these simplification procedures on the more complex climate metrics proposed for including non-$CO_2$ effects in emission trading systems, more detailed analyses, based on a larger number of actual or modeled flight missions will be needed. Furthermore, it needs to be verified that products with superior emission performance are correctly represented by these procedures, to avoid penalizing airlines which invest into more environmentally compatible technologies.

Section 5 presents the existing framework conditions for monitoring, reporting and verification (MRV) for aircraft operators for the EU ETS and the newly established CORSIA for compliance purposes. . Performing the administrative tasks required – such as collecting data, processing it, or carrying out relevant but non-data related activities – imposes a financial burden on aircraft operators in terms of staff resources allocated but also direct costs paid to third-parties for relevant services delivered. The overall administrative effort and cost incurred is highly dependent on the specifics of an individual aircraft operator's operations; therefore, key simplifications and assumptions are used in this work to estimate the compliance burden.

Based on a breakdown of the cyclical MRV process into discrete steps, current practice compliance costs under the EU ETS and anticipated compliance costs under CORSIA are estimated for three aircraft operator size categories: small (<100'000 tCO2), medium (100'000 – 2'000'000 tCO2), large (> 2'000'000 tCO2). While certain synergies are foreseen between EU ETS and CORSIA MRV, monitoring for CORSIA will add additional effort compared to an operator's existing EU ETS compliance. Overall, administrative compliance costs incurred by aircraft operators are non-negligible, however in most cases the largest cost in complying with these regulatory schemes will rather be the actual price placed on their emissions.

The inclusion of non-$CO_2$ climate species into existing climate protecting measures like the EU ETS or CORSIA will lead to additional administrative efforts and costs for aircraft operators (Section 6). The level of these additional expenses will be strongly depending on the method to estimate $CO_2$ equivalents ($^{eq}CO_2$). A higher accuracy in taking into account the relevant atmospheric processes will result in larger benefits for climate mitigation. But, however, more accurate $^{eq}CO_2$ approaches will also require a higher amount of data for monitoring, reporting and verification. The distance dependent $^{eq}CO_2$ factor is the simplest calculation method for equivalent $CO_2$ emissions under consideration here. It can be estimated easily by multiplying $CO_2$ emissions with the equivalent $CO_2$ coefficient provided by the supervising authority. However, since reductions in $NO_x$ emissions as well as changes in flight regions or altitude are not taken into account by the distance dependent $^{eq}CO_2$ factor at all, very small incentives for airlines are created here to mitigate the climate effect of non-$CO_2$ effects.

To calculate climatological latitude-height dependent equivalent $CO_2$ emissions, aircraft operators have to provide the emission location as well as the amount of emission at that point. 3D waypoint profile data can be collected by the aircraft operators with reasonable effort. The estimation of the individual emission quantitates is based on fuel flow data, which can be obtained in four different ways, implying different levels of data accuracy and administrative efforts. The calculation of emission inventories for $CO_2$ and $H_2O$ is possible with a high level of precision, and by applying a relatively simple formula. However, estimating emission inventories for $NO_x$ will lead to a relatively high administrative effort for the aircraft operators. To ensure that airlines do not withhold waypoint profile or emission data on purpose, the system must generate a financial incentive for airlines to provide them. This means that the calculation of $CO_2$ equivalents based on rough assumptions should lead to (insignificantly) higher values.

A weather and spatial dependent $^{eq}CO_2$ factor the same administrative efforts from the aircraft operators as a climatological latitude-height dependent factor plus efforts for collecting meteorological data. The required meteorological information is provided by two world area forecast centers in London (Met Office) and Washington (NOAA).

# Zusammenfassung

Dieser Abschlussbericht fasst die Ergebnisse des Arbeitspakets 2 (Bestimmung der Emissionen durch den Flugzeugbetreiber) und des Arbeitspakets 3.1 (Identifizierung und Behebung bestehender Datenlücken) in sechs Kapiteln zusammen.

Nach der Einführung (Abschnitt 1) werden direkte Flugzeugemissionen, die bei der Verbrennung von Kohlenwasserstoffbrenn-stoffen ausgestoßen werden, vorgestellt (Abschnitt 2). Die dabei entstehenden Hauptverbrennungsprodukte sind $CO_2$ und $H_2O$, die beide direkt proportional zum Kraftstoffstrom sind. Sind Schwefelrückstände im fossilen Treibstoff enthalten, so werden diese bei der Verbrennung zu Schwefeldioxid (SO2) oxidiert. Die Schwefelmenge im Treibstoff hängt dabei vom Rohöl ab, aus dem der Kraftstoff raffiniert wurde. Da Schwefel für den Betrieb der Gasturbine nicht benötigt wird, ist in synthetischen Kraftstoffen kein Schwefel vorhanden. Um Triebwerke verschiedener Größen miteinander vergleichen zu können, wird die Menge der Emissionen eines Spurenstoffes im Verhältnis zum Kraftstoffdurchfluss des Triebwerks angegeben. Dieser als Emissionsindex (EI) bezeichnete Parameter wird in der Regel in Gramm Emissionen pro Kilogramm Kraftstoff (g/kg) angegeben. Die Emissionsindizes von $CO_2$ und $H_2O$ können als konstant angenähert werden; der Emissionsindex von $SO_2$ ist eine Funktion des Schwefelgehalts des Kraftstoffs.

Die sekundären Verbrennungsemissionen (Abschnitt 3), wie Stickoxide ($NO_X$) und nichtflüchtige Partikel (nvPM), sind im Gegensatz zu $CO_2$, $H_2O$ und $SO_2$ stark von der Art und dem Betriebszustand eines Flugzeugmotors abhängig. Um die Emissionsmenge an $NO_X$ und nvPM bestimmen zu können, sind daher komplexere Methoden erforderlich. Viele Abschätzmethoden simulieren allerdings nicht die physikalischen und chemischen Prozesse der Emissionsbildung (obwohl viele von ihnen aus vereinfachten Modellen dieser Prozesse abgeleitet sind), sondern korrelieren gemessene Emissionsdaten mit thermodynamischen Parametern des Triebwerks, die den Betriebszustand der Brennkammer charakterisieren. Diese Methoden werden deshalb auch als Korrelationsmethoden bezeichnet und lassen sich in zwei allgemeine Kategorien unterteilen: Direkte Korrelationsmethoden und relative oder verhältnisbasierte Korrelations-methoden. Direkte Korrelationsmethoden werden typischerweise von Triebwerksherstellern entwickelt und basieren auf ihren fundierten Kenntnissen der Triebwerksleistung und der physikalischen Parameter der Brennkammer. Diese Methoden liefern sehr genaue Ergebnisse, sind aber in der Regel triebwerkspezifisch oder brennkammerspezifisch. Um diese Methoden anwenden zu können, müssen daher explizite Daten dieser Triebwerke bzw. Brennkammern vorliegen. Relative oder verhältnisbasierte Korrelationsmethoden bestimmen die Emissionsmenge eines bestimmten Betriebszustandes in Bezug auf einen Referenzzustand, für den die Emissionsmenge bekannt ist. Die Referenzbedingungen werden dazu mit einem charakteristischen Parameter beschrieben, der so ausgewählt oder definiert ist, dass Betriebsbedingungen mit dem gleichen charakteristischen Parameter eine ähnliche Emissionsproduktion aufweisen. Soll dabei der Einfluss der unterschiedlichen Umgebungsbedingungen in großen Flughöhen berücksichtigen werden, sind oft weitere Korrekturterme erforderlich. Die am häufigsten verwendeten Methoden zur Berechnung von $NO_X$ und nvPM sind in diesem Bericht kurz zusammengefasst.

Ansatzmöglichkeiten zur Verringerung der notwendigen Datenmenge zur Abschätzung der Nicht-$CO_2$-Effekte werden in Abschnitt 4 diskutiert. So werden für die Berechnung von Emissionskatastern bereits Verfahren der Kategorisierung und Mittelwertbildung eingesetzt, die auch auf die Berechnung von $^{eq}CO_2$-Faktoren anwendbar sind. Um die Auswirkungen dieser Vereinfachungen auf die Berechnungsmethoden zur Einbeziehung von Nicht-$CO_2$-Effekten in

Emissionshandelssysteme zu quantifizieren sind jedoch detailliertere Analysen erforderlich, die auf einer größeren Anzahl tatsächlicher oder modellierter Flugmissionen basieren. Darüber hinaus muss sichergestellt werden, dass das Emissionsverhalten von Produkten mit neuen Technologien zur Emissionsreduzierung durch diese Verfahren korrekt dargestellt wird, damit Fluggesellschaften, die in diese umweltfreundlicheren Technologien investieren, nicht benachteiligt werden.

In Abschnitt 5 werden die für das EU ETS und des neu gegründeten CORSIA bestehenden Rahmenbedingungen zur Überwachung, Berichterstattung und Überprüfung («Monitoring, Reporting and Verification» oder MRV) für Luftfahrzeugbetreiber (LfzB) vorgestellt. Um die Einhaltung der Vorschriften zu belegen müssen LfzB Emissionsdaten aufzeichnen und an die zuständigen Behörden weitergeben. Die Erfüllung der erforderlichen Verwaltungsaufgaben, wie die Erhebung von Daten, deren Verarbeitung oder die Durchführung relevanter, aber nicht datenbezogener Tätigkeiten, führt zu einer finanziellen Belastung der Flugzeugbetreiber in Form von zusätzlichen Personalressourcen, aber auch von direkten Kosten für erbrachte Dienstleistungen von Dritten. Der gesamte Verwaltungsaufwand und die dazu anfallenden Kosten hängen stark von den Eigenschaften des Betriebs des einzelnen Flugzeugbetreibers ab, daher werden in dieser Studie wichtige Vereinfachungen und Annahmen getroffen, um den, mit dem Einhalten der Vorschriften verbundenen, Aufwand abzuschätzen.

Basierend auf einer Aufschlüsselung des zyklischen MRV-Prozesses in einzelne Schritte werden die Einhaltungskosten der gängigen Praxis nach dem EU ETS und die zu erwartenden Einhaltungskosten nach CORSIA für drei Größenkategorien von Flugzeugbetreibern geschätzt: klein (<100'000 tCO2), mittel (100'000 - 2'000'000 tCO2), groß (> 2'000'000 tCO2). Während gewisse Synergien zwischen dem EU ETS und dem CORSIA MRV vorgesehen sind, wird die Überwachung des CORSIA, im Vergleich mit den bestehenden EU ETS Vorschriften, dennoch zusätzliche Anstrengungen für die Betreiber erfordern. Insgesamt sind die Verwaltungskosten für die Einhaltung der Vorschriften durch die Flugzeugbetreiber nicht unerheblich, aber in den meisten Fällen werden die größten Kosten für die Einhaltung dieser Regulierungssysteme eher dem tatsächlichen Preis für ihre Emissionen entsprechen.

In Abschnitt 6 wird der für LfzB entstehende zusätzliche Verwaltungsaufwand durch den Einbezug von Nicht-$C0_2$-Effekten in die bestehende umweltökonomische Konzepte (EU ETS, CORSIA) untersucht. Die Höhe dieser zusätzlichen Kosten hängt dabei stark von der Berechnungsmethode der $CO_2$-Äquivalente ($^{eq}CO_2$) ab. Je genauer dabei die relevanten atmosphärischen Prozesse berücksichtigt werden, umso größer ist der resultierende Mitigationsnutzen. Mit zunehmenden Detaillierungsgrad der $^{eq}CO_2$-Ansätze steigt allerdings auch die benötigte Datenmenge für MRV (Monitoring, Reporting und Verifikation) Tätigkeiten. Die in dieser Studie einfachste Berechnungsmethode zur Bestimmung von $CO_2$-Äquivalenten ist dabei der distanzabhängige $^{eq}CO_2$-Faktor, bei dem $CO_2$-Äquivalente durch Multiplikation der (bekannten) $CO_2$-Emissionsmenge mit einem für alle Spurenstoffe einheitlichen distanzabhängigen $CO_2$-Koeffizienten berechnet werden. Da allerdings Mitigationsbemühungen, wie eine Reduzierung der $NO_x$-Emissionen oder eine Veränderung der Flugroute oder –höhen, durch eine rein distanzabhängige Berechnungsmethode nicht berücksichtig werden, werden bei diesem Ansatz kaum Anreize für Fluggesellschaften geschaffen, ihre Klimawirkung zu reduzieren.

Soll eine Ortsabhängigkeit in die $^{eq}CO_2$-Berechnung integriert werden, müssen Flugzeugbetreiber 3D-Emissionskataster entlang der Flugroute vorliegen. Die Erfassung und Bereitstellung von 3D-Wegpunktprofildaten durch den LfzB ist mit geringem Aufwand möglich. Die Abschätzung der verschiedenen Emissionsmengen erfolgt mithilfe von Kraftstoffflussdaten, die auf vier verschiedene Arten gewonnen werden können, was ein unterschiedliches Maß an Datengenauigkeit und Verwaltungsaufwand impliziert. Für $CO_2$ und $H_2O$ können dabei Emissionskataster nach einer relativ einfachen Formel mit hoher Genauigkeit bestimmt werden. Der Aufwand zur Abschätzung von $NO_x$ Emissionskataster ist deutlich höher und ungenauer. Um bei dieser Berechnungsmethode sicherzustellen, dass die Fluggesellschaften Wegpunktprofile oder Emissionsdaten nicht absichtlich zurückhalten, muss das System so ausgelegt sein, dass die Bereitstellung der benötigten Daten finanziellen attraktiv ist. Dies bedeutet, dass eine Berechnung der $CO_2$-Äquivalente auf Basis grober Annahmen zu (geringfügig) höheren $^{eq}CO_2$-Werten führen sollte.

Bei einem wetter- und ortsabhängiger $^{eq}CO_2$-Faktor erhöht sich der administrativen Aufwand für LfzB weiter, da in diesem Fall zusätzlich noch meteorologische Daten erfasst werden müssen. Alle dafür benötigten meteorologischen Daten werden bereits weltweit durch zwei „World Area Forecast Centre“ (WAFC) in London (Met Office) und Washington (NOAA) bereitgestellt.

# 1 Introduction

The report on suitable climate metrics for assessing the relation of non-$CO_2$ und $CO_2$ climate effects discusses atmospheric impacts of aircraft emissions and potential metrics to account for their climate effects in an emissions trading system or marked-based-measures (MBM). These climate metrics require information on the amount of emissions resulting from aircraft operations with different levels of detail and accuracy. This report therefore focuses on methods to establish this information.

According to today's state of knowledge, emission species that contribute to the climate impact of aviation are carbon dioxide ($CO_2$), water vapor ($H_2O$), nitrogen oxides ($NO_X$) and aerosols. The aerosols are further subdivided in volatile and non-volatile particulate matter (vPM and nvPM, respectively). While the latter basically consists of black carbon, volatile particles can form from several sources, mainly unburned hydrocarbons (HC), $NO_X$ and sulfur oxides ($SO_2$), which result from the combustion of sulfur compounds contained in the fuel. Beside to these emissions the climate is influenced by the formation of contrails and contrail-cirrus due to the emission of warm and humid exhaust.

Emissions from combustion processes subdivide into two categories: All products resulting from complete oxidation of the fuel components are known as direct emissions. For conventional hydrocarbon fuel these are $CO_2$, $H_2O$ and $SO_2$. Products that are formed during the combustion process, but are not a direct result of oxidation of the fuel, are known as secondary emissions. The most important secondary emissions are $NO_X$ and particulate matter. Products of incomplete combustion, such as unburnt hydrocarbons (HC) and carbon monoxide (CO), also fall into this category, but are more relevant to local air quality.

An important trade-off exists between $CO_2$ and $NO_X$ emissions, which needs to be considered when talking about aviation emissions reduction: To improve the efficiency of the aircraft engine thermodynamic cycle and hence reduce its $CO_2$ emissions, pressure ratio and peak temperature need to be increased. On the other hand, both measures increase the $NO_X$ formation rates, and as a result, controlling $NO_X$ emissions becomes more and more difficult with increasing fuel efficiency of aircraft engines.

# 2 Direct combustion emissions

## 2.1 Carbon dioxide ($CO_2$) and water ($H_2O$)

$CO_2$ and $H_2O$ are the main products of the combustion of hydrocarbon fuels. Thanks to the high combustion efficiency of modern gas turbine engines (close to 100% over the normal operating range, including idling [Lefebvre and Ballal, 2010]), emissions of these combustion products are directly proportional to the fuel flow: With an average molecular formula of $C_{12}H_{23}$, complete combustion of 1 kg of jet fuel gives 3.1573kg $CO_2$ and 1.2372kg water [Rachner, 1998][5]. Often, the amount of emissions of a species is quoted in relation to the fuel flow of the engine, to enable easy comparisons between engines of different sizes. This parameter is known as Emission Index (EI) and it is usually given in grams of emissions per kilogram of fuel (g/kg).

For $CO_2$ and $H_2O$ the emission index is only a function of the fuel composition (due to the high combustion efficiency, unburned or partially burned fuel can be neglected). Therefore, the emission indices for carbon dioxide and water can be given as

$$EI\ CO_2 = 3157.3\ {}^{g}/_{kg} \tag{1}$$

$$EI\ H_2O = 1237.2\ {}^{g}/_{kg} \tag{2}$$

These values are independent of engine type or operating condition.

## 2.2 Sulphur dioxide ($SO_2$)

Sulfur is contained in jet fuel in varying amounts. Typical fuel sulfur content is in between <0.05 and 0.075% by mass with an average of approximately 0.06% [Barrett et al., 2012], depending on the crude oil the fuel was refined from. The maximum allowed by the fuel specification is 0.30% [ASTM international, 2012]. Sulfur is not needed for the operation of the gas turbine and therefore is more considered a contaminant[6]. Synthetic fuels do not contain any sulfur. During the combustion process, all sulfur is oxidized and leaves the engine as $SO_2$. Therefore, the emission index of $SO_2$ is a function of the fuel sulfur content $f_S$ only:

$$EI\ SO_2 = \frac{M_{SO_2}}{M_S} \cdot f_S = 2 \cdot f_S \tag{3}$$

where $f_S$ is the mass fraction of Sulfur in the fuel, given in grams per kilogram. $M_S$ and $M_{SO2}$ are the molar masses of sulfur and sulfur dioxide, respectively.

[5] Slightly different values have been published by various sources, depending on the average fuel composition assumption. For example, the ICAO Carbon Calculator uses a value of 3.16kg $CO_2$ per kg fuel [ICAO, 2017a]

[6] However, removing sulfur from the fuel comes with the issue that the same technical processes, which are used to remove sulfur, also remove fuel compounds which are needed for the lubrication of fuel pumps and other engine components

# 3 Secondary combustion emissions

## 3.1 Nitrogen oxides ($NO_X$) and non-volatile particulate matter (nvPM)

Contrary to $CO_2$, $H_2O$ and $SO_2$, emissions of $NO_X$ and nvPM are strongly dependent on the type and operating condition of an aircraft engine. Nitrogen oxides are produced when the nitrogen contained in the combustion air is oxidized during (relatively) long residence times under high temperature and pressure conditions. Formation and oxidation of non-volatile particles occurs under fuel-rich and fuel -lean conditions, respectively. The exact formation mechanisms are not yet fully understood. The amount of particles emitted is the net result of production (formation) and consumption (oxidation) processes, which occur simultaneously in the combustor.

Therefore, more complex methods are required to establish the amount of these species, emitted by an aircraft engine. Several methods are available, which differ in their data requirements and hence the resulting accuracy. The most common methods are described in the subsequent section.

## 3.2 $NO_X$ emission prediction methods

Quantities of in-flight emissions from aircraft engines are required to estimate the impact of global air transport on air quality and climate change. However, since $NO_X$ and nvPM emissions are not directly proportional to the fuel burn and measuring these emissions in the engine plume in flight is extremely difficult and expensive, modelling methods have been established to predict in flight emissions of these species, based on data from ground measurements. Typically, these prediction methods do not model the physical and chemical processes of emissions formation (although many are derived from simplified models of these processes), but correlate measured emissions data with thermodynamic parameters of the engine, which characterize the operating condition of the combustor. That is why these methods are also known as correlation methods.

A number of different emission prediction methods have been proposed, which divide into two general categories: Direct prediction methods and relative or ratio prediction methods. Most of these methods have been originally designed to model $NO_X$ emissions, but it is believed that the same principles are also applicable to model nvPM emissions. However, due to the more complex and yet partly unknown processes of nvPM formation, additional parameters and more complex reference functions may need to be considered for nvPM modeling.

## 3.3 Direct prediction methods

Typically, direct emission prediction methods are developed by engine manufacturers and based on their deep knowledge of engine performance and combustor physical parameters. These methods have the potential to give quite accurate results, but are usually specific to a particular engine or combustor type. Often, they include coefficients which need to be calibrated for the specific engine type under consideration.

The following example of a more generalized formulation of a direct prediction method, which includes factors that allow a calibration of the equation for different engine or combustor types, has been used by MTU [Schumann, 1995]:

$$EI\ NO_X = A + B \cdot \left(\frac{p_C}{29.83}\right)^{0.4} \cdot exp\left(\frac{1.8 \cdot T_C - 1487.27}{349.9}\right), \qquad (4)$$

where $p_C$ and $T_C$ are combustor inlet pressure and temperature, respectively. The factors A and B might be used to calibrate the correlation for a specific engine.

A similar method with specified coefficients (probably for a particular engine type) has been proposed by General Electric [Prather et al., 1992]:

$$EI\ NO_x = 2.2 + 0.12325 \cdot p_C^{0.4} \cdot exp\left(\frac{T_C}{194.4}\right), \tag{5}$$

Further prediction methods of this type have been published (for an overview, see [Schumann, 1995], but their application is principally limited to institutions or companies which have access to internal engine or combustor data. However, if such a method would be implemented e.g. in the engine control software, the amount of $NO_X$ produced could be calculated with good precision at any time when the engine is operating.

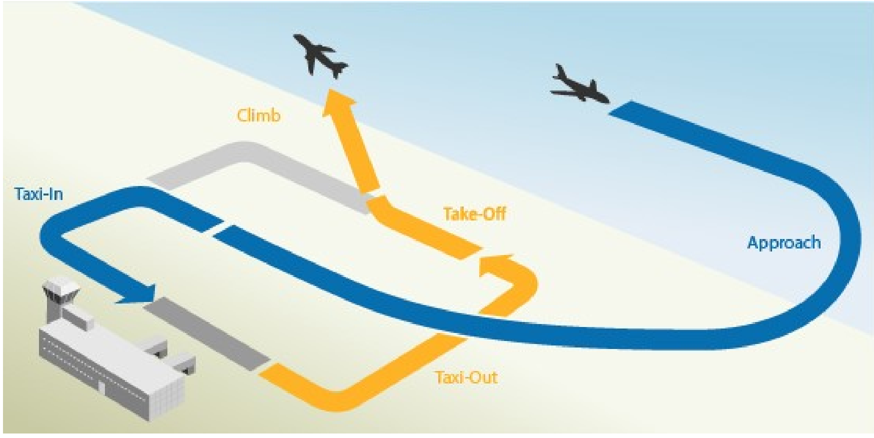
## 3.4 Relative/Ratio prediction methods

The limitations of direct $NO_X$ prediction methods due to the use of engine internal thermodynamic data and their need to be calibrated individually for each engine type has led to the development of more generally applicable methods, which are known as ratio or relative correlation methods. The principle of these methods is to calculate the amount of emissions of a certain operating condition in relation to a reference condition, for which the emission amount is known. In order to select this reference condition, relative correlation methods make use of a characteristic parameter, which is selected or defined in a way that operating conditions with the same characteristic parameter have similar emission production. For accurate prediction of cruise emissions, usually further correction terms are required to account for the impact of the different ambient conditions in high altitudes.

These methods take advantage from the obligation of aircraft engine manufacturers to publish Sea Level Static (SLS) emissions data of every certified turbofan engine with more than 26.7kN of rated thrust in a publically available databank, the ICAO Aircraft Engine Emissions DataBank (EDB) [ICAO, 2018]. Therefore, the required reference data are always available and as the reference flight condition usually SLS (0m altitude, Mach number 0) is selected.

In the ICAO EDB, emission and fuel flow data are published for four different operating conditions of each engine, which together are part of a standardized landing and take-off (LTO) cycle. This LTO cycle was originally defined to assess the impact of aviation on local air quality and was designed to represent the typical operating conditions of an aircraft engine in the vicinity of an airport below 3000ft (915m) flight altitude (Figure 1).

**Figure 1: The ICAO LTO-cycle, modes, thrust settings and times in mode**




LTO cycle

| Mode | Thrust | Time |
|---|---|---|
| Take-off | 100% | 0.7 min |
| Climb | 85% | 2.2 min |
| Approach | 30% | 4.0 min |
| Taxi | 7% | 26 min |

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Such data are available for Nitrogen Oxides ($NO_X$), Carbon Monoxide (CO), unburnt Hydrocarbons (HC) and Smoke Number (SN). The Smoke Number is coupled to the exhaust mass concentration of non-volatile Particulate Matter (nvPM) and conversion formulae are available to convert SN data into nvPM emission indices. However, it is expected that more detailed, higher quality nvPM emissions data will be published in the future [ICAO, 2016].

In the following, the most commonly used methods for calculating $NO_X$ and nvPM are briefly summarized.

## 3.4.1 Nitrogen Oxides ($NO_X$)

### 3.4.1.1 The p3-T3 method

As seen in the previous chapter, many prediction methods concentrate on pressure and temperature in the combustion zone as the most influential parameters on $NO_X$ production. Consequently, a relative prediction method based on these parameters has been proposed by Rolls-Royce [Madden and Park, 2003] and is preferred today for $NO_X$ estimation by many manufacturers. This method makes use of the combustor inlet temperature $T_3$ as characteristic parameter. Furthermore, it includes corrections for combustor pressure ($p_3$) and fuel to air ratio (FAR). Since these data are almost never publically available, engine performance models or engine decks are often used to determine the required values. For conventional Rich – Quench – Lean Combustion System (RQL) combustors, the impact of FAR changes can be neglected, because in these types of combustors the FAR in the primary combustion zone is always stoichiometric.

For application of the method, as a first step reference functions need to be established to correlate the parameters used by the method with its characteristic parameter $T_3$. These reference functions will subsequently be used to interpolate between the four operating conditions of the LTO-Cycle:

$$EI\ NO_{X,Ref} = f_1(T_3) \quad (6)$$

$$p_{3,Ref} = f_2(T_3) \quad (7)$$

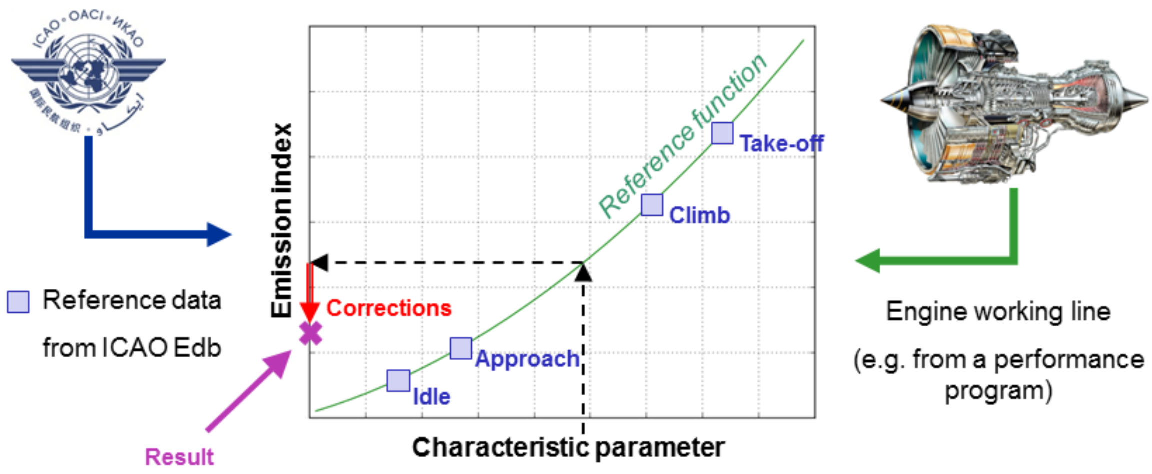
$$FAR_{Ref} = f_3(T_3) \quad (8)$$

In most applications of the method, second order polynomials have been used to establish these reference functions. To calculate the EI $NO_X$ of any operating condition, characterized by its combustor inlet temperature $T_3$, the reference values $p_{3,\,Ref}$ and, if needed, $FAR_{Ref}$ need to be calculated with these reference functions. Then the current EI $NO_X$ is calculated from the reference values and the current $p_3$ and FAR by the following equation:

$$EI\ NO_X = EI\ NO_{X,Ref} \cdot \left(\frac{p_3}{p_{3,Ref}}\right)^{\alpha} \cdot \left(\frac{FAR}{FAR_{Ref}}\right)^{\beta} \tag{9}$$

The pressure exponent $\alpha$ is in the range from 0.3 to 0.5 for conventional combustors. The FAR exponent $\beta$ is usually set to 0, because, as mentioned above, for conventional RQL combustors the fuel to air ratio in the primary combustion zone is always stoichiometric. However, for advanced combustion technology (particularly lean burn), the exponents may significantly deviate from these values. The following Figure 2 helps to illustrate the application of this method as a general example for any relative/ratio type emission prediction method:

**Figure 2: Illustration of the general application of a relative/ratio type emission prediction method**

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For the p3-T3 method, the characteristic parameter is $T_3$. From the ICAO emissions data base and an engine model, data pairs (e.g. [$EINO_X$, $T_3$] and [$p_3$, $T_3$]) for the four points of the LTO-cycle are collected or calculated, and the reference function(s) are established. In the next step, the reference values (in this example $EINO_{X,Ref}$ and $p_{3,\,Ref}$) are read off the respective reference function. In the final step, the emission index of the operating condition under consideration is calculated by applying the formula above.

The p3-T3 method is considered the most accurate relative/ratio type $NO_X$ correlation method with an accuracy of the predicted values of ±5% [Schumann, 1995]. However, the need for highly sensible internal combustor pressure and temperature data restricts the application of the method to engine manufacturers. For other entities it is possible to use an engine performance model to calculate the required data, however in this case the additional inaccuracy of the engine model and modeling software must be added to the inaccuracy of the method itself.

#### 3.4.1.2 The DLR fuel flow method

The need to apply $NO_X$ prediction methods without knowledge of sensible internal combustor data has led to a further simplification of $NO_X$ correlation methods. In [Döpelheuer and Lecht, 1999] it is described how the fuel flow, corrected for ambient conditions ($w_{FF,corr}$), can be used as a surrogate for the internal combustor data. The idea behind this simplification is that the operating condition of a turbofan engine is determined only by the conditions of the ambient air and the fuel flow to the combustor. From the literature, it is well known that a corrected fuel flow can be defined which is similar for thermodynamically similar operating conditions of a gas turbine engine (see e.g. [Walsh and Fletcher, 1998]):

$$w_{FF,corr} = \frac{w_{FF}}{\delta \cdot \sqrt{\theta}} \qquad (10)$$

where

$$\delta = \frac{p}{p_0} \quad (p_0 = 101325\text{Pa}) \qquad (11) \qquad \text{and} \qquad \Delta\theta = \frac{T}{T_0} \; (T_0 = 273.15\text{K}) \qquad (12)$$

These equations use total (stagnation) pressures and temperatures. Assuming an isentropic exponent of air of 1.4, these can be calculated from the static values $p_S$ and $T_S$ with help of the flight Mach number Ma by

$$p = p_S \cdot (1 + 0.2 \cdot Ma^2)^{3.5} \qquad (13) \qquad \text{and} \qquad T = T_S \cdot (1 + 0.2 \cdot Ma^2) \qquad (14)$$

Similar to the p3-T3 method, a reference function is created, based on data from the ICAO EDB. In this case only one reference function is required:

$$EI\ NO_{X,Ref} = f\left(w_{FF,corr}\right) \qquad (15)$$

Second order polynomials have been used frequently to create this reference function, however sometimes curve shapes are not well reproduced by this function. Therefore, it is suggested to apply and compare also the curve-fitting method of the Boeing fuel flow method (see next paragraph) and select the most appropriate reference function.

To calculate the EI $NO_X$ of any operating condition, characterized by its corrected fuel flow $w_{FF,corr}$, the reference value EI $NO_{X,Ref}$ is read off the reference function. Then the current EI $NO_X$ is calculated from the reference values and the ambient conditions ($\delta$, $\theta$) by the following equation:

$$EI\ NO_X = EI\ NO_{X,Ref} \cdot \delta^a \cdot \theta^b \qquad (16)$$

The exponents of the pressure and temperature correction terms, *a* and *b*, have been established with help of measurement data and comparisons to other, more exact emission prediction methods. For conventional RQL combustors, the method could demonstrate a satisfactory accuracy of ±10% with values of *a*=0.4 and *b*=3.0 in most cases [Norman et al., 2003].

#### 3.4.1.3 The Boeing fuel flow method

This method is similar to the DLR fuel flow method, but uses a different fuel flow correction, which is defined in a way that the corrected fuel flow is similar for operating conditions with the same combustor inlet temperature $T_3$ [Dubois and Paynter, 2007]. This fuel flow correction is applied using static ambient temperature ($T_S$) and pressure ($p_S$) and the flight Mach number (Ma):

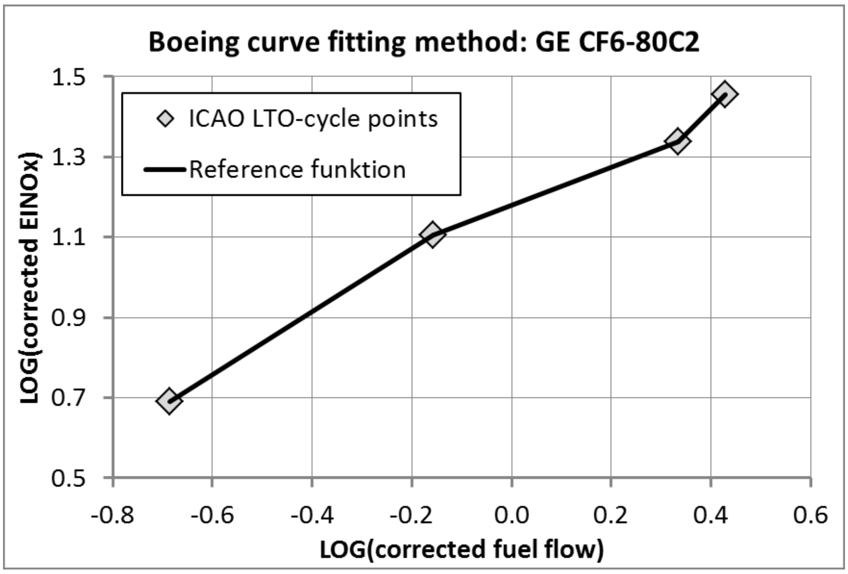
$$W^*_{FF,corr} = w_{FF} \cdot \frac{\theta_S^{3.8}}{\delta_S} \cdot e^{0.2 \cdot Ma^2} \qquad (17)$$

Where

$$\delta_s = \frac{p_s}{p_0} \quad (p_0 = 101325\text{Pa}) \qquad (18) \qquad \text{and} \qquad \theta_s = \frac{T_s}{T_0} \quad (T_0 = 273.15\text{K}) \qquad (19)$$

This method comes with a predefined procedure to create the reference function: Any two adjacent data points of the ICAO LTO-cycle are connected with a linear function in log space. An example of this curve fitting method is given in the following Figure 3:

**Figure 3: Boeing curve fitting method of connected linear functions in log space**

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This procedure has demonstrated good results with a lot of conventional engines and is suitable for automatic application. It can also be used with the DLR fuel flow method; and for automated application it is recommended to use either of the two methods, but with the Boeing curve fitting method.

#### 3.4.1.4 More detailed methods

The $NO_X$ correlation methods described in the previous paragraphs have been developed and verified for older (rich burn) and state-of-the-art (rich-quench-lean, RQL) combustors. Latest developments in combustion technology are lean burn and advanced RQL combustors, which allow for further significant reductions in $NO_X$ and nvPM emissions. However, the emission characteristics of these new combustor generations may significantly differ from those of the previous ones. This is particularly the case if some sort of fuel staging is included, for example in lean burn combustors. In these cases the conventional correlation methods may fail to correctly predict the emissions of engines with such combustors and more detailed correlations and application procedures will be needed. An overview over potential emission prediction methods for advanced technology combustors is given in [Plohr, 2016]. These are either based on the correlation methods described above, supplemented by terms taking into account impacts of additional parameters and/or fuel staging, or on more detailed correlations, which include a larger set of thermodynamic combustor data (like e.g. flame temperature, fuel to air ratio, residence time, etc.) to better reflect the combustion processes (e.g. [Stöppler, 1992]). Such methods are only applicable with deeper knowledge of the respective engine data or a sufficiently accurate engine model.

### 3.4.2 Particulate Matter

#### 3.4.2.1 Non-volatile particulate matter

Up to now, very few information on non-volatile particles emitted from aircraft engines is publically available. For certification purposes, a Smoke Number (SN) is established with represents the loss of reflectivity of a paper filter after a pre-defined amount of exhaust gas has been passed through. This smoke number is published in the ICAO EDB. Although only the publication of the maximum smoke number is mandatory, most manufacturers have additionally published SN data for the operating conditions of the LTO-cycle. The smoke number is coupled to the mass concentration of nvPM in the exhaust and several authors have tried to correlate the two. The latest correlation, using the largest data background, is published with ICAO's FOA3 method [ICAO, 2011]. Still the precision of this method is only fair, due to large measurement uncertainties of the Smoke Number and the resulting data scatter.

Using this information, DLR has developed a correlation method to predict an emissions index of nvPM mass under all operating conditions [Döpelheuer, 2002]. However, the accuracy of this method is limited by the low quality of the available base data. Moreover, compared to $NO_X$, nvPM emission (or SN) characteristics are much more diverse: While $NO_X$ is always increasing with engine power, as a consequence of increasing combustion temperature, the maximum smoke number might occur anywhere in the engine operating range, because the emitted amount of particles is the net result of formation and oxidation processes, which themselves are dependent on a number of different parameters.

While the smoke number standard was originally introduced to prevent aircraft from producing visible smoke trails, in the past years potential hazardous effects of particles on the environment and particularly on human health have become a concern. As a consequence, ICAO has started work on a new certification standard for non-volatile particulate matter emitted from aircraft engines that will be based on direct measurements of mass and/or number of these particles. The adoption of this standard is expected by the 11. meeting of ICAO's Committee on Aviation Environmental Protection (CAEP) in 2019 [ICAO, 2016]. Following the implementation of this standard, the publication of measured nvPM emissions data in the ICAO EDB is expected, which will potentially help to significantly improve nvPM modelling methods.

#### 3.4.2.2 Volatile particles

Even less information than on nvPM is available for emissions of volatile particles from aircraft engines. Due to the high exhaust temperatures, most of these particles do only form in the plume and therefore are not measureable at the engine exit. Sources of volatile particles may be unburned hydrocarbons, sulfur oxides, nitrogen oxides and, of course, water. Non-volatile particles, not only from the engine but also from the atmospheric background, are known to act as condensation cores for these volatile substances. ICAO has published a first approach to model volatile particle emissions with their FOA3 estimation method [ICAO, 2011]. No other, simply applicable methods are available at this point in time.

### 3.4.3 Advanced combustion technology

Some latest engine certifications include new technology combustors with significantly reduced $NO_X$ emissions. At this point in time the fuel flow correlation methods are not validated for these combustor types. Furthermore, fuel staging is often used to maintain the operational stability of such designs. For these reasons, the p3-T3 method seems more appropriate to model $NO_X$ emissions of such engine types, however even for this method further information would be required, e.g. pressure and FAR-exponents and a potential fuel staging schedule. These, as well as the required combustor inlet pressures and temperatures, are most sensible data.

# 4 Secondary combustion emissions

In earlier projects which aimed for the calculation of global air transport emission inventories, the concept of representative aircraft-engine combinations has been used to reduce the number of engine and aircraft models required to accurately represent the global fleet. The EU-funded project AERO2k [Eyers et al., 2004] has categorized aircraft to cover noise and $NO_X$ technology, the DLR-internal project PaZi-2 [Kärcher et al., 2008] classified aircraft engines into groups of similar $NO_X$ and nvPM emission characteristics. The procedure to categorize the individual aircraft types into groups, represented by a single type, was similar to both projects, however including nvPM emissions in PaZi-2 increased the number of representative engine types from 26 (AERO2k) to 52 (PaZi-2), mainly due to the more diverse nvPM emission characteristics. In the following paragraphs, the categorization procedures used in both projects are summarized.

## 4.1 Aircraft representation

As a first step, the aircraft of the global fleet were categorized by their seat capacity. 9 seat classes were used in AERO2k (seat class 9 was reserved for a potential growth variant of the A380 which was not yet realized). The aircraft in each seat class were further categorized according to their environmental performance (Noise and $NO_X$ by the respective limit the aircraft would meet, e.g. Chapter 3, Chapter 4, or CAEP/4, CAEP/6).

For each seat category, the most frequent aircraft type in the global fleet at that time was selected to represent all types in the category (obviously this selection needs to be revised from time to time due to the changing global fleet). In case significantly different aircraft configurations were found in one category (e.g. two- and three-/four-engined aircraft) these were represented by individual types from each respective configuration. Finally, the civil aircraft fleet of the year 2002, consisting of more than 300 different types, was represented by 40 representative aircraft types in AERO2k.

Comparisons with airline data and flight planning tools showed good agreement of the mission fuel calculated with the AERO2k set of representative aircraft. The mean deviation was within 5%, however for individual types could be as large as 8.5%. Additional uncertainties arise from deviations of the actual flight path and altitude profile of individual flights compared to the assumed great circle distances and standardized flight altitudes. Effects of head or tail winds and deviations to avoid weather or restricted airspace could also not be taken into account. While wind effects tend to cancel out on a global scale, the remaining effects result in an underestimate of the actual fuel consumption.

## 4.2 Representative engines

Usually, most aircraft types are available with a choice of engines from different (or even the same) manufacturers. Due to market pressure, the fuel efficiency of these different engine types is very similar. Even in the case of the Boeing B777-200, where engine options with bypass ratios between 5.7 and 8.3 were available, the maximum range with the different engine options was within 1% of the mean value [Eyers et al., 2004]. However the maximum $EINO_X$ varies by more than 26% between these engine options. Similar differences in $NO_X$ (and nvPM) reduction performance are also found in today's most modern aircraft types. Therefore, to correctly account for their non-$CO_2$ emissions, a categorization of engines, according to their $NO_X$ (and later potentially nvPM) emissions is crucial.

The best available source to base this engine categorization upon is the ICAO engine emissions database (EDB), where $NO_X$ (and other) emissions at the four operating conditions of the LTO-cycle are published for every engine type in commercial service. The most recent version of this database (version 25, [EASA, 2018]) includes 587 different entries. However, many of these engines are different thrust variants from the same engine family, to fit to aircraft with different certified MTOW, and their emission performance is identical for the same absolute thrust. These engine types can easily be combined into one class, represented by the highest thrust variant (to cover the full range of thrust required by the different applications). However, sometimes improved combustors were introduced into an existing engine family, changing the emissions performance drastically, although the engine designation was the same. In these cases, the engine class needs to be split up according to the combustor type installed (which is usually published in the EDB).

On the other hand, as a result of market forces, engine types from different manufacturers that are intended to be used on the same or similar aircraft types often have very similar emissions performance. These engines may also be combined into one class, again represented by the highest thrust variant.

By these procedures, 52 representative engine types in terms of $NO_X$ and nvPM mass emissions were selected in PAZI-2 to power the global fleet of the year 2002. As with the aircraft categories, this representative engine type selection needs to be revised periodically to account for latest developments in low emissions combustion technology and new engine types entering into service.

## 4.3 Flight profile

Where no actual flight profile is available, fuel flow and emissions data need to be modeled on the basis of standardized flight profiles. With increasing mission distance, more take-off and climb thrust will be required due to the higher fuel weight needed to accomplish the flight mission. This will also affect the emissions performance of the engines.  Therefore it is useful to categorize flight missions into distance classes which are represented by a single standardized mission, in order to avoid modelling every individual flight.

The number and width of these classes will be dependent on the accuracy required by the different climate metrics. For the distance-dependent $^{eq}CO_2$ factor a simple representation of the global route network will probably be sufficient, while the climatological latitude-height dependent $^{eq}CO_2$ factor will need different flight altitudes and latitudes taken into account. For the weather and spatial dependent $^{eq}CO_2$ factor a detailed representation of the actual flight profile is essential.

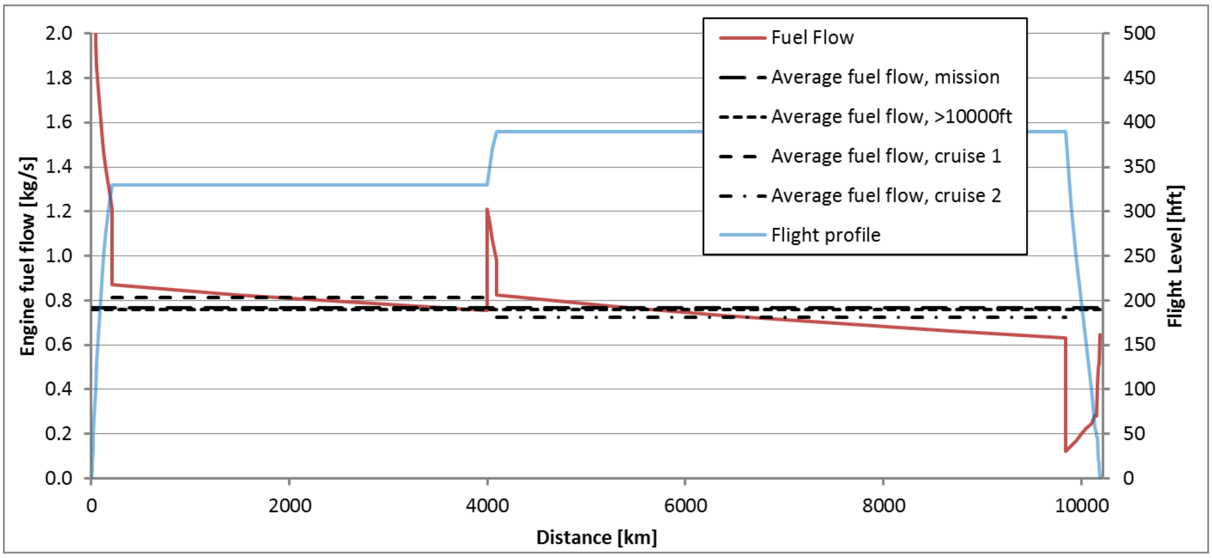
Using simplified flight missions or distance classes might significantly reduce the effort of reporting equivalent $CO_2$ emissions; however, depending on the climate metrics used, the loss of accuracy coupled to these simplifications might also be significant. A more detailed analysis would be needed to determine the trade-off between loss of accuracy and reduction of the effort.

## 4.4 Fuel flow and/or $NO_X$ averaging

### 4.4.1 Fuel flow

If simplified (categorized) flight missions are used to determine $^{eq}CO_2$ factors, a further simplification step would be to use average fuel flow and/or $NO_X$ data to represent the whole flight mission. The following Figure 4 shows different average fuel flow values, compared to the (modeled) actual fuel flow on a typical long range flight mission[7].

**Figure 4: Actual (modeled) and average fuel flows on a long range flight mission**

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In this figure the mission profile is displayed in blue, the engine fuel flow in red. Clearly, the fuel flow is highest during take-off and climb to the first cruise altitude (33000ft), although decreasing with increasing flight altitude. In the first cruise segment, the fuel flow is significantly lower than in the top of climb condition, and slowly decreasing with distance (or flight time) due to the reducing weight of the aircraft when fuel is burned. After approximately 4000km, a short step climb to a higher altitude is performed in order to match the flight altitude to the reduced weight of the aircraft. This results in an increased fuel flow during the step climb, followed by a slightly higher, but again decreasing fuel flow during the second cruise segment. Finally, for descent the fuel flow is reduced to flight idle level. On final approach some flight path corrections may be needed, resulting in a slightly higher fuel flow.

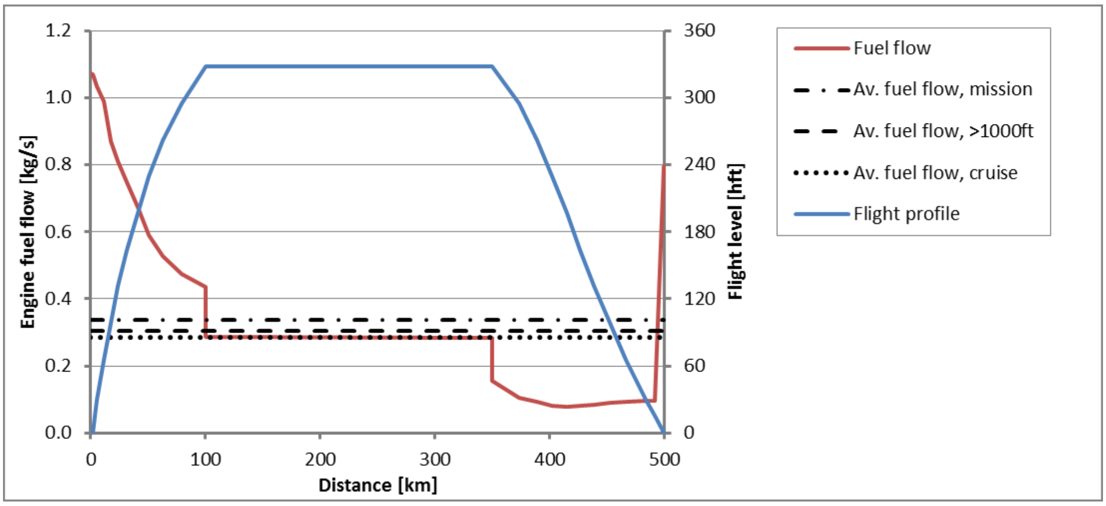
Different average fuel flow values are displayed in the figure as black lines. The first two (long and short dashed) lines show the average fuel flow on the whole mission (=mission fuel divided by mission time) and the average fuel flow above flight level 100 (10000ft or 3048m), thereby excluding take off and climb out as well as final approach procedures. Obviously, these two values are nearly identical.

The next two (dashed and dash-dotted) lines represent the average fuel flow of the two cruise segments. It turns out that the average fuel flow of the first cruise segment is higher than the whole flight average, while the second cruise average is lower.

For shorter flight missions, the effect of the decreasing fuel flow in cruise is less pronounced and the impact of the higher fuel flows during take-off and climb becomes more important. Figure 5 shows a short flight mission of a smaller aircraft type than in the previous figures.

[7] The flight missions shown in this section were modeled with DLR-owned tools and generic aircraft and engine models

**Figure 5: Actual (modeled) and average fuel flows on a short-range mission**

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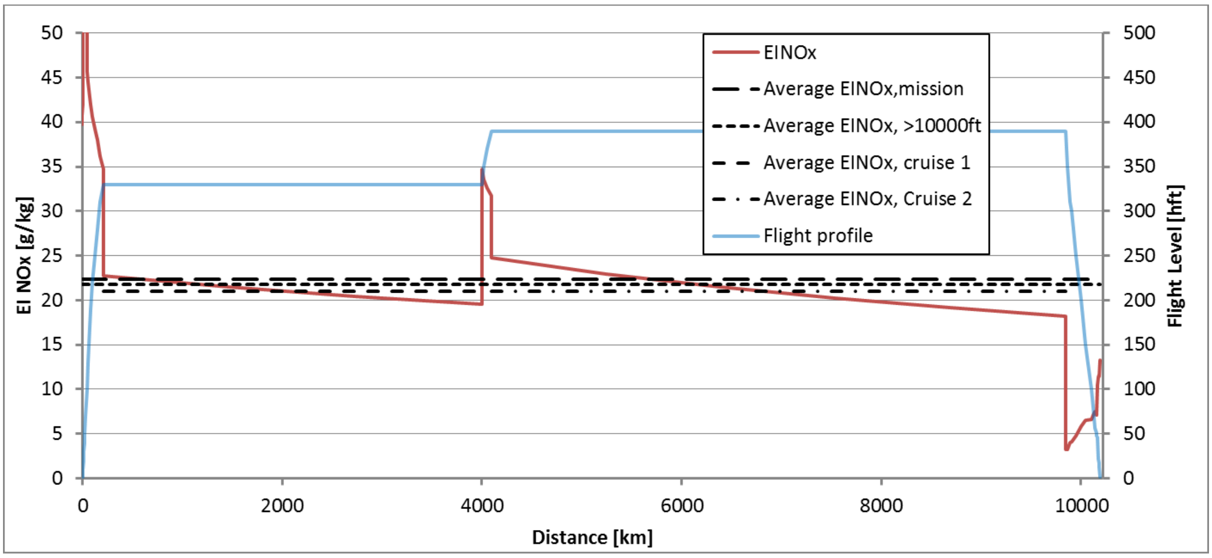
In this case the average mission fuel flow is larger than the fuel flow above 10000ft, and this is again larger than the cruise fuel flow, due to the relatively greater proportion of the take-off and climb phases.

### 4.4.2 $NO_X$

Figure 6 shows the $NO_X$ emission index, modeled with the p3-T3 method, during the long-range flight mission already shown in Figure 4:

**Figure 6: Actual (modeled) and average EI $NO_X$ on a long-range flight mission**

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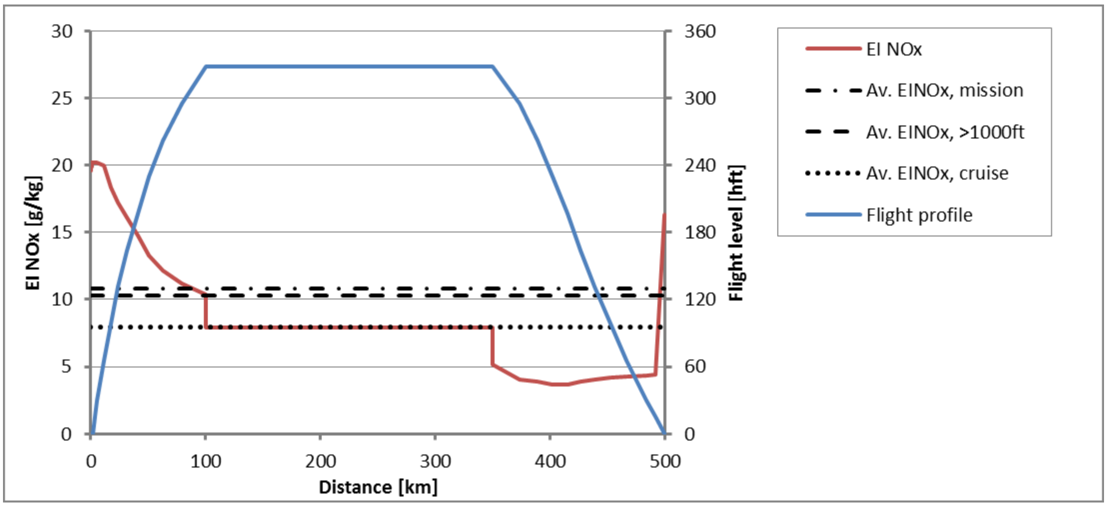
Compared with the average fuel flows, the average EI $NO_X$ values for the whole mission and for the flight segments above 10000ft show a greater difference. This is because the EI $NO_X$ is much higher in low altitude and high power conditions and reduces with reducing ambient pressure.

Furthermore, the average EI $NO_X$ values of the two cruise segments are nearly identical, in contrast to the average fuel flows, which were significantly different. This is caused by the opposing effects of lower combustor pressure and higher temperature on $NO_X$ production. With increasing flight altitude, the air density becomes lower and therefore less air is entering the combustor. To produce the required thrust, the combustor needs to operate at a higher temperature. As a result, the EI $NO_X$ at the beginning of the second cruise segment is significantly higher than anywhere in the first one, although the fuel flow is mostly lower. In combination, the EI $NO_X$ increase and the fuel flow decrease cancel each other out, and as a result the average EI $NO_X$ values of the two cruise segments are nearly identical.

On the short-range mission, the effect of increased $NO_X$ production in low altitudes is even more pronounced, while the take-off/climb and approach/landing phases below 10000ft nearly cancel each other out (Figure 7):

**Figure 7: Actual (modeled) and average EI $NO_X$ on a short-range mission**

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This different behavior of fuel flow and $NO_X$ production has implications on the potential simplifications by using average fuel flow or EI $NO_X$ values in the different climate metrics.

### 4.4.3 Implications for $^{eq}CO_2$ factors

From the figures in the previous paragraphs it is obvious that averaging fuel flows or $NO_X$ emissions is a potential way to simplify calculations of the climate impact of individual flights, as long as the exact location and altitude where the emission occurs is not taken into account. Different average EI $NO_X$ and fuel flow values show only small variation on a long-range flight mission. However, on short flight missions the mission average values will significantly over-estimate the cruise $NO_X$ emissions.

The use of average values is not appropriate for climate metrics, which take into account the actual location and altitude of the emission. Because the fuel flow and, as a result, the EI $NO_X$ is varying significantly during the flight mission, large errors would result from the use of average instead of the exact current fuel flow and emission index. However, average values of sufficiently short flight segments (e.g. five minutes) might be sufficiently close to the actual values during that time.

The level of simplification achievable is different for the three $^{eq}CO_2$ calculation methods described by Dahlmann et al. (2018):

- **Distance dependent ${}^{eq}CO_2$ factor**: The most simple climate metric under consideration here, the distance dependent ${}^{eq}CO_2$ factor, could benefit from using average fuel flow data. Because no information on the location of the $NO_X$ emission is used to calculate the climate effect, neglecting the changes in EI $NO_X$ during the flight mission will not change the result. Therefore, using an average fuel flow (e.g. mission fuel divided by mission time) and standardized flight altitude to calculate an average EI $NO_X$ will probably produce sufficiently accurate results.
- **Climatological latitude-height dependent ${}^{eq}CO_2$ factor**: This climate metric uses some geographical information and, more important, the flight altitude to establish the climate effect of a flight. As seen in Figure 6, the flight altitude has a significant effect on the EI $NO_X$. The $NO_X$ correlation methods described in section 3.4.1 account for the flight altitude and therefore the application of these methods with the actual flight altitude and an average fuel flow might give sufficiently accurate results for application of this climate metric. However, a more detailed analysis on the effect using average fuel flow and EI $NO_X$ data, and particularly on the impact of the mission distance, seems appropriate to establish the exact level of inaccuracy introduced with this type of simplification.
- **Weather and spatial dependent ${}^{eq}CO_2$ factor**: This climate metric requires accurate local emissions data to match with the accuracy of the climate impact assessment. If the weather information is given in discrete time intervals, e.g. five minutes, it would be possible to use the average fuel flows of these time intervals to calculate the amount of $NO_X$ emitted, but this does not appear to be a significant reduction in the effort of data collection.

The exact effect of using average fuel flows on the different ${}^{eq}CO_2$ factors is dependent on the mission profile (altitude, distance) and the climate metric itself. A more detailed analysis of a variety of missions would be required to estimate the error to be expected by introducing the averaging methods presented in this section.

## 4.5 Summary

In the previous paragraphs, potential ways to reduce the amount of data required to estimate the climate impact of non-$CO_2$ emissions have been discussed. Categorization and averaging procedures have been used successfully in the past to simplify the calculation of emission inventories and appear to be also applicable to the calculation of ${}^{eq}CO_2$ factors. However, to quantify the effect of these simplification procedures on the more complex climate metrics proposed for including non-$CO_2$ effects in emission trading systems, more detailed analyses, based on a larger number of actual or modeled flight missions will be needed.

Furthermore, it needs to be verified that products with superior emission performance are correctly represented by these procedures, to avoid penalizing airlines which invest into more environmentally compatible technologies.

# 5 Data acquisition by the aircraft operator

## 5.1 Regulatory overview

Emissions of $CO_2$ from fossil fuel combustion in the aviation sector are currently regulated under the EU's emissions trading system (EU ETS) as dictated by Directive 2003/87/EC. For each tonne of carbon dioxide emitted, one allowance unit must be surrendered by the aircraft operator to the competent national authority. This scheme covers intra-European flights (i.e. departure and arrival in EEA Member States) and requires – since 2013 – that relevant fuel consumption and $CO_2$ emissions data be monitored and reported. Global international flights will also soon be subject to similar monitoring and reporting requirements for carbon emissions under ICAO's upcoming Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). The scheme will follow a phased implementation approach starting officially on January 1, 2019.

Complying with the EU ETS, and the anticipated CORSIA, demands that aircraft operators establish defined processes to collect the relevant data, continuously retrieve this data throughout the compliance period and then report it to the competent authority. This data collection cycle and process involves various discrete steps and is known as monitoring, reporting and verification, or MRV. The costs to operators of meeting these regulatory requirements depend primarily on the scope of their operations and robustness of internal process. From a high-level perspective, a few aspects come into consideration when examining these costs:

- **Frequency**: certain steps in the MRV process are repeated annually and the related costs are therefore incurred on a recurring basis. Others are only relevant at one specific point in time and the costs are therefore single occurrences for the operator.
- **Cost type**: the cost types incurred are two-fold and consist of (a) costs associated with staff resources deployed to carry out the steps in the MRV process (i.e. staff-days), as well as (b) direct costs paid to third-parties for services delivered in performing MRV steps.
- **Effort type**: while collecting and reporting data is the main task and source of costs for the aircraft operator, non-data related tasks (e.g. monitoring regulatory framework) are also a key component of the process and are important to ensure efficient data monitoring.

As these two schemes have their own specific scope and compliance requirements, the MRV frameworks are distinct. It is therefore necessary to understand both in more detail before an overview of the level of effort and costs can be provided.

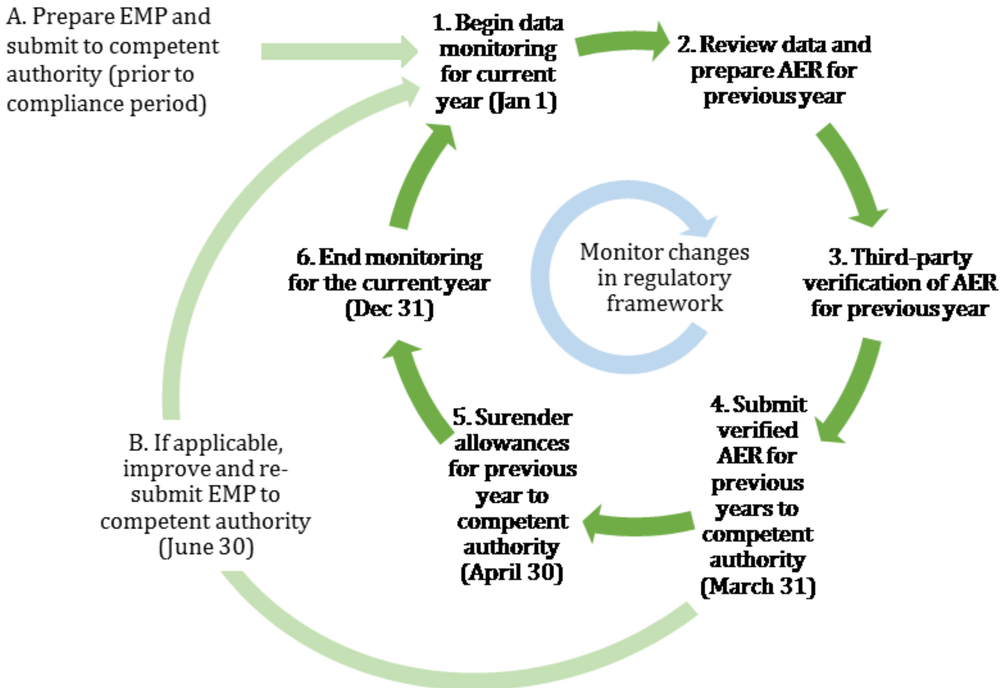
## 5.2 Current compliance context under the EU ETS

### 5.2.1 MRV system

Aircraft operators are required to participate in the EU ETS if the emissions from qualifying flights (full scope[8]) are over 10'000 $tCO_2$ per annum and if they operate more than 243 flights in each of the three periods January to April, May to August and September to December.

The MRV compliance cycle is based on the calendar year and involves the steps described in the diagram below. The process starts with the preparation of an Emissions Monitoring Plan (EMP) describing all relevant processes to collect the required data. At the end of the monitoring period, the data is reviewed, data gaps are closed and an Annual Emissions Report (AER) is generated using a standard template. The operator then seeks external verification of the AER before submitting it to the competent authority and surrendering the required allowances. Improvements to the EMP may be made on an annual basis following the results of the reporting process. In addition, for their own benefit, aircraft operators also keep track of ongoing regulatory changes and manage the administrative requirements of participating in the scheme.

**Figure 8: Compliance cycle for aircraft operators under the EU ETS [European Commission (2018)].**

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To quantify the annual emissions for which allowances must be surrendered under the scheme and in order to attribute these emissions to specific aerodrome-pairs, flight information (e.g. aerodromes, aircraft type) and activity data (i.e. fuel consumption) for each flight needs to be

[8] Qualifying flights for determining whether an aircraft operator is included in the EU ETS are all those flights which depart from or arrive in an aerodrome situated in the territory of a "EEA Member State" minus any exempted flights. This is known as "full scope".

collected. Participating aircraft operators have two alternatives to collect activity data, depending on their scope of operations:

- **Normal procedure:** aircraft operators monitor their actual consumption of fuel ($F_N$) for each flight operated and covered under the EU ETS. Two methods are available, which rely on different sets of parameters.

**Table 1: Actual fuel use monitoring methods under the EU ETS [European Commission (2018)].**

| Monitoring method | Description and formula | Monitoring Parameters |
|---|---|---|
| Method A | Fuel data is collected from block-off of the current flight to block-off of the subsequent flight: $F_{N,A} = T_N - T_{N+1} + U_{N+1}$ | $T_N$ = Amount of fuel in aircraft tanks once fuel uplift for the flight under consideration (= N) is complete [in tonnes]; $T_{N+1}$ = Amount of fuel in aircraft tanks once fuel uplift for the subsequent flight (=N+1) is complete [in tonnes]; $U_{N+1}$ = Fuel uplift for the subsequent flight [in tonnes] |
| Method B | Fuel data is collected from block-on of the previous flight to block-on of the current flight: $F_{N,B} = R_{N-1} - R_N + U_N$ | $R_{N-1}$ = Amount of fuel remaining in aircraft tanks at the end of the previous flight (=N–1) [t]; $R_N$ = Amount of fuel remaining in aircraft tanks at the end of the flight under consideration (=N) [t]; $U_N$ = Fuel uplift for the flight considered [t] |
| Method A | Fuel data is collected from block-off of the current flight to block-off of the subsequent flight: $F_{N,A} = T_N - T_{N+1} + U_{N+1}$ | $T_N$ = Amount of fuel in aircraft tanks once fuel uplift for the flight under consideration (= N) is complete [in tonnes]; $T_{N+1}$ = Amount of fuel in aircraft tanks once fuel uplift for the subsequent flight (=N+1) is complete [in tonnes]; $U_{N+1}$ = Fuel uplift for the subsequent flight [in tonnes] |
| Method B | Fuel data is collected from block-on of the previous flight to block-on of the current flight: $F_{N,B} = R_{N-1} - R_N + U_N$ | $R_{N-1}$ = Amount of fuel remaining in aircraft tanks at the end of the previous flight (=N–1) [t]; $R_N$ = Amount of fuel remaining in aircraft tanks at the end of the flight under consideration (=N) [t]; $U_N$ = Fuel uplift for the flight considered [t] |

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As fuel delivery to the aircraft is typically measured in units of volume, aircraft operators must also monitor the actual fuel density ($\rho$) for conversion to units of mass. In case biofuels are used for a given flight, aircraft operators must be able to account for these and attribute them to the EU ETS where applicable.

- **Simplified procedure**: Aircraft operators with annual emissions from qualifying flights (full scope) below 25’000 $tCO_2$ are considered “small emitters” under the EU ETS and as such are eligible for simplified procedures to alleviate some of the administrative burden. Simplifications include the use of the Eurocontrol Small Emitters Tool (SET), which calculates fuel consumption and emissions automatically directly from flight information (aerodrome pairs, aircraft type), and the exemption from requiring external verification of emissions data if the SET is used in conjunction with the ETS Support Facility to produce the annual emissions report.

### 5.2.2 Administrative effort required by the operator

Based on (i) focused input solicited directly from airline operators[9] as well as (ii) internal expertise of the authors with MRV processes in the aviation sector, the administrative effort required from aircraft operators to comply with the EU ETS has been quantified. Given the complexities of individual aircraft operators' processes and scope, this effort can vary considerably from one operator to the next. Certain simplifications and assumptions were therefore necessary in order to develop useful estimates. The table below presents this set of considerations.

**Table 2: Simplifications and assumptions considered for estimation of administrative effort and compliance costs.**

| | |
|---|---|
| **Geographical restriction** | Administrative effort presented is for EU-based aircraft operators only as these are likely the most concerned with the EU ETS. |
| **Size of operations** | Three size categories of aircraft operators are considered based on their total annual emissions: small (<100'000 $tCO_2$), medium (100'000 – 2'000'000 $tCO_2$), large (> 2'000'000 $tCO_2$). It is also assumed that total emissions are a reasonable indicator of the magnitude of an operator's EU ETS compliance requirements. |
| **Actual fuel use monitoring** | Estimates of administrative effort are based on collecting activity data through actual fuel use monitoring. The specific case of operators eligible for the simplified approach (i.e. small emitters) is not considered. |
| **Staff involved** | Administrative effort encompasses time spent by operations and management staff of the aircraft operator throughout the MRV process but does not include the time spent by the flight crew in recording data. It is assumed that data would be collected by the flight crew even in the absence of EU ETS compliance. |
| **Annually recurring effort** | Only annually recurring administrative effort is considered as this represents the bulk of compliance costs for aircraft operators. Single occurrence steps in the MRV process (e.g. preparing the EMP) are therefore not included in the evaluation. |
| **Sourcing and purchasing allowances and offsets** | Costs for procuring and purchasing allowances and/or offsets are not considered |
| **MRV process breakdown** | Administrative effort required is attributed to the completion of specific steps in the MRV process rather than to the monitoring of individual parameters. |

| *EU ETS Compliance Step* | *Explanation* |
|---|---|
| ***Monitoring and reporting of fuel and emissions data*** | |
| *Collecting relevant data* | *Collection of flight and fuel data relevant to EU ETS reporting.* |
| *Ensuring data collection is as per EMP* | *Ensuring consistency with scope (e.g. aircraft types) and processes (e.g. fuel monitoring method) stated in the EMP. Updating the monitoring plan if material changes have occurred.* |

[9] Altogether, feedback was received from 6 aircraft operators in the following size categories as defined in Table 2: small (1), medium (3), large (2).

| | |
|---|---|
| *Reporting and internal approval of emissions report* | *Closing data gaps, data validation and preparation of annual emissions report.* |
| ***Verification of annual emissions report*** | |
| *Retaining verifier and verification of emissions report* | *Securing verification services and working with verifier for the verification of emissions report.* |
| ***Submission of verified emissions report*** | |
| *Internal auditing of emissions and verification reports* | *Final internal review of the reports and results prior to submission (e.g. for controlling cost of compliance and reconciliation of results with other reporting requirements)* |
| *Submitting verified annual emissions report* | *Submission of verified annual emissions report to the competent national authority.* |
| ***Following regulatory changes*** | |
| *Monitoring regulatory compliance requirements* | *Monitoring of changes in applicable rules and regulations, working with industry associations (e.g. lobbying or other).* |
| *Maintaining link to regulatory authority* | *Maintaining specific link to the relevant EU regulatory authority (e.g. maintaining up to date contact person, up to date software systems).* |

| | |
|---|---|
| **Cost of staff time** | An average daily cost of EUR 500 (incl. overhead, social security, etc.) for aircraft operator operations and management staff is assumed |

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The resulting estimated EU ETS administrative effort and compliance costs are presented below. The value ranges reflect the scope of inputs collected from various aircraft operators. Overall (see row "Total estimated administrative effort"), the results show a clear progression of increasing effort from small to large aircraft operators[10].

[10] Due to the limited data sample available, in certain categories of administrative effort the range of man-days is not always consistent from one size of operator to the next (e.g. for "reporting and internal approval of emissions report" the range for large operators is smaller than for medium operators). On an aggregated level (total administrative effort) the consistency is nevertheless respected.

**Table 3: Estimated annual compliance effort and costs for aircraft operators under the EU ETS. Notes: (*) A +/- 50% uncertainty range was assumed where only one data point was available.; (**) For administrative effort under "collecting relevant data" for medium-sized operators, the range is based on the input from one operator only.**

| EU ETS Compliance Step | Small Aircraft Operator | Medium Aircraft Operator | Large Aircraft Operator | Third-party costs |
|---|---|---|---|---|
| **Monitoring and reporting of fuel and emissions data** | **6 to 22 days** | **32 to 70 days** | **30 to 69 days** | |
| *Collecting relevant data* | *4-12** | *15-20*** | *15-24* | |
| *Ensuring data collection is as per EMP* | *1-5** | *2-10* | *10-30** | |
| *Reporting and internal approval of emissions report* | *1-5** | *15-40* | *5-15** | |
| **Verification of annual emissions report** | **5 to 15 days** | **3 to 20 days** | **7 to 10 days** | |
| *Retaining verifier and verification of emissions report* | *5-15** | *3-20* | *7-10* | *In addition, costs of actual third-party verification services: 5'000 - 20'000 EUR/year* |
| **Submission of verified emissions report** | **2 to 8days** | **3 to 5 days** | **3 to 40 days** | |
| *Internal auditing of emissions and verification reports* | *1-5** | *2-3* | *2-30* | |
| *Submitting verified annual emissions report* | *1-3** | *1-2* | *1-10* | |
| **Following regulatory changes** | **2 to 8 days** | **3 to 12 days** | **15 to 70days** | |
| *Monitoring regulatory compliance requirements* | *1-5** | *1-7* | *10-35* | |
| *Maintaining link to regulatory authority* | *1-3** | *2-5* | *5-35* | |
| **Total estimated administrative effort** | **15 to 53 days** | **41 to 107 days** | **55 to 189 days** | |
| | | | | |
| **Total estimated compliance cost** | **EUR 6'000 to 21'200** | **EUR 16'400 to 42'800** | **EUR 22'000 to 75'600** | **EUR 5'000 to 20'000** |

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## 5.3 Upcoming compliance context under CORSIA

### 5.3.1 MRV system

Civilian international flights between ICAO member States will be covered, as of 2019, by CORSIA. In contrast to the EU ETS, where an absolute cap on emissions is in place, the ambition of this new scheme is to ensure carbon neutral growth of the international aviation sector. To do so, aircraft operators will be required to offset emissions corresponding to their share of annual sector growth by purchasing eligible carbon credits through the voluntary carbon markets. At the present time, the bulk of the rules and regulations relating to MRV procedures under the scheme are known, however for the offsetting component of the scheme significant uncertainties still remain.

The threshold for compliance with the scheme is set at 10’000 tCO2: aircraft operators with annual emissions on non-exempt flights in excess of this limit will be subject to monitoring and reporting requirements. While these obligations begin officially in January 2019, the offsetting obligations of the scheme will only be in full effect starting in 2027. Till then, several preliminary phases are planned (see the table below). The compliance cycles for data monitoring and reporting will follow calendar years, similarly to the EU ETS (see Figure 8), however offsetting will occur in three-year cycles.

**Table 4: Compliance phases under CORSIA.**

| Baseline phase (2019-2020) | Pilot phase (2021-2023) | First Phase (2024-206) | Second Phase (2027-) |
|---|---|---|---|
| Monitoring and reporting of emissions data to establish the baseline; no offsetting | Monitoring and reporting of emissions data; offsetting only on flights between volunteering ICAO States | Monitoring and reporting of emissions data; offsetting only on flights between volunteering ICAO States | Monitoring and reporting of emissions data; offsetting on flights between all ICAO member States |

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Prior to the baseline phase, an emissions monitoring plan describing the data collection processes will have to be submitted for approval to the competent authority. For the years after 2020, i.e. when offsetting has commenced, the important annual MRV deadlines for aircraft operators will be the following:

- **January-December:** data monitoring for the current year;
- **30 April:** submission of verified annual emissions report for the previous year to the competent authority;
- **30 November:** operators receive a notification of their provisional offsetting requirements for the previous year.

Furthermore, the following deadlines apply for the three-year offsetting cycles starting in 2021:

- **30 November** (2024, 2027, etc.): operators receive notification of their final offsetting requirements for the previous three-year period;
- **31 January** (2025, 2028, etc.): cancellation of required number of carbon credits for the previous three-year period;

- **30 April** (2025, 2028, etc.): submission of verified emission unit cancellation report (EUCR) to the competent authority for the previous three-year period.

To quantify the annual emissions for which offsets will need to be cancelled under the scheme and in order to attribute them to specific aerodrome-pairs (or State pairs), flight information (e.g. aerodromes, aircraft type) and activity data (i.e. fuel consumption) for each flight needs to be collected. Participating aircraft operators have two alternatives to collect activity data, depending on their scope of operations:

- **Normal procedure:** similarly to the EU ETS, aircraft operators monitor their actual fuel consumption for all flights covered by CORSIA. In addition to the two existing methods in the emissions trading scheme (Method A, Method B), three more are available under CORSIA for this purpose.

**Table 5: Actual fuel use monitoring methods under CORSIA. In addition, Method A and Method B of the EU ETS are also applicable to CORSIA [IATA (2018)].**

| Monitoring method | Description and formula | Monitoring Parameters |
|---|---|---|
| **Block-off / Block-on** | Fuel data is collected from block-off of the previous flight to block-on of the current flight: $F_{N,BB} = S_N - R_N$ | $S_N$ = Amount of fuel in aircraft tanks at block-off at the start of the flight under consideration (= N) [t]; $R_N$ = Amount of fuel remaining in aircraft tanks at the end of the flight under consideration (=N) [t] |
| **Fuel uplift** | Fuel data is collected from fuel uplift of the current flight: $F_{N,U} = U_N$ | $U_N$ = Fuel uplift for the flight considered [t] |
| **Block hours** | Fuel data is collected from average fuel burn ratio (specific to the aircraft type) and block hours of the current flight: $F_{N,BH} = fuel\ burn\ ratio \times block\ hours$ | Total fuel uplifts and total block hours for each aeroplane used needs to be monitored |

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- **Simplified procedure:** aircraft operators are eligible to use the ICAO CORSIA $CO_2$ Estimation and Reporting Tool (CERT) to calculate fuel consumption and emissions directly from information on aerodrome pair and aircraft type or total block hours per aircraft type. From the start of the offsetting period (2021), these simplified procedures can be used for flights subject to offsetting only if an operator's annual emissions from these flights is below 50'000 $tCO_2$. The CERT tool may also be used by any operator for flights not subject to offsetting requirements.

### 5.3.2 Administrative effort required by the operator

As the actual annually recurring MRV processes have yet to begin under CORSIA, a qualitative approach was selected for the assessment of administrative effort and compliance costs rather than quantitative estimates as for the EU ETS. For each step in the MRV process, the anticipated additional effort required compared to what is currently incurred for the EU ETS is assessed using the grading system presented in the table below.

**Table 6: Grading system for estimation of future administrative effort under CORSIA: additional effort compared to current compliance with EU ETS.**

| / | + | ++ |
|---|---|---|
| No particular additional effort (i.e. strong synergies between administrative effort required for EU ETS and CORSIA) | Limited additional effort required (i.e. some synergies between administrative effort required for EU ETS and CORSIA) | Significant additional effort required (i.e. limited synergies between administrative effort required for EU ETS and CORSIA) |

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A similar set of assumptions and simplifications to those considered for the EU ETS in Table 2 Table 2are used in this case to facilitate a straightforward comparison. As a further simplification, the ratings below are provided without consideration of the size of the aircraft operator and the offsetting process under CORSIA is not quantified due to the current high level of regulatory uncertainties. It should be noted that the below results are provided indicatively.

**Table 7: Estimated additional compliance effort for aircraft operators under CORSIA in comparison to the EU ETS.**

| CORSIA Compliance Step | Estimated additional administrative effort compared to EU ETS | Comments |
|---|---|---|
| **Monitoring and reporting of fuel and emissions data** | | |
| Collecting relevant data | ++ | The scope of CORSIA is different than for the EU ETS, therefore aircraft operators will be required to monitor data for entirely different groups of flights. |
| Ensuring data collection is as per EMP | + | Data validation and corrective action processes may be aligned between both schemes, providing some synergies. However, the specifics regarding the scope and fuel monitoring methods for CORSIA will have to be adhered to. |
| Reporting and internal approval of emissions report | ++ | Different schemes, hence different reporting and internal approval requirements. |
| **Verification of annual emissions report** | | |
| Retaining verifier and verification of emissions report | + | Same verification services can be used, producing some synergies. |
| **Submission of verified emissions report** | | |
| Internal auditing of emissions and verification reports | ++ | CORSIA emissions and verification reports will require internal auditing in addition to what is done for the EU ETS. |

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## 5.4 Conclusions on current administrative effort

The compliance costs incurred by aircraft operators in implementing MRV processes for the EU ETS are non-negligible, however these must be considered in the broader context of overall compliance costs with the EU ETS. Indeed, aircraft operators incur the majority of compliance costs from the carbon price placed on their emissions. At an EUA price of approximately 20 EUR/tCO2 as of August 2018, the costs of a large aircraft operators' emissions would be orders of magnitude greater than its MRV compliance costs.

For smaller aircraft operators (in terms of annual emissions), the relative significance of MRV compliance costs becomes greater. Smaller emitters therefore experience disproportionately high MRV costs compared to larger aircraft operators.

A similar set of assumptions and simplifications to those considered for the EU ETS in Table 2 are used in this case to facilitate a straightforward comparison. As a further simplification, the ratings below are provided without consideration of the size of the aircraft operator and the offsetting process under CORSIA is not quantified due to the current high level of regulatory uncertainties. It should be noted that the below results are provided indicatively.

# 6 Additional administrative efforts for aircraft operators compared to existing procedures

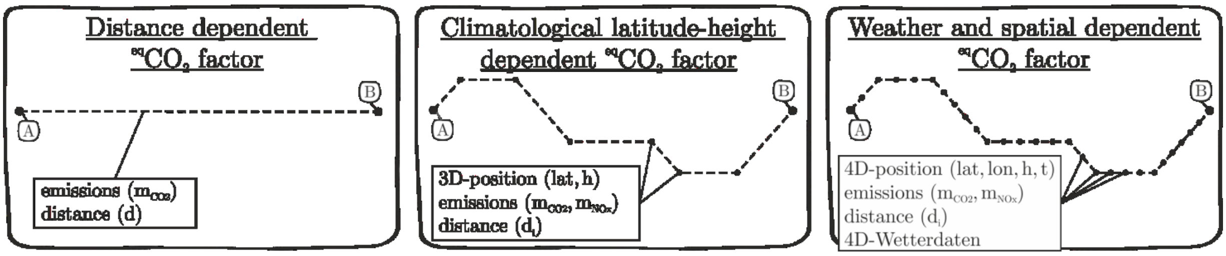
The inclusion of non-$CO_2$ climate species into existing climate protecting measures like the EU ETS or CORSIA will lead to additional administrative efforts and costs for aircraft operators. The level of these additional expenses will be strongly depending on the method to estimate $CO_2$ equivalents ($^{eq}CO_2$). A higher accuracy in taking into account the relevant atmospheric processes will result in larger benefits for climate mitigation. But, however, more accurate $^{eq}CO_2$ approaches will also require a higher amount of data for monitoring, reporting and verification.

Within the framework of this research project, three different approaches to address the non-$CO_2$ species of aviation have been worked out by Dahlmann et al. (2018):

(1) a relatively simple distance dependent $^{eq}CO_2$ factor,
(2) a climatological latitude-height dependent $^{eq}CO_2$ factor,
(3) and a detailed weather and spatial dependent $^{eq}CO_2$ factor.

In the following sections, we will be estimating the additional administrative efforts for aircraft operators caused by introducing the selected $^{eq}CO_2$ factors (see Figure 9).

**Figure 9: Illustration of data requirements for selected methods to calculate $CO_2$ equivalents ($^{eq}CO_2$)**

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## 6.1 Distance dependent $^{eq}CO_2$ factor

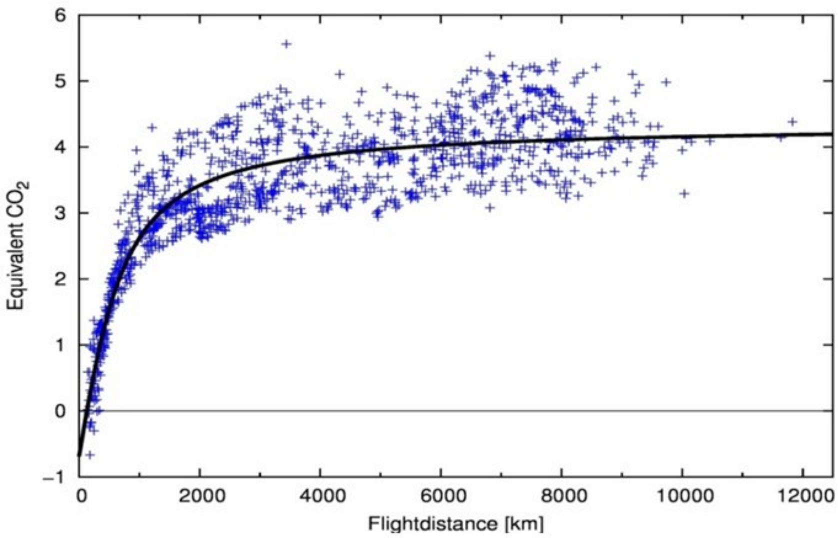
The distance dependent $^{eq}CO_2$ factor is the simplest calculation method for equivalent $CO_2$ emissions $\left(^{eq}E_{CO_2}\right)$ under consideration here. In this case, $^{eq}E_{CO_2}$ can be estimated easily by multiplying $CO_2$ emissions $\left(E_{CO_2}\right)$ with the equivalent $CO_2$ coefficient $\left(^{eq}CO_2\right)$ provided by the supervising authority (see Figure 10):

$$^{eq}E_{CO_2}(d) = E_{CO_2}(d) \cdot {}^{eq}CO_2(d) \qquad (20)$$

<u>Data required for aircraft operators (see Section 3.1):</u>

- $d$: Flown flight distances
- $E_{CO_2}(d)$: $CO_2$ emissions
- $^{eq}CO_2$: Accumulated equivalent $CO_2$ coefficient for all climate agents

Figure 10: **Equivalent $CO_2$ coefficient $\left({}^{eq}CO_2\right)$ in dependency of the flight distance (blue crosses) and according curve fit (black)**




© Dahlmann et al, 2018b

Minimal administrative effort will be caused by a distance dependent eqCO2 factor, if CO2 emissions are reported for all flights of an aircraft during a reporting period ($E_{CO_2,tot}$) for other reasons anyhow. This is the case in the EU ETS for CO2, for instance. To estimate CO2 emissions of a single flight $\left(E_{CO_2}\right)$, $E_{CO_2,tot}$ has to be weighted by the flown flight distance and the flight frequency $f_{ij}$ (an example is shown in Figure 11), as fuel consumption increases disproportionately with flight distance and flight altitude (see Figure 12):

$$E_{CO_2}(d) = \frac{f_{ij} \cdot d_{ij}}{\sum f_{ij} \cdot d_{ij}} \cdot E_{CO_2,tot} \tag{21}$$

Figure 11: **Share of Airbus A330-200 flights per range segments in January 2015**

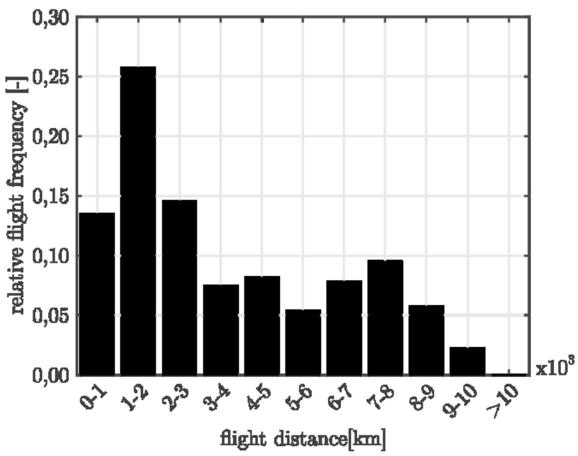



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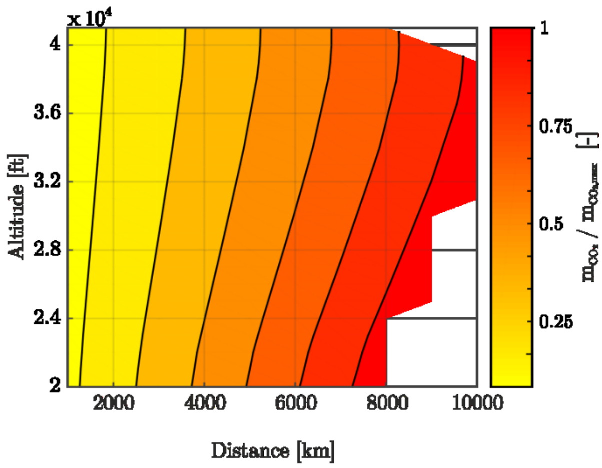
Figure 12: **Estimated $CO_2$ emissions as function of altitude and distance for the Airbus A330-200**

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Flight distances between city pairs $(d_{ij})$ can be approximated by great circle distances $(d_{GC,ij})$ plus a constant of $95km$ for detours and holding patterns:

$$d_{ij} = d_{GC,ij} + 95km \quad (22)$$

However, $E_{CO_2}(d)$ is estimated here without taken into account wind effects. The accuracy of this approach and the possible discrepancies should be analyzed in detail in further studies.

Alternatively, aircraft operators can also report fuel consumption and, if necessary, fuel flow separately for each flight to the national authorities. As monitoring and reporting is required here individually for each flight, the administrative effort of a distance dependent ${}^{eq}CO_2$ factor might increase. Future work has to be carried out to analyze if existing onboard fuel monitoring systems (see Figure 13 and Figure 14) can also be used for $E_{CO_2}$ reporting.

**Figure 13: Fuel system display of A320**

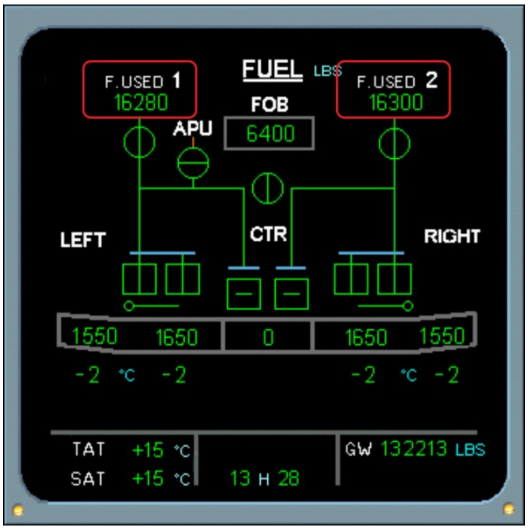


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**Figure 14: Engine warning display of A320**


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To increase accuracy and give an incentive for airlines to buy low emissions engines, the factor could be calculated based on the LTO $NO_X$ data of the engine. This would require knowledge of the exact engine and combustor.

Nevertheless, since reduction in $NO_x$ emissions as well as changes in flight regions or altitude are not taken into account by the distance dependent ${}^{eq}CO_2$ factor at all, very small incentives for airlines are created here to mitigate the climate effect of non-$CO_2$ effects. However, a distance dependent ${}^{eq}CO_2$ factor will lead to negligible additional efforts for the aircraft operators under the MBM.

## 6.2 Climatological latitude-height dependent ${}^{eq}CO_2$ factor

To calculate climatological latitude-height dependent equivalent $CO_2$ emissions $({}^{eq}E_{CO_2})$, aircraft operators have to provide latitude $(\varphi)$, longitude $(\lambda)$ and altitude $(h)$ of the emissions as well as the amount of emission at that point $E_i(\boldsymbol{x})$:

$${}^{eq}E_{CO_2}(\boldsymbol{x}) = E_{CO_2} + E_i(\boldsymbol{x}) \cdot {}^{eq}CO_2{}^{i}(\boldsymbol{x}) + d(\boldsymbol{x}) \cdot {}^{eq}CO_2{}^{CiC}(\boldsymbol{x}) \quad (23)$$

with $\boldsymbol{x} = [\varphi; \lambda; h]^T$

Individual equivalent $CO_2$ coefficients $\left({}^{eq}CO_2{}^{i}\right)$ have to be supplied by the supervising authority for various climate agents with ${}^{eq}CO_2{}^{i}(\boldsymbol{x})$ for $i \in \{H_2O, NO_x\}$ and ${}^{eq}CO_2{}^{CiC}(\boldsymbol{x})$ for contrail-induced cloudiness (CiC). The amount of emissions can be calculated by a fuel flow method, when the fuel flow is known.

<u>Minimum data required for aircraft operators (see Section 4.2):</u>

- $\boldsymbol{x}$: 3D waypoint profile
- $d(\boldsymbol{x})$: Flown flight distances
- $E_{CO_2}$: $CO_2$ emissions per flight
- $E_i(\boldsymbol{x})$: 3D emission inventory per flight for $i \in \{H_2O, NO_x\}$
- ${}^{eq}CO_2{}^{i}(\boldsymbol{x})$: individual equivalent $CO_2$ coefficient for various climate agents $i$ as function of emission location $\boldsymbol{x}$

### 6.2.1 3D waypoint profile data

Flown flight trajectories are documented in detail for each flight by the aircraft flight recorder (e.g. flight time, pressure altitude, airspeed, heading, and aircraft attitude) automatically. Flight data is downloaded and analyzed by most aircraft operators on a regular and routine basis, as they shall establish and maintain a flight data analysis program as part of their safety management system for all aircraft with a maximum certificated take-off mass exceeding 27,000 kg (ICAO Annex 6, Part I). Existing Automated Flight Information Reporting Systems (AFIRS) offer real time flight tracking capabilities that exceed ICAO's Global Aeronautical Distress and Safety System (GADSS) definitions (ICAO, 2017b); see Figure 15.

4D flight profiles are also collected by air navigation service providers (ANSP) such as EUROCONTROL. However, an investigation from a legal point of view is necessary whether or not ANSP data can be used by aircraft operators and/or supervising authorities for the purpose mentioned above. Currently, ANSP data can be used by supervising authorities on request, but not by aircraft operators.

**Figure 15: Automated Flight Information Reporting System (AFIRS)**


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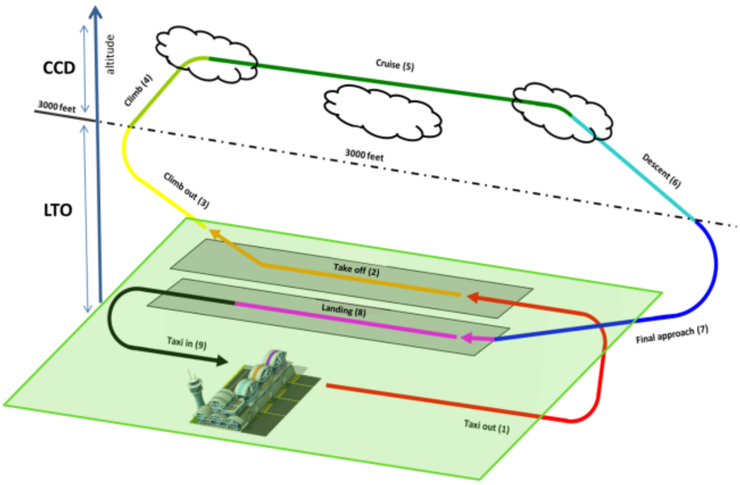
### 6.2.2 3D emission inventory per flight

3D emission inventory calculations are based on the fuel flow ($w_{FF}$) during a flight. Fuel flow data $w_{FF}(\boldsymbol{x}, t)$ can be obtained alternatively in four different ways:

(1) From onboard fuel monitoring systems (see Figure 14; maximum precision; minimal effort).

(2) By modeling the fuel consumption with existing aircraft and engine databases (medium to high precision; high effort):
**Below 3000 ft** (compare Figure 16), fuel flow data can be taken from the LTO cycle defined by the ICAO Engine Certification specifications.
**Above 3000 ft,** fuel flow calculation can be based on EUROCONTROL's Base of Aircraft Data (BADA), which provides altitude- and latitude-dependent performance and fuel burn data for more than 150 aircraft types.
To be able to apply a fuel flow correlation method it is necessary to know the exact engine and combustor type (compare chapter 3.4). Simplifications are possible by categorizing engine types with similar emission levels (see chapter 4 for a more detailed description of potential simplifications), however sometimes different combustor types with very different emission levels can be used in the same engine type. As long as the combustor type is unknown it is impossible to accurately estimate the engine's $NO_X$ emissions.

**Figure 16: The ICAO LTO and CCD cycles**




© EUROCONTROL (2016)

(3) By applying basic estimation techniques (low to medium accuracy; low to medium effort; compare Figure 4 - Figure 7):
It is possible to calculate an average fuel flow from the $CO_2$ emitted (i) during the entire flight (see Eq. (24), lowest accuracy), (ii) during the entire cruise phase (see Eq. (25)) or (iii) during various sections *i* of the flight (see Eq. (26)). The shorter these sections are, the more accurate is the $NO_x$ estimate.

$$w_{FF,av} = \frac{amount\ of\ fuel\ used}{mission\ time} \qquad (24)$$

$$w_{FF,av,cr} = \frac{amount\ of\ fuel\ used}{mission\ time} \cdot \prod \frac{m_i}{m_{i-1}} \qquad (25)$$

$$w_{FF,i} = \frac{amount\ of\ fuel\ used\ per\ segment\ i}{mission\ time\ per\ segment} \quad (26)$$

with statistical weight ratios $(m_i/m_{i-1})$ for taxi, take off, climb and descent (Raymer, 2012). A more detailed analysis of the effects of using average data is presented in section 4.4

(4) By using aircraft specific consumption maps (lowest accuracy; low to medium effort; compare Figure 12)

Emission inventories for $\mathrm{CO_2}$, $\mathrm{H_2O}$, $\mathrm{SO_2}$ and $\mathrm{NO}_x$ are calculated according to Eq. (27):

$$^{eq}E_{CO_2}(\boldsymbol{x}) = E_{CO_2} + E_i(\boldsymbol{x}) \cdot {^{eq}CO_2}^{i}(\boldsymbol{x}) + d(\boldsymbol{x}) \cdot {^{eq}CO_2}^{CiC}(\boldsymbol{x}) \quad (27)$$

Corresponding emission indices for carbon dioxide ($EICO_2$) and water vapor ($EIH_2O$) are independent of engine type or operating condition (see Section 2.1). $EISO_2$ is depending on the mass fraction of Sulfur in the fuel (see 2.2). For accurate $E_{NO_x}(\boldsymbol{x})$ modeling, the exact aircraft and engine type, the combustor variant, and the fuel flow ($w_{FF}$) in sufficiently short intervals (e.g. every five minutes) is required (see Section 3.2):

To sum it up, it is possible to meet the minimum data requirements for this $^{eq}CO_2$ factor by the aircraft operators, but the associated administrative effort shows a broad range: 3D waypoint profile data can be collected by the aircraft operators with reasonable effort. Here, legal issues have to be investigated. Fuel flow data can be obtained in four different ways, implying different levels of data accuracy and administrative efforts. Finally, calculating emission inventories for $CO_2$ and $H_2O$ will be possible with a high level of precision, and by applying a relatively simple formula. However, estimating emission inventories for $\mathrm{NO}_x$ will lead to a relatively high administrative effort for the aircraft operators.

To ensure that airlines do not withold waypoint profile or emission data on purpose, the system must generate a financial incentive for airlines to provide them. This means that the calculation of $CO_2$ equivalents based on rough assumptions should lead to (insignificantly) higher $^{eq}E_{\mathrm{CO_2}}(\boldsymbol{x})$ values.

## 6.3 Weather and spatial dependent $^{eq}CO_2$ factor

Basically, this $^{eq}CO_2$ factor requires the same administrative efforts from the aircraft operators as the $^{eq}CO_2$ factor discussed in the previous section plus efforts for collecting meteorological data.

$$^{eq}E_{CO_2}(\boldsymbol{x},t) = E_{CO_2} + E_i(\boldsymbol{x},t) \cdot {^{eq}CO_2}^{i}(\boldsymbol{x},t) + d(\boldsymbol{x},t) \cdot {^{eq}CO_2}^{CiC}(\boldsymbol{x},t) \quad (28)$$

for $i \in \{\mathrm{H_2O}, \mathrm{NO}_x\}$

Minimum data required for aircraft operators (see Section 3.3):

- $\boldsymbol{x}, t$: 4D waypoint profile
- $d(\boldsymbol{x}, t)$: Flown flight distances
- $E_{\mathrm{CO_2}}$: $CO_2$ emissions per flight
- $E_i(\boldsymbol{x}, t)$: 4D emission inventory per flight segment for $i \in \{\mathrm{H_2O}, \mathrm{NO}_x\}$
- ${^{eq}\mathrm{CO_2}}^{i}(\boldsymbol{x}, t)$: individual equivalent $CO_2$ coefficient for various climate agents $i$ as function of emission location $(\boldsymbol{x})$ and time $(t)$
- Weather situation of the day

Here, an accurate estimate of the $NO_X$ emissions along the flight path is required to match the accuracy of the climatologic methodologies. The exact aircraft and engine type, the combustor variant, the exact flight path and the fuel flow in sufficiently short intervals (e.g. every 5 minutes) is required for accurate $NO_X$ modeling with a fuel flow method.

Meteorological data:
Meteorological information necessary for flights according to Annex 3 to the ICAO Convention on Civil Aviation are provided by two World Area Forecast Centres (WAFC), London (Met Office) and Washington (NOAA). To contribute towards the safety, regularity and efficiency of international air navigation WAFCs prepare gridded global forecasts of:

1) upper wind
2) upper-air temperature and humidity
3) geopotential altitude of flight levels
4) flight level and temperature of tropopause
5) direction, speed and flight level of maximum wind
6) cumulonimbus clouds
7) icing and
8) turbulence

for operators, flight crew members, air traffic services units, etc.

As a result, the administrative efforts associated with introducing the weather and spatial dependent $^{eq}CO_2$ factor can be characterized as being slightly higher than the efforts for the climatological latitude-height dependent $^{eq}CO_2$ factor.

## 6.4 Summary

The following table presents the main results of the previous discussions in chapter 6.

**Table 8: Qualitative estimation of the additional effort for the aircraft operators**

| $^{eq}CO_2$ factor | Additional effort for aircraft operators |
|---|---|
| Distance dependent $^{eq}CO_2$ factor | * |
| Climatological latitude-height dependent $^{eq}CO_2$ factor | *** |
| Weather and spatial dependent $^{eq}CO_2$ factor | **** |

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# Part C: Practice in Voluntary Carbon Markets for Estimating $CO_2$ and non-$CO_2$ Effects of Air Travel

Final report

by

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On behalf of the German Environment Agency

**Abstract**

Climate footprint assessment tools are readily available to online users for the purpose of offsetting in the voluntary carbon markets, and most allow for the calculation of air travel related climate effects. The tools analysed in the scope of this study include both $CO_2$ effects and non-$CO_2$ effects in the overall climate effect but vary in the approaches used to estimate each component. Varying assumptions and levels of sophistication are demonstrated in each tool, leading to differences – in certain cases over 50% – in the total climate effect for identical flights when comparing different tools. These results are primarily due to different assumptions in the calculation of flight distance and fuel consumed, as well as to the different methodologies in applying the radiative forcing index for estimating the contribution of non-$CO_2$ climate species. Overall, approaches for estimating non-$CO_2$ effects on the voluntary markets are rather simplistic.

**Kurzbeschreibung**

Verschiedenste Instrumente zur Berechnung der Klimabilanz sind online verfügbar mit dem Ziel die berechneten Klimawirkungen auf dem freiwilligen Kohlestoffmarkt zu kompensieren. Die meisten dieser online Instrumente ermöglichen speziell die Berechnung der Klimawirkung aus dem Luftverkehr. Im Rahmen dieser Studie wurden einige Instrumente analysiert, die sowohl die $CO_2$ als auch nicht-$CO_2$-Effekte zur Berechnung der Klimawirkung beinhalten unterscheiden sich aber in den Ansätzen zur Schätzung der einzelnen Komponenten. Die untersuchten Instrumente unterscheiden sich nicht nur in den verwendeten Annahmen, sondern auch in dem Komplexitätsniveau der Berechnungen. Beim Vergleich der Instrumente kann dies zu Unterschieden von bis zu 50% in der resultierenden Klimawirkung identischer Flüge führen. Diese Ergebnisse sind in erster Linie auf unterschiedliche Annahmen bei der Berechnung der Flugdistanz und des Treibstoffverbrauchs, sowie auf die unterschiedlichen Methoden bei der Anwendung des «Radiative Forcing Index», der zur Abschätzung der Klimawirkung von nicht-$CO_2$-Effekten gebraucht wird, zurückzuführen. Insgesamt sind die Ansätze zur Abschätzung der Nicht-$CO_2$-Effekte auf dem freiwilligen Kohlestoffmarkt eher vereinfachend.

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## List of Abbreviations

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| **DEFRA** | UK Department for Environment, Food & Rural Affairs |
| **DLR** | German Aerospace Centre |
| **EEA** | European Environment Agency |
| **GCD** | Great Circle Distance |
| **GHG** | Greenhouse gas |
| **GWP** | Greenhouse Warming Potential |
| **IFEU** | Institut für Energie und Umweltforschung Heidelberg |
| **ICAO** | International Civil Aviation Organization |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **RFI** | Radiative Forcing Index |

## Summary

For offsetting purposes in the voluntary carbon markets, climate footprint calculation tools are readily available online and provide quantitative estimates of the climate effect of various activities, namely air travel. The present study covers four tools from reputable providers (myclimate, South Pole, atmosfair and UBA) with the objective of analysing the methods used for estimating the climate effect of passenger air travel.

All tools function with an input-output approach, whereby the user provides specific characteristics of the flight as input – namely departure and arrival airports, one-way or return flight, and seating class – and the calculator delivers an estimate of the climate effect expressed as the mass of climate species emitted, measured in tonnes of $CO_2$ equivalent. In each tool, the overall climate effect comprises both $CO_2$ effects and non-$CO_2$ effects, however the methodologies for each of these two components differ – at times significantly – between providers.

$CO_2$ climate effects are directly proportional to the fuel quantity consumed for each flight and the input parameters are therefore used to calculate this value. Standard best-practices in the aviation sector are used in all four tools, i.e. distance calculation based on Great Circle Distance and application of standard emission factors for aviation fuels. As the evaluation of each tool's technical guidance document reveals, the primary differences between providers lie in the assumptions made. Specifically, all tools account differently for flight detours and for fuel burn rates. For the former, fixed or distance-dependant factors are applied, while for the latter varying approaches are used to determine average aircraft characteristics for the route in question. Only one of the four tools (i.e. atmosfair) provides the option of specifying directly the aircraft type used and thus bypass the calculation of average fuel burn rates.

The climate effects of non-$CO_2$ climate species are quantified in all four tools on the basis of their radiative forcing effect. A dimensionless multiplier is applied to calculate the overall impact of climate species ($CO_2$ and non-$CO_2$) relative to one unit of $CO_2$ emission. This simplified approach is applied alike by each provider, however the magnitude of the multiplier and the methodology for applying it vary. In the case of providers South Pole and myclimate, a constant factor is applied on all flights, while UBA's calculation tool introduces a differentiated multiplier approach by opting not to apply it to short-haul flights. Atmosfair's tool demonstrates the most sophisticated approach of the four providers analysed and applies a variable factor with a simplistic distance dependency. Overall, the non-$CO_2$ effect methodologies applied by the online providers analysed correlate with the constant factor approach or simplistic versions of the distance-dependent factor approach described in previous work packages of this project (AP1, AP2).

# Zusammenfassung

Zu Kompensationszwecken im freiwilligen Kohlestoffmarkt stehen Instrumente zur Berechnung des $CO_2$-Fussabdrucks online zur Verfügung. Diese Instrumente bieten eine quantitative Schätzung der Klimaauswirkung von verschiedenen Aktivitäten, insbesondere dem Luftverkehr. Die vorliegende Studie umfasst vier Instrumente namhafter Anbieter (myclimate, South Pole, atmosfair und UBA) mit dem Ziel, die Methoden zur Abschätzung der Klimawirkung des Passagierflugverkehrs zu analysieren.

Alle Instrumente arbeiten mit einem Eingabe-Ausgabe-Ansatz, bei dem der Benutzer spezifische Merkmale des Fluges angibt (Abflug- und Ankunftsflughafen, einfacher Flug oder Hin- und Rückflug, und Sitzklasse) und der Rechner eine Schätzung der Klimawirkung, gemessen in Tonnen $CO_2$-Äquivalent, liefert. In jedem Tool umfasst die Gesamtklimawirkung sowohl $CO_2$-Effekte als auch Nicht-$CO_2$-Effekte, jedoch unterscheiden sich die Methoden für jede dieser beiden Komponenten teilweise erheblich zwischen den Anbietern.

Die $CO_2$-Klimawirkung ist direkt proportional zur Treibstoffmenge, die für jeden Flug verbraucht wird, und daher werden die Eingangsparameter zur Berechnung dieses Wertes verwendet. Bei allen vier Instrumenten werden standardisierte Best-Practice Methoden des Luftfahrtsektors verwendet, wie zum Beispiel die sogenannte «Great Circle Distance» zur Distanzberechnung und die Anwendung von Standard-Emissionsfaktoren für Flugzeugtreibstoffe. Wie die Auswertung der technischen Leitfäden von den einzelnen Instrumenten zeigt, liegen die Hauptunterschiede zwischen den Anbietern in den getroffenen Annahmen. Insbesondere werden bei allen Instrumenten die Flugumwege und die Werte zum Treibstoffverbrauch unterschiedlich berücksichtigt. Für ersteres werden fixe oder distanzabhängige Faktoren angewandt, während für letzteres unterschiedliche Ansätze gewählt werden, um die durchschnittlichen Flugzeugeigenschaften der jeweiligen Strecke zu bestimmen. Nur eines der vier Instrumente (d.h. atmosfair) bietet die Möglichkeit, den verwendeten Flugzeugtyp direkt anzugeben und damit die Berechnung der durchschnittlichen Werte zum Treibstoffverbrauchs zu umgehen.

Die Klimawirkung von Nicht-$CO_2$-Effekten werden bei allen Instrumenten auf der Grundlage des so genannten «Radiative Forcing Index» quantifiziert. Ein dimensionsloser Multiplikator wird verwendet, um die Gesamtauswirkung der Klimaeffekte ($CO_2$ und Nicht-$CO_2$) in Abhängigkeit von einer Einheit $CO_2$ zu berechnen. Dieser vereinfachte Ansatz wird von allen vier Anbietern verwendet, jedoch variieren die Grösse des Multiplikators und die Methodik für dessen Anwendung. Bei den Rechnern von SouthPole und myclimate wird bei allen Flügen der gleiche konstante Faktor angewandt, während das Berechnungstool des UBA sich einem differenzierteren Ansatz bedient, indem der Multiplikator nicht auf Kurzstreckenflüge angewandt wird. Atmosfair entwickelt das komplexeste Berechnungstool der vier Anbieter und wendet einen variablen Faktor mit einer vereinfachten Distanzabhängigkeit an. Insgesamt korrelieren die von den analysierten Online-Anbietern angewandten Nicht-$CO_2$-Effekt-Methoden mit dem Ansatz eines konstanten Faktors oder der vereinfachten Version des distanzabhängigen Faktoransatzes, die in früheren Arbeitspaketen dieses Projekts beschrieben wurden (AP1, AP2).

# 1 Introduction

## 1.1 Offsetting tools in the voluntary carbon markets

In the voluntary carbon markets, organisations or individuals seeking to offset the climate effect of their activities may use publicly available tools to calculate their climate "footprint". The metric used for this purpose is the mass of climate species emitted while performing a specific activity. Typically, for climate footprint purposes, these emissions would be greenhouse gases (i.e. most commonly $CO_2$, $CH_4$, $N_2O$) measured in mass of $CO_2$ equivalents. Online carbon footprint calculators allow the user to determine these emissions for various types of activities – and in particular for passenger air travel – by using relatively basic data inputs. A variety of online tools are available and most also provide the user with the possibility of directly purchasing carbon credits from specific emission reduction projects or programmes to offset the produced $CO_2$ equivalents.

The objective of this assessment is to evaluate, from a sample of online tools available in the voluntary carbon markets, the methods currently used for estimating the climate effect of passenger air travel.

## 1.2 Scope of the assessment

In this study, four reputable providers of carbon footprint tools for air travel are analysed, including the datasets and approaches used. These are: myclimate, South Pole, atmosfair and UBA, the latter in cooperation with KlimAktiv[11]. If not otherwise stated, the information discussed in the sections below are derived from the respective technical guidance papers published by each online provider. For UBA's tool, additional information was also derived from direct exchange with KlimAktiv[12].

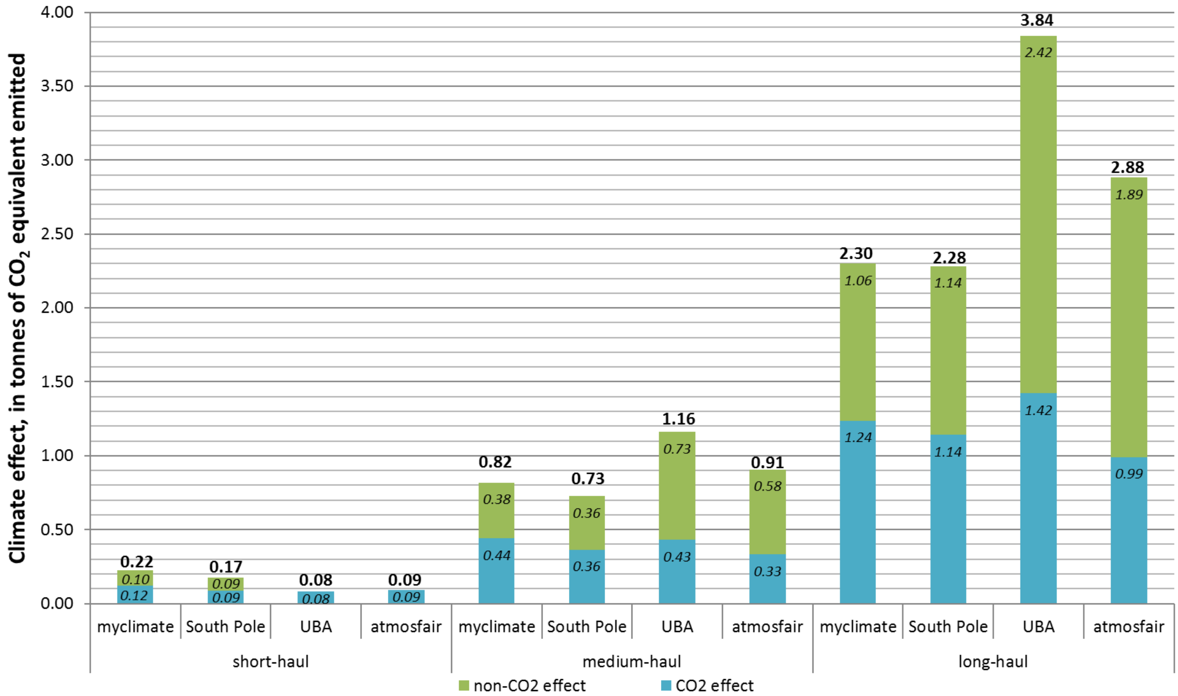
In the following figure, exemplarily climate effects of air travel are presented using the four tools selected, for three different flight distances and for a default aircraft type:

- **Short-haul** flight from Zurich, Switzerland, to Munich, Germany, representing a distance of less than 400 km;
- **Medium-haul** flight from Oslo, Norway, to Rome, Italy, or approximately 4'000 km;
- **Long-haul** flight from Zurich, Switzerland, to New York, US, with a distance of more than 12'000 km.

[11] The UBA "$CO_2$ Rechner" suite of tools comprises, among others, a carbon footprint calculator ("Meine $CO_2$-Bilanz") for various activities, including air travel. All references to UBA in this study refer to this specific calculator.

[12] KlimAktiv was contacted by phone and email for the purpose of this study.

**Figure 1: Example carbon footprint calculation for a short-, medium- and long-haul return flight in economy class. Short-haul flight is ZRH-MUC (<400 km), medium-haul is OSL-FCO (~4'000 km) and long-haul is ZRH-JFK (~12'000 km). In all cases, no specific aircraft type was specified (i.e. the calculators' default settings for aircraft type are applied).**

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As evidenced by the results in Figure , reputable offsetting tools in the voluntary market include both $CO_2$ and non-$CO_2$ climate effects in their calculated flight emissions. In the cases examined, non-$CO_2$ effects represent a share of the overall climate effect in all but two instances. Of further note at this point is the large variability in total climate effect from one provider to another. For medium- and long-haul flights, a factor of more than 50% can be noted between the climate effect determined by the tools of South Pole and UBA. Differences among the tools can also be observed at the level of the $CO_2$ effect and non-$CO_2$ effects, respectively, whereby the variations are greatest for the non-$CO_2$ effects.

To better understand the reasons for the variations of both components, the methodologies applied by each provider are analysed in the following sections. The main focus, however, is set on the calculations of the non-$CO_2$ effects.

# 2 $CO_2$ effects

Each of the four tools analyzed calculate the $CO_2$ climate effects using standard best-practices for the sector. These include distance calculation based on Great Circle Distance (GCD) with corrections applied to account for detours, as well as standard emission factors for aviation fuel. In contrast to reporting $CO_2$ emissions under the EU ETS and CORSIA, where the specific aircraft type flown is known, voluntary market tools apply assumptions on aircraft type in order to determine fuel consumption. The specific approach and assumptions used by each provider's tool to calculate the $CO_2$ effect of flights is described in this section.

## 2.1 Calculation methods

### 2.1.1 Data input

The minimum data input requested by all tools includes the departure and arrival airport and a selection of either one-way or return flight (see Table 1). Based on these elements, the distance flown and, in most cases, also the fuel consumption, is calculated. Atmosfair is the only provider enabling a more refined assessment of fuel consumption by allowing for more detailed information about the flight and the aircraft type to be entered in the tool. In addition, the seating class is requested by all tools in order to make a proper allocation of emissions per passenger

**Table 1: Data input required by the various online tools.**

| Input | Myclimate | South Pole | UBA | atmosfair |
|---|---|---|---|---|
| Departure & arrival airports | ✓ | ✓ | ✓ | ✓ |
| One-way or return | ✓ | ✓ | ✓ | ✓ |
| Seating class | ✓ | ✓ | ✓ | ✓ |
| Chartered or scheduled | × | × | × | ✓ |
| Aircraft type | × | × | × | ✓ |

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### 2.1.2 Main assumptions

The variations in flight emissions observed in Figure  can be explained by each provider's use of different assumptions. All tools make use of a set of specific assumptions to calculate the $CO_2$ effect from flights and, while some similarities are noted in between providers, no two tools assume exactly the same parameters. These assumptions can be grouped into parameters relating to distance, aircraft type and fuel consumption, and emission factors. An overview for each provider is presented in Table and further discussed in the following sections.

**Table 2: Summary of common features and major differences of the online providers.**

| | Myclimate | South Pole | UBA | atmosfair |
|---|---|---|---|---|
| Distance | - GCD<br>- +50km short-haul<br>- +125km long-haul | - GCD<br>- +9% on all flights | - GCD<br>- +50 km on all flights | - GCD<br>- Detours based on distance-dependent factor (approx. 50 km on all flights)<br>- For holding patterns, +1 kg fuel/passenger |
| Aircraft type / fuel consumption | - Hybrid aircraft based on weighted average | - Not included specifically | - Average fuel consumption independent of aircraft type | - Selected aircraft or hybrid aircraft based on weighted average<br>- +2.5 kg fuel/passenger for taxiing |
| Emission factor | - 3.15 kgCO2/kg fuel<br>- for upstream fuel production: 0.5064 kg CO2e/kg fuel | - Emissions based on DEFRA dataset (kg CO2e per passenger km) | - 3.15 kgCO2/kg fuel | - 3.15 kgCO2/kg fuel |

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### Distance

As basis for the distance flown, the four tools studied calculate the Great Circle Distance between airport pairs and correct this value by applying various factors to ensure a realistic estimate. Indeed, the actual distance flown is generally greater than GCD due to inefficiencies in routing, weather events, or holding patterns prior to landing. The use of distance-correcting factors reflects these uncertainties in a simplified manner and their use is standard practice under the EU ETS and CORSIA.

**Box 1: Assumptions used by providers of carbon footprinting tools for flight distance calculation**

**Myclimate**'s approach is to add a fixed correction factor of +50 km on all short-haul flights and +125 km on all long-haul flights. This approach is adapted from the International Civil Aviation Organization (ICAO) emissions calculator handbook [ICAO, 2010]. **South Pole** implements a different methodology and applies a factor of 9% on all flights as determined by the IPCC special report on aviation [IPCC, 1999]. The $CO_2$-calculator of **UBA** uses a fixed distance correction of 50 km for any type of flight, regardless of the distance travelled.

In the case of **atmosfair**'s tool, a more comprehensive method is used, whereby the different causes of an increase in distance flown are each addressed separately. Detours are captured using a distance-dependent factor developed empirically by the provider – based on analysis of a statistical sample of detours on flights in Germany – and amounting to approximately 50 km on all flights. Holding patterns prior to landing are accounted for with an additional surcharge of 1 kilogram of fuel of per passenger rather than an addition to the GCD directly. This value is derived from a Lufthansa environmental report [Lufthansa, 2002].

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### Aircraft types and corresponding fuel consumption

The type of aircraft operated dictates the fuel consumption for a given fight distance. As the aircraft type is not a standard input parameter in most online carbon footprint tools, different methods are used to estimate the fuel consumption without this information. Most providers use the concept of a “hybrid aircraft", presenting the averaged characteristics of a specific group of aircraft types. In order to create the profile of this hybrid aircraft, each provider uses a different approach and dataset.

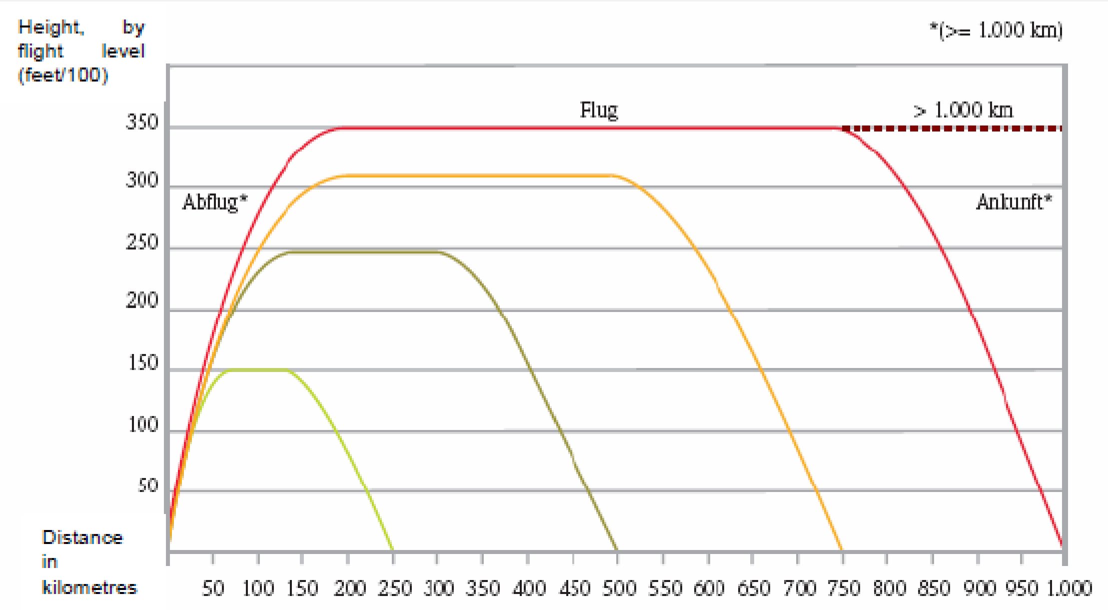
**Box 2: Assumptions used by providers of carbon footprinting tools for calculation of fuel consumption**

**Myclimate**'s tool does not enable the user to select an aircraft type but rather applies the concept of a hybrid aircraft. Here, the fuel consumption is estimated using a weighted average of fuel burn rates based on the total distance travelled for common aircraft types of the 10 largest airlines in 2008. The dataset used in this case is the ICAO DATA tool [ICAODATA, 2012]. Based on this, a generalized function of the fuel consumption for any flight distance is approximated. No distinction is made between fuel consumption at different stages of a flight (e.g. take-off, cruising, landing).

The **South Pole** tool relies on data developed and made publicly available by DEFRA [DEFRA, 2018a]. In this dataset, emission factors in kilogram of $CO_2$ equivalent per kilometre flown are made available for various flight categories (domestic, short-haul, long-haul). South Pole performed a regression analysis on the various size categories to develop a distance-dependant formula for the direct calculation of the $CO_2$ effect. Aircraft type and fuel consumption information are thus not material to South Pole's tool but are relevant upstream in DEFRA's approach to develop the emission factors in the first place. In DEFRA's dataset, emission factors are developed using data from EUROCONTROL Small Emitters Tool as basis as well as a representative set of aircraft types for each flight category (domestics, short-haul, long-haul) [DEFRA, 2018b].

**Atmosfair**'s tool is the only one of the four tools assessed allowing for the user to select a specific aircraft type. If a selection is made among the list of common aircraft types, the tool then accesses a database where fuel consumption is available for a variety of flight profiles for the specific aircraft. These flight profiles comprise a climb, cruise and descent phase – with fuel consumption defined for each phase – and are available for standard distances (see examples shown in Figure 2). In between these standard distances, the tool interpolates fuel consumption to obtain a final value. The database of flight profiles is based on data from DLR [DLR, 2000] and real flight data from QinetiQ [QinetiQ, 2005].

**Figure 2: Example of standardized flight profiles for different standard distances showing the three flight phases: climb, cruising and descent. Source: atmosfair n.d.; DLR 2000.**




If no aircraft type is specified by the user of atmosfair's tool, the concept of a hybrid aircraft is used to estimate fuel consumption. The hybrid aircraft is a blend of the four most operated aircraft types in the region of the selected flight. The tool defines 19 specific regions to achieve a more precise fuel consumption with greater relevance to the flight route. This selection is based on the same real

**Box 2: Assumptions used by providers of carbon footprinting tools for calculation of fuel consumption**

flight database as mentioned above [QinetiQ, 2005].
Further to the fuel consumption per aircraft, a factor of 2.5 kg fuel consumed per passenger is added for taxiing on ground prior to take-off and after landing based on the scientific study of Brockhagen (1995).
The UBA calculation tool is based on an average fuel consumption per flight distance independent of aircraft type. More specific information about the datasets used was not available from the technical guidance paper or from direct exchange with KlimAktiv. It would appear that, similarly to myclimate's tool, no distinction is made for the different flight phases. As of 2020, UBA will be updating the tool's assumptions and intends to use real fuel burn rates from Eurocontrol.

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### Emission factor

Across three of the four tools, the standard IPCC [IPCC, 2006] emission factor for jet fuel is applied, i.e. 3.15 kg $CO_2e$/kg jet fuel.

**Box 3: Emission factors used by providers of carbon footprinting tools**

In addition to the standard emission factor, **myclimate's** tool applies a fuel production emission factor of 0.5064 kg $CO_2e$/kg jet fuel to account for upstream emissions (exploration, production, transport) and emissions related to refining [ecoinvent, 2010].

**South Pole's** emission factor is based on the DEFRA database as mentioned previously, where the emissions per passenger-km are directly available. In order to develop these figures, the DEFRA methodology uses an emission factor of 3.18 kg $CO_2e$/kg jet fuel, similar to the IPCC value above [Exergia et al., 2015].

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# 3 Non-$CO_2$ effects

Work package 1 (AP1) of this project described in detail the various climate metrics available to measure non-$CO_2$ climate effects. The selection of a metric is often a trade-off between seeking the highest relevance possible vis-à-vis the impacts considered (e.g. temperature change, impact on ecosystems, etc.) and the need for it to be easily understandable and simply usable. While a host of metrics exist, radiative forcing is a commonly used one for this purpose, reflecting the net change in energy balance due to the emission of a particular climate species. Contrary to $CO_2$, the emissions of non-$CO_2$ climate species (e.g. $NO_x$, aerosols) are not directly proportional to fuel consumption but are dependent on a host of other operating parameters as well. Considering also the complex interplay of these non-$CO_2$ climate species in the atmosphere and their varied consequences (e.g. ozone production, elimination of $CH_4$, formation of contrails), straightforward methods for calculating the amount of these species emitted for a given flight are not currently available. Tools in the voluntary carbon markets therefore apply a simplified approach to quantify the non-$CO_2$ effects of air travel.

## 3.1 Calculation methods

In the four carbon footprint tools assessed, the total radiative forcing effect of non-$CO_2$ climate species is estimated – from publicly available literature sources – using the concept of the radiative forcing index (RFI). This approach calculates the overall impact of climate species ($CO_2$ and non-$CO_2$) relative to one unit of $CO_2$ emission through the application of a dimensionless multiplier (i.e. the RFI) according to the generic formula below.

$$E_{total} = E_{CO2} \times M \quad (1)$$

Where:

- $E_{total}$ = Total climate effect ($CO_2$ and non-$CO_2$) of flight in $CO_2$ equivalent
- $E_{CO2}$ = $CO_2$ climate effect of flight in $CO_2$ equivalent
- $M$ = Multiplier or Radiative Forcing Index

The resulting $CO_2$ equivalents are then assumed to represent the amount of $CO_2$, which, when emitted, would cause the same climate effect as the $CO_2$ and non-$CO_2$ species combined.

While all the tools apply the concept of a RFI multiplier to account for non-$CO_2$ climate effects, significant differences are nevertheless apparent from one tool to the other when calculating the emissions for a given flight (see Figure ). This stems from the use of different multiplier values as well different methods in applying them. An overview of the different multipliers used, their sources and their underlying methods is shown in Table and explained in more detail in the following sections.

**Table 3: Summary of RFI multiplier values and approaches used by online providers.**

| Input | myclimate | South Pole | UBA | atmosfair |
|---|---|---|---|---|
| Multiplier | 2 | 2 | 2.7 | 3 |
| Approach | Same multiplier on all flights. Multiplier is only applied to $CO_2$ emissions from combustion and not from fuel production | Same multiplier on all flights | Only for flights longer than 400 km | Only applied to flights in altitudes above 9km: - no multiplier for flights less than 400km - no multiplier during climb and descent phase |
| Sources | Kollmuss & Crimmins (2009) | Kollmuss & Crimmins (2009) | ifeu (2007) | IPCC Fourth Assessment 2007 [Graßl & Brockhagen, 2007] |
| Correlation with calculation methods in AP1 & AP2 | Constant factor | Constant factor | Variable factor | Variable factor |

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### 3.1.1 South Pole & myclimate

The two online providers South Pole and myclimate are analysed together, as they use a multiplier based on the same reference source. Both use a constant factor that is applied on all flights regardless of distance flown. The multiplier value selected is derived from the research paper of Kollmuss and Crimmins (2009), where the authors recommend the use of a multiplier of at least 2 to account conservatively for non-$CO_2$ effects. In addition, it should be noted that myclimate applies the multiplier only to the emissions it calculates from fuel combustion and not the emission resulting from pre-production of the fuel. Effectively, the resulting multiplier in flight emissions calculated by myclimate's tool is less than 2.

The report by Kollmuss and Crimmins provides a stocktake of existing approaches and metrics for quantifying non-$CO_2$ effects as well recommendations on the use of multipliers. The reasoning behind the recommendation of a multiplier of at least 2 is, firstly, the recognition that although uncertainty still exists related to the correct quantification of climate impacts of non-$CO_2$ effects, the total contribution to climate change is greater than that of $CO_2$ alone. Therefore, a multiplier system with a value larger than 1 is required. Secondly, the authors highlight the ethical imperative that given the urgency of climate change all known warming effects should be included in such a quantification. Finally, the impact of the time horizon considered is also discussed. The authors advocate for a short time horizon of 20 years in order to include the short-lived effects of non-$CO_2$ species. If a longer time horizon were considered, these short-lived effects would not be captured.

The authors acknowledge that the use of a simple multiplier has benefits from a climate protection point of view, although from a scientifically-minded perspective this is an approach that should be discouraged. In Work Package 1 (AP1) of this project, the authors also emphasize that the use of a constant factor is highly inaccurate as strong interdependencies between climate impact and emission location as well as between flight altitude and flight distance exist. As a result, at a minimum, a variable or distance-dependant multiplier should be used.

### 3.1.2 **UBA**

The UBA calculation tool uses a more differentiated multiplier approach with a variable factor based on a simplified distance-based method. The multiplier is applied only on flights over 400 km as the methodology assumes that below this critical distance the flight does not reach an altitude where non-$CO_2$ effects are relevant. UBA bases its approach on a report by the Institut für Energie und Umweltforschung Heidelberg [ifeu, 2007], which emphasizes the outsized impact of non-$CO_2$ species emitted at higher altitudes compared to those emitted at lower altitudes. The value of the multiplier is based on IPCC (1999), where an RFI range of 2-4 is recommended with a best estimate of 2.7.

It is unclear from the report how the distance of 400 km is identified as the threshold for applying the distance-dependent multiplier. The specific altitude assumed to be reached for a flight over 400 km is also not evident in the report. In atmosfair's tool an identical distance threshold of 400 km is used, and the reasoning may therefore be similar (see next section).

A variable multiplier better represents the overall climate effect of a flight compared to a constant factor and the additional effort needed is very small. However, only limited improvement in accuracy would be gained from the simplified distance-dependent factor used in UBA's tool.

### 3.1.3 **Atmosfair**

The last tool selected demonstrates the most sophisticated approach of the four providers analysed. Atmosfair applies a factor that varies with distance as well as to some extent with altitude. The multiplier value used is based on the RFI range of 1.9-4.7 given by the IPCC in the Fourth Assessment Report [Graßl & Brockhagen, 2007]. The range is adapted from the earlier IPCC [IPCC, 1999] report and atmosfair argues that a value of 3 represents the middle of this new range.

Graßl & Brockhagen (2007) indicate that some non-$CO_2$ effects do not occur on flights below a certain threshold altitude and that therefore short-hauls flights could be exempted from applying a multiplier. On this basis, atmosfair assigns a threshold altitude of 9 km and only applies the multiplier to flights reaching this altitude. In addition, the multiplier is also not applied during the climb and descent phase. The RFI-multiplier is consequently effectively always below 3.

The tool operates on the basis of flight profiles as discussed in section 2.1.2. For a given flight distance a specific altitude-distance profile is available encompassing a climb, cruise and descent phase, each with defined fuel consumptions. Atmosfair considers that flights over 400 km reach the critical altitude of 9 km for non-$CO_2$ effects to be relevant. Prior to applying the multiplier, the tool therefore eliminates the $CO_2$ emissions associated with the climb and descent phases, and discards emissions from the cruise phase if the flight distance is less than 400 km.

Atmosfair's variable factor approach is primarily a simplified distance-dependent method. The altitude dependency is acknowledged by atmosfair but is in effect modelled based on the flight distance. This approach is more precise than a constant factor and the additional data and effort required still seems acceptable.

# 4 Concluding remarks

Reputable providers of carbon footprint calculators in the voluntary carbon market take into account both the $CO_2$ and non-$CO_2$ effects in the calculated emissions from passenger air travel. Across different tools, stark variations in the calculated emissions of a given flight are noticeable, hinting at the challenges of quantifying the climate effect of air travel. For short-haul flights, myclimate and South Pole calculate higher emissions than the other two tools, whereas the opposite is true for medium- and long-haul flights.

While the overall approach for determining the $CO_2$ effects is scientifically sound, the complexities of quantifying non-$CO_2$ effects result in the use of a rather simplistic approach via the Radiative Forcing Index. In this approach, a dimensionless multiplier is used, which varies between 2 and 3 in the various tools. For the non-$CO_2$ effects, it is interesting to note that the methods of applying the multiplier differ as well, namely in complexity and additional computational effort required. The methods mostly correlate with the constant factor approach or simplistic versions of the distance-dependent factor approach described in previous work packages of this project (AP1, AP2). However, even atmosfair's tool, the most sophisticated of the four, remains a rather simplistic calculator.

The relevance and transferability of any knowledge from these existing non-$CO_2$ calculation methods for the purpose of the EU ETS, CORSIA, or other regulatory frameworks remains to be discussed but appears rather limited.

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# Part D: Verifiability of Reporting Aviation's non-$CO_2$ Effects in EU ETS and CORSIA

Final report

by

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**Abstract**

The EU Emissions Trading System (EU ETS) and CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) are introduced or planned market-based measures (MBM) in aviation to reduce $CO_2$ emissions. As the amount of $CO_2$ emissions is proportional to the fuel consumption, it is relatively straight forward to monitor, to report and to verify (MRV) these instruments. In a new or revised MBM that would also take into account non-$CO_2$ effects from air transportation, additional MRV efforts would become necessary, which will largely depend on the actually chosen calculation methodology.

This report collects the required database and assesses the additional administrative burden for three different calculation methods: (1) a relatively simple distance dependent $CO_2$ equivalence (${}^{eq}CO_2$) factor, (2) a climatological latitude-height dependent ${}^{eq}CO_2$ factor and (3)a detailed weather and spatial dependent ${}^{eq}CO_2$ factor. Greater accuracy in considering the relevant atmospheric processes will lead to greater benefits for climate protection. However, more accurate ${}^{eq}CO_2$ approaches require more data for MRV. The use of a distance-dependent factor, for example, is not suitable for emissions trading because it does not create incentives for airlines to reduce their climate impact of $CO_2$ and non-$CO_2$ effects. If a latitude-height dependent ${}^{eq}CO_2$ is applied, the competent authority (CA) would require 3D emission inventories to check the non-$CO_2$ emissions reported by the operator, which would result in substantially more administrative effort and the need for tools to model and verify the reported emissions as fuel consumption and the exact waypoints would not be immediately available to the CA. The administrative burden would increase further if detailed weather information is necessary.

**Kurzbeschreibung**

Der EU-Emissionshandel (European Union Emissions Trading System, EU ETS) und CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) sind in der Luftfahrt eingeführte bzw. geplante marktbasierte Maßnahmen zur $CO_2$-Reduktion. Da die Menge der freigesetzten $CO_2$-Emissionen proportional zum Kraftstoffverbrauch ist, ist die Überwachung, Berichterstattung und Überprüfung (Monitoring, Reporting, Verification, MRV) dieser Instrumente relativ einfach. Bei einer neuen oder überarbeiteten marktbasierten Maßnahme, bei der auch Nicht-$CO_2$-Klimaeffekte des Luftverkehrs, wie z.B. die Kondensstreifenzirren- oder Ozonbildung, berücksichtigt würden, wären zusätzliche MRV-Anstrengungen erforderlich, die weitgehend von der tatsächlich gewählten Berechnungsmethode abhängen.

Dieser Bericht erfasst die erforderliche Datenbasis und bewertet den zusätzlichen Verwaltungsaufwand für drei verschiedene Berechnungsmethoden: (1) einen relativ einfachen entfernungsabhängigen $CO_2$-Äquivalenzfaktor (${}^{eq}CO_2$-Faktor), (2) einen klimatologischen, von der Breite und Höhe abhängigen ${}^{eq}CO_2$-Faktor und (3) einen detaillierten wetter- und ortsabhängigen ${}^{eq}CO_2$-Faktor. Mit zunehmender Genauigkeit der relevanten atmosphärischen Prozesse steigt die Wirksamkeit (Klimaeinsparpotenzial) deutlich. Genauere ${}^{eq}CO_2$-Ansätze erfordern aber auch ein komplexeres MRV-System. So ist beispielsweise der Einsatz eines distanzabhängigen Faktors für den Emissionshandel nicht geeignet, da dieser keine Anreize für Fluggesellschaften erzeugt, ihre Klimawirkung ($CO_2$ und nicht-$CO_2$-Effekte) zu reduzieren. Wenn ein vom Breitengrad-Höhen abhängiger ${}^{eq}CO_2$-Faktor angewendet wird, müssen die zuständigen Behörden 3D-Emissionsinventare überwachen, um die vom Betreiber gemeldeten Nicht-$CO_2$-Emissionsmengen zu überprüfen. Da jedoch sowohl die tatsächlichen Emissionen als auch die genauen Wegpunkte der zuständigen Behörde nicht zur Verfügung stehen, muss eine Fähigkeit zur (modellbasierten)

Abschätzung diese Daten aufgebaut werden. Der Verwaltungsaufwand steigt weiter, wenn zusätzlich noch detaillierte Wetterinformationen benötigt würden.

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## List of Abbreviations

| | |
|---|---|
| **CA** | competent authority |
| **CORSIA** | Carbon Offsetting and Reduction Scheme for International Aviation |
| **DEHSt** | Deutsche Emissionshandelsstelle (German Emission Trading Authority) |
| **$^{eq}CO_2$** | Carbon dioxide equivalent |
| **EU ETS** | European Union Emissions Trading System |
| **MBM** | Market based measures |
| **MRV** | Monitoring, Reporting, Verification |
| **UAP** | Unterarbeitspaket (sub work package) |
| **UBA** | Umweltbundesamt (German Environment Agency) |

## Summary

A globally harmonized, functioning MRV system (Monitoring, Reporting, Verification) is an essential pillar of a global, market-based environmental measure in order to guarantee both ecological effectiveness and a level playing field for all participants. In Europe, such a system has been established within the EU ETS for aviation, with a comparable framework currently being introduced globally as part of CORSIA (**C**arbon **O**ffsetting and **R**eduction **S**cheme for **I**nternational **A**viation). Both MRV systems only consider $CO_2$ emissions which are relatively straightforward to monitor and verify as they correlate with fuel consumption by a fixed factor.

In a new or revised market-based measure that would also take into account non-$CO_2$ effects from air transportation, additional verification efforts of the competent authorities (CA) would become necessary, which will largely depend on the actually chosen calculation methodology and thus on the number, type and availability of additional values and metrics that would have to be checked.

This report contains the results of sub work packages (UAP) 4.1 and 4.2 and assesses the required data basis and the additional administrative effort of three different methods for calculating and considering non-$CO_2$ emissions in a market-based measure: (1) a relatively simple distance dependent $CO_2$ equivalence (${}^{eq}CO_2$) factor, (2) a climatological latitude-height dependent ${}^{eq}CO_2$ factor, and (3) a detailed weather and spatial dependent ${}^{eq}CO_2$ factor.

The consideration of non-$CO_2$ effects as a **simple, distance-dependent factor of the $CO_2$ emissions** would be easy to handle administrative-wise but is not recommended as important factors like the actual route or weather conditions would be ignored. We would expect the administrative burden of the CA to rise by approximately 10-20%.

If a **latitude-height dependent ${}^{eq}CO_2$ factor** was applied, the CA would require 3D emission inventories to check the non-$CO_2$ emissions reported by the operator, which would result in substantially more administrative effort and the need for tools to model and verify the reported emissions as fuel consumption and the exact waypoints would not be immediately available to the competent authority. A major requirement for successful verification activities by the CA would hence be a similar data basis and the availability of a modelling tool for NOx and other species along the route. Even in this case, we would still expect an increase in administrative effort of at least 100%.

If **detailed weather and spatial dependent ${}^{eq}CO_2$ factors** were to be considered, not only 3D emission inventories but also meteorological data would be needed to check the reported figures. This would require even more administrative effort. An increase by more than 100% would be likely.

Generally-speaking, even if the required additional data and models were available, deviations would be much more complex to assess. This is of special importance as different competent authorities (e.g. in European or worldwide comparison) have different capabilities and manpower. For this reason, it cannot be ruled out that the CAs of certain countries would do less accurate checks than others, which could have adverse impacts on the level playing field.

A suitable method to tackle non-$CO_2$ emissions with reasonable administrative effort at the competent authority (and possibly also aircraft operator) level could be to make use of a public reference table, e.g. modelled and published by the EU Commision or by Eurocontrol, which

would contain ${}^{eq}CO_2$ estimates for non-$CO_2$ emissions by airport-pair and engine/aircraft type, considering different routes, flight profiles and possibly climate tables.

## Zusammenfassung

Ein weltweit harmonisiertes, funktionierendes MRV-System (Monitoring, Reporting, Verification) ist eine wichtige Säule einer globalen, marktbasierten Umweltmaßnahme, um sowohl die ökologische Wirksamkeit als auch gleiche Wettbewerbsbedingungen für alle Beteiligten zu gewährleisten. In Europa wurde ein solches System im EU ETS für die Luftfahrt eingeführt, wobei derzeit ein vergleichbarer Rahmen weltweit als Teil von CORSIA (**C**arbon **O**ffsetting and **R**eduction **S**cheme for **I**nternational **A**viation) eingeführt wird. Beide MRV-Systeme berücksichtigen jedoch nur $CO_2$-Emissionen, die relativ einfach zu erfassen, zu berichten und zu überprüfen sind, da sie mit dem Kraftstoffverbrauch durch einen festen Faktor korrelieren.

Bei einer neuen oder überarbeiteten marktbasierten Maßnahme, bei der auch Nicht-$CO_2$-Klimaeffekte des Luftverkehrs, wie z.B. die Kondensstreifenzirren- oder Ozonbildung, berücksichtigt würden, wäre zusätzlicher Verwaltungsaufwand der zuständigen Behörde erforderlich, der weitgehend von der tatsächlich gewählten Berechnungsmethode abhängen würde.

Dieser Bericht enthält die Ergebnisse der Unterarbeitspakete (UAP) 4.1 und 4.2 und erfasst und bewertet die erforderliche Datenbasis und den zusätzlichen Verwaltungsaufwand für drei verschiedene Ansätze, um die Nicht-$CO_2$-Emissionen in einer marktbasierten Maßnahme zu berechnen und zu berücksichtigen: (1) einen relativ einfachen entfernungsabhängigen $CO_2$-Äquivalenzfaktor ($^{eq}CO_2$-Faktor), (2) einen klimatologischen, von der Breite und Höhe abhängigen $^{eq}CO_2$-Faktor und (3) einen detaillierten wetter- und ortsabhängigen $^{eq}CO_2$-Faktor..

Die Berücksichtigung von Nicht-$CO_2$-Effekten über einen einfachen, entfernungsabhängigen Faktor auf die $CO_2$-Emissionen wäre einfach zu handhaben und nur mit einem geschätzten Verwaltungsmehraufwand von 10-20% verbunden, wird jedoch nicht empfohlen, da Faktoren wie die tatsächliche Route oder die Wetterbedingungen ignoriert würden.

Wenn ein vom Breitengrad-Höhen abhängiger $^{eq}CO_2$-Faktor angewendet wird, würden 3D-Emissionsinventare benötigt, um die vom Betreiber gemeldeten Nicht-$CO_2$-Emissionen zu überprüfen. Jedoch stehen sowohl die tatsächlichen Emissionen als auch die genauen Wegpunkte der zuständigen Behörde nicht Verfügung. Selbst bei einer ähnlichen Datenbasis wie die Carrier und der Verfügbarkeit der nötigen Tools für die Berechnung von $NO_x$ und andere Emissionen entlang der Route ist mit einem Verwaltungsmehraufwand von mindestens 100% zu rechnen.

Wenn zusätzlich noch detaillierte wetterabhängige $^{eq}CO_2$-Faktoren berücksichtigt würden, wären nicht nur 3D-Emissionsinventare, sondern auch meteorologische Daten erforderlich, um die gemeldeten Zahlen zu überprüfen, was noch mehr Verwaltungsaufwand erfordern würde. Eine Erhöhung des Verwaltungsaufwands um mehr als 100% wäre wahrscheinlich.

Im Allgemeinen wären Abweichungen sehr viel komplexer zu bewerten, selbst wenn die erforderlichen zusätzlichen Daten und erforderlichen Modelle verfügbar wären. Dies ist von besonderer Bedeutung, da verschiedene zuständige Behörden (z. B. im europäischen oder weltweiten Vergleich) unterschiedliche Fähigkeiten und Budgetausstattungen haben. Aus diesem Grund kann nicht ausgeschlossen werden, dass die zuständigen Behörden bestimmter Länder weniger genaue Kontrollen durchführen würden als andere, was negative Auswirkungen auf den Wettbewerb zwischen den Airlines haben kann.

Eine geeignete Methode zur Berücksichtigung von Nicht-$CO_2$-Emissionen in einer marktbasierten Maßnahme mit vertretbarem Verwaltungsaufwand auf Behördenebene könnte daher die Verwendung einer z.B. von Eurocontrol oder der EU-Kommission veröffentlichten Referenztabelle sein, die $^{eq}CO_2$-Referenzwerte für die Nicht-$CO_2$-Emissionen für jede Flughafenpaar-Flugzeug/Triebwerkskombination (unter Berücksichtigung verschiedener Routen, Flugprofile und möglicherweise Klimatabellen) enthalten würde.

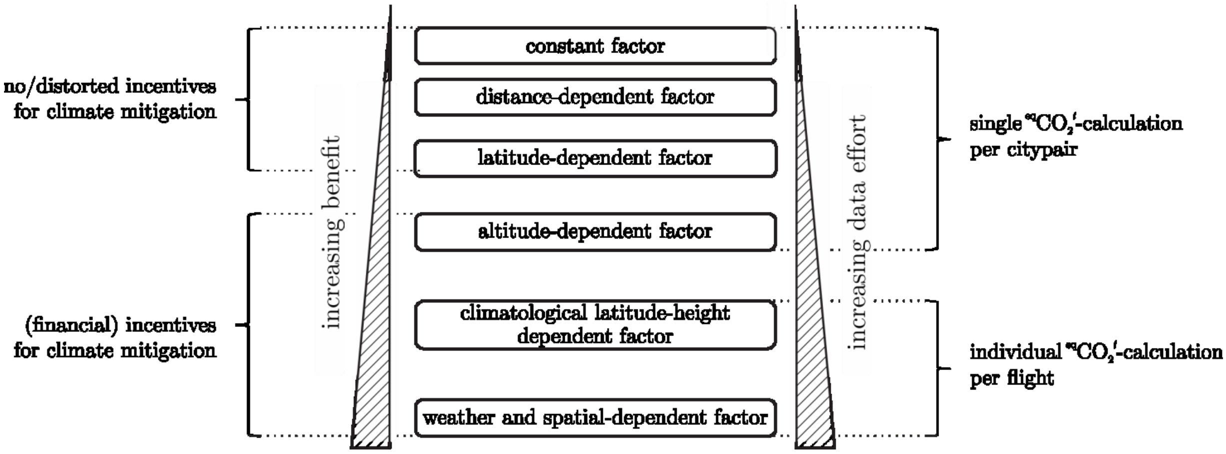
# 1 Introduction

A globally harmonized, functioning MRV system (Monitoring, Reporting, Verification) is an essential pillar of a global, market-based environmental measure in order to guarantee both ecological effectiveness and a level playing field for all participants. In Europe, such a system has been established within the EU ETS for aviation, with a comparable framework currently being introduced globally as part of CORSIA. Both MRV systems only consider $CO_2$ emissions that are relatively straightforward to monitor and verify because they correlate with fuel consumption by a fixed factor.

In a new or revised market-based measure (MBM) that would also take into account non-$CO_2$ effects from air transportation, some verification tasks are likely to be similar to the existing, $CO_2$-related ones in CORSIA and the EU ETS. These include, on the one hand, the general review of the monitoring and reporting concepts of aircraft operators and, on the other hand, some items that occur during the verification of emission reports, such as checking the completeness of the reported flights, the types of aircraft used, or the fuel consumption and completeness of the fuel bills.

The peculiarities and differences in the monitoring, reporting and verification of non-$CO_2$ emissions and effects will largely depend on the actually chosen calculation methodology. Greater accuracy in considering the relevant atmospheric processes will lead to greater benefits for climate protection. However, more accurate ${}^{eq}CO_2$ approaches also require more data for monitoring, reporting and verification (see Figure).

**Figure 1: Increasing benefit and data effort for increasing consideration of non-$CO_2$ processes**




Based on Dahlmann et al., 2018, p. 27 and Niklaß, 2019, p. 42

As already argued above (see e.g. section 4 in Dahlmann et al., 2018 and section 5 in Plohr et al., 2018), the reporting or estimation of non-$CO_2$ effects as a simple, fixed factor of $CO_2$ emissions is insufficient as additional data such as time, route length, altitude and/or weather conditions would have to be taken into account to calculate ${}^{eq}CO_2$ the best possible way. At the same time, it will be a challenge to limit the data requirements to an acceptable level, which would enable verification with a justifiable effort, without reducing the ecological effectiveness or providing disincentives.

This report relates to Work Package 4 of the study and assesses the verifiability of the reporting of aviation's non-$CO_2$ emissions in a market-based measure such as the EU ETS or CORSIA, with a focus on the additional administrative efforts for the competent authority (CA) depending on the selected calculation methodology. It consists of two steps, which have been labelled as sub work packages (Unterarbeitspakete; "UAP") 4.1 and 4.2:

UAP 4.1 ("Required data basis"): For different calculation methodologies, we examine which data must be transmitted to the competent authority in which aggregation level in order to make the emission calculation verifiable. We also determine which existing reference data can be used for independent reviews of reports, and which additional data would have to be made available (see Sections 2.1 to 2.4).

UAP 4.2 ("Estimation of additional administrative effort"): Based on the results of UAP 4.1 as well as on process analyses and related stakeholder talks with representatives from the German Emission Trading Authority (DEHSt), we assess the additional administrative effort expected for the verification of emission reports by the competent authority compared to the existing regime, which only covers $CO_2$ emissions (see Section 2.5).

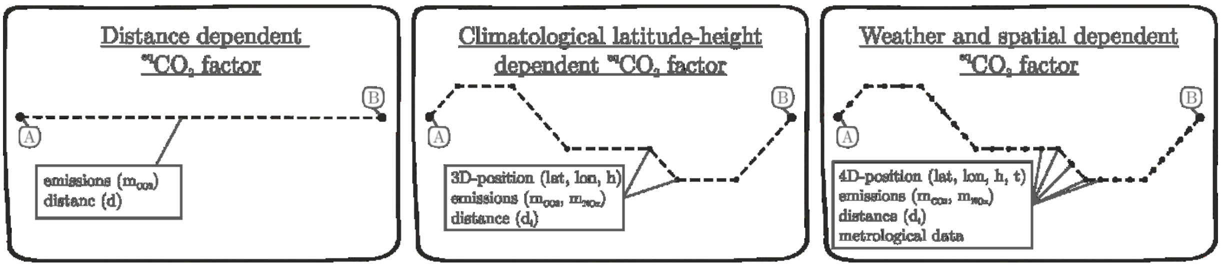
# 2 Required data basis for the verifiability of reported non-$CO_2$ emissions

The inclusion of non-$CO_2$ climate species into existing climate protecting measures like the EU ETS or CORSIA will lead to additional administrative efforts and costs. The level of these additional expenses will be strongly depending on the method to estimate $CO_2$ equivalents ($^{eq}CO_2$). A higher accuracy in taking into account the relevant atmospheric processes will result in larger benefits for climate mitigation. But, however, more accurate $^{eq}CO_2$ approaches will also require a higher amount of data for monitoring, reporting and verification.

Within the framework of this research project, three different approaches to address the non-$CO_2$ species of aviation have been worked out by Dahlmann et al. (2018) (see Figure 2):

(1) a relatively simple distance dependent $^{eq}CO_2$ factor,
(2) a climatological latitude-height dependent $^{eq}CO_2$ factor,
(3) and a detailed weather and spatial dependent $^{eq}CO_2$ factor.

**Figure 2: Illustration of data requirements for selected methods to calculate $CO_2$ equivalents ($^{eq}CO_2$)**

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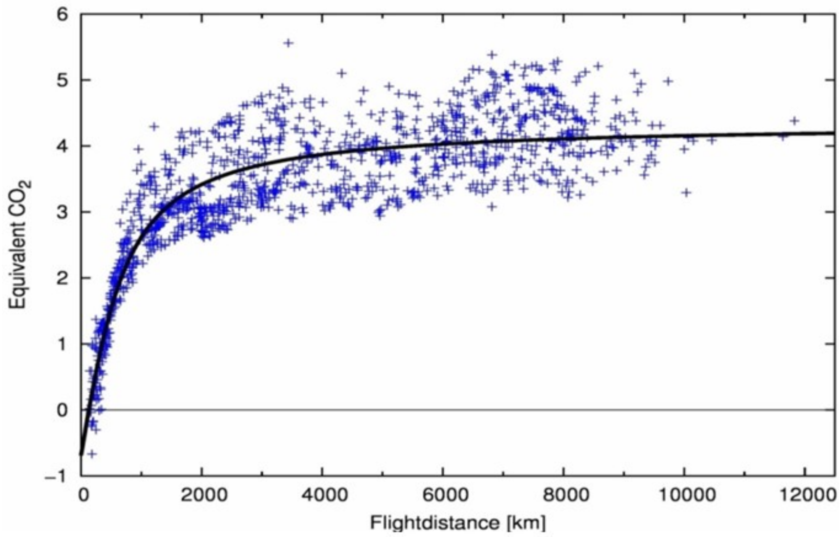
The required data basis for the verifiability of these three $^{eq}CO_2$ calculation methods is presented in the following sections.

## 2.1 Distance dependent $^{eq}CO_2$ factor

The distance dependent $^{eq}CO_2$ factor is the simplest calculation method for equivalent $CO_2$ emissions under consideration here: As the climate impact strongly depends on the emission location and the flight altitude depends on the flight distance (lower altitude for short distances) it is meaningful to use at least a factor depending on the flight distance, which uses implicit different flight altitudes. In Figure 3 the equivalent $CO_2$ emissions in dependency of flight distance are provided.

**Figure 3: Equivalent $CO_2$ coefficient ($^{eq}CO_2$) in dependency of the flight distance (blue crosses) and according curve fit (black)**




© Dahlmann et al., 2018, p. 35

Fitting these data provides following function:

$$^{eq}CO_2(dist) = (3.20 \cdot arctan(0.00167 \cdot dist) - 0.69), \quad (1)$$

$$^{eq}E_{CO_2}(dist) = {}^{eq}CO_2(dist) \cdot E_{CO_2} \quad (2)$$

where $^{eq}CO_2$ is the $CO_2$-equivalent factor in kg, $dist$ the flown distance in km, $E_{CO_2}$ the amount of emitted $CO_2$ in kg and $^{eq}E_{CO_2}$ the amount of $CO_2$ equivalents.

It has to be mentioned that this factor strongly depend on the assumed emission indices (e.g. $NO_x$). The distance dependent factor, which is presented here, is based on a world fleet of an A330-200 with an average emission index of $NO_x$ of 19 g/kg and a specific fuel consumption of about 6 kg/km. If an aircraft with different emission indices or specific fuel consumption, e.g. newer engines, is used the constant factor will differ significantly. This is also possible for aircrafts flying in different regions, e.g. tropics, as for example contrails occur in higher altitudes than for mid-latitudes.[13] General changes in flight altitudes, e.g. new aircrafts optimized for lower altitudes would also result in changing factors.

The Data required for implementing a distance dependent $^{eq}CO_2$ factor is listed in the table below:

[13] Most emissions of the considered A330-200 fleet take place in mid-latitudes with a mean flight altitude of 11.3kft.

**Table 1: Data required for implementing a distance dependent ${}^{eq}CO_2$ factor**

| | | |
|---|---|---|
| **Calculation method for equivalent $CO_2$ emissions:** | $^{eq}E_{CO_2}(dist) = {}^{eq}CO_2(dist) \cdot E_{CO_2}$ | |
| **Data required per flight:** | $E_{CO_2}$ | $CO_2$ emissions per flight |
| | $dist$ | Flown distances per flight |
| | ${}^{eq}CO_2(d)$ | Accumulated Equivalent $CO_2$ coefficient for all climate agents in dependency of the flight distance (see Figure 10) |
| **Data to be provided by the aircraft operator:** | Airport Pairs (Origin – Destination) | |
| | Number of flights per airport pair | |
| | Total fuel consumption of the fleet per airport pair | |
| **Data to be collected by the authority:** | Operated aircraft types per city pair | |
| | Number of flights of an aircraft type per city pair | |
| | Fuel consumption of an aircraft type per airport pair | |

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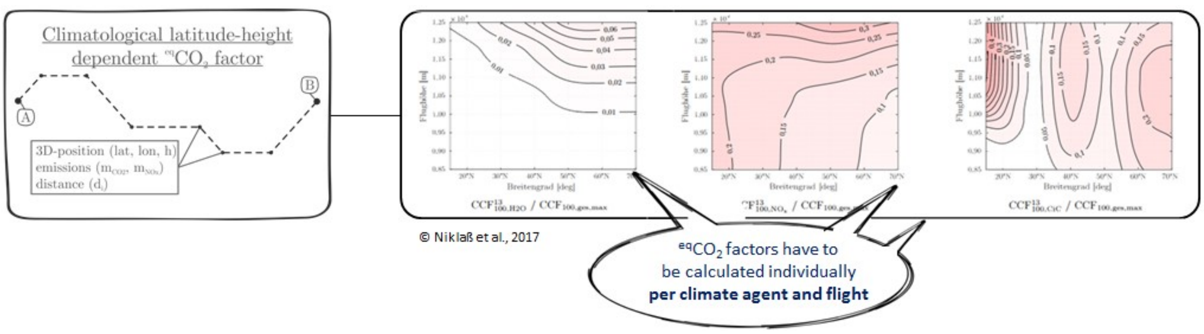
Using a distance dependent factor for emission trading does not give incentives for airliners to reduce climate impact of non-$CO_2$ effects. As the calculated equivalent $CO_2$ emissions only depends on the $CO_2$ emissions and therewith the fuel consumption, airlines will try to reduce only $CO_2$ emissions. Although a reduction in $CO_2$ leads to a reduced climate impact of $CO_2$, a potential increase in non-$CO_2$ effects could overcompensate this benefit. Increasing flight altitudes, for example, can lead to decreasing fuel consumption due to reduced friction, but can increase the impact of CiC, $H_2O$ and $O_3$ (Frömming et al., 2012; Dahlmann et al., 2016a).

Such a simple factor can be used for public to see an estimate of the total climate impact of aviation, e.g. for compensation market or personal $CO_2$ footprint. Nevertheless it is not suitable for a use in emissions trading or MBMs as it cannot produce incentives for airlines to reduce the non-$CO_2$ climate impact, as changes in flight regions or altitude and reduction in $NO_x$ emissions will not lead to reducing $CO_2$ equivalents.

## 2.2 Climatological latitude-height dependent ${}^{eq}CO_2$ factor

To gain incentives to reduce the climate impact of non-$CO_2$ effects, an altitude and latitude dependencies have to be taken into account (compare FigureFigure). If $CO_2$ equivalent factors vary from region to region, they have to be calculated separately for each individual flight:

**Figure 4: Data required for a climatological latitude-height dependent ${}^{eq}CO_2$ factor**



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To estimate latitude and altitude dependent ${}^{eq}CO_2$ coefficients, climate response models like AirClim (Grewe and Stenke, 2008; Dahlmann, 2012; Dahlmann et al., 2016b) or climate change functions (CCF; see Matthes et al., 2012; Grewe et al., 2014; Niklaß et al., 2017) can be used. Both methods require detailed information about the location of $CO_2$ and non-$CO_2$ emissions $\boldsymbol{x}$ (longitude, latitude, altitude) and the amount of emission in each region $E_i(\boldsymbol{x})$ (see Figure ):

$$ {}^{eq}E_{CO_2}(\boldsymbol{x}) = E_{CO_2} + E_i(\boldsymbol{x}) \cdot {}^{eq}CO_2{}^{i}(\boldsymbol{x}) + dist(\boldsymbol{x}) \cdot {}^{eq}CO_2{}^{CiC}(\boldsymbol{x}) \tag{3} $$

The multiplication of $E_i(\boldsymbol{x})$ with individual equivalent $CO_2$ coefficients $\left({}^{eq}CO_2{}^{i}\right)$ along the trajectory provides a measure of the climate impact from individual components. The data required for implementing a climatological latitude-height dependent ${}^{eq}CO_2$ factor is listed in Table 2:

**Table 2: Data required for implementing a climatological latitude-height dependent ${}^{eq}CO_2$ factor**

| | | |
|---|---|---|
| **Calculation method for equivalent $CO_2$ emissions:** | $\boldsymbol{{}^{eq}E_{CO_2}(x) = E_{CO_2} + E_i(x) \cdot {}^{eq}CO_2{}^{i}(x) + dist(x) \cdot {}^{eq}CO_2{}^{CiC}(x)}$ | |
| **Data required per flight:** | $\boldsymbol{x}$ | 3D waypoint profile per flight |
| | $dist(\boldsymbol{x})$ | Flown distances per flight |
| | $E_{CO_2}$ | $CO_2$ emissions per flight |
| | $E_i(\boldsymbol{x})$ | 3D emission inventory per flight for $i \in \{H_2O, NO_x\}$ |
| | ${}^{eq}CO_2{}^{i}(\boldsymbol{x})$ | equivalent $CO_2$ coefficient for $i \in \{H_2O, NO_x\}$ as function of emission location |
| | ${}^{eq}CO_2{}^{CiC}(\boldsymbol{x})$ | equivalent $CO_2$ coefficient for contrail induced cloudiness (CiC) as function of emission location |
| **Data to be provided by the aircraft operator:** | Airport Pairs (Origin – Destination) | |
| | Number of flights per airport pair | |
| | Aircraft type per flight | |
| | (Flown) 3D trajectory per flight | |
| | Fuel consumption per flight | |
| | 3D emission inventory ($CO_2$, $NO_x$) per flight | |
| **Data to be collected by the authority:** | Operated aircraft types per city pair | |
| | Number of flights of an aircraft type per city pair | |
| | Aircraft type per flight | |
| | (Flown) 3D trajectory per flight | |
| | (Flown) distances per flight $\left(dist = \sum dist_{GC,i} + 95km\right)$ | |
| | Distance-dependent fuel consumption per flight | |
| | 3D emission inventory ($CO_2$, $NO_x$) per flight | |
| | Individual ${}^{eq}CO_2$ factor per climate agents and city pair | |

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To verify the provided data by the aircraft operator, supervising authorities have different options:

Operated aircraft types and 3D waypoint profile data of each single flight can be requested from air navigation service providers (ANSP) such as EUROCONTROL. The flown flight distance can be approximated by great circle distances ($dist_{\mathrm{GC},i}$) between individual waypoints $i$ plus a constant of $95km$ for detours and holding patterns:

$$dist = \sum dist_{GC,i} + 95km \tag{4}$$

To check the reported 3D emission inventories $E_i(\boldsymbol{x})$ of individual species, CA has to estimate the fuel flow $w_{FF}(\boldsymbol{x})$ of the flight, the emission indices of different climate agents ($EI_i$) and the mission time ($t_\mathrm{m}$):

$$E_i(\boldsymbol{x}) = EI_i \cdot w_{FF}(\boldsymbol{x}) \cdot t_m \tag{5}$$

The fuel flow estimation can be performed in three different ways (see Figure 5 and Section 6.2 in Plohr et al., 2018):

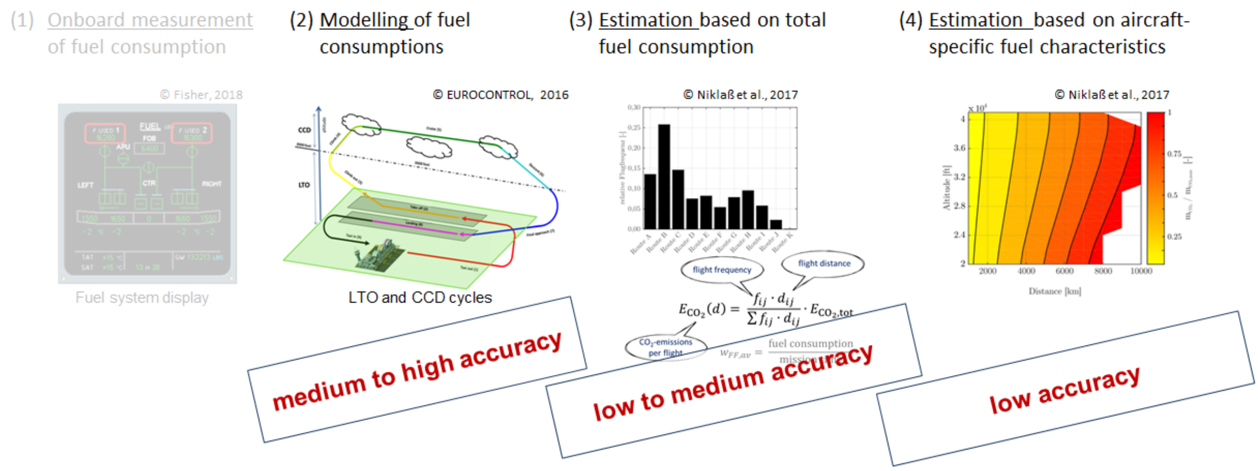
(1) By modeling the fuel flow with existing aircraft and engine databases (BADA, etc.) (medium to high precision; high effort)

(2) By applying basic estimation techniques for the fuel flow (low to medium accuracy; low to medium effort):

(3) By using aircraft specific consumption maps (lowest accuracy; low to medium effort)

Emission indices for carbon dioxide ($EICO_2$) and water vapor ($EIH_2O$) are independent of engine type or operating condition. For accurate $E_{NO_x}(\boldsymbol{x})$ modeling, the exact aircraft and engine type, the combustor variant, and the fuel flow ($w_{FF}$) in sufficiently short intervals (e.g. every five minutes) is required (see Section 3.2 in Plohr et al., 2018).

**Figure 5: Fuel flow verification options**




A benefit of the climatological latitude-height dependent $^{eq}CO_2$ calculation method is that it provides incentives for airliners to reduce the climate impact of non-$CO_2$ effects. Dahlmann et al. (2016b), for instance, analysed the impact of changing flight altitudes and speed. They showed that changing flight altitudes can reduce the climate impact of the global A330-200 fleet by 42% by reducing flight altitude and speed. Nevertheless, this flight altitude change increases COC through longer flight time and increased fuel costs. Including non-$CO_2$ effects in an emission trading scheme or MBM could compensate these additional costs and leading to reduced climate impact of aviation. Additionally, these incentives could lead to introduction of re-designed aircraft, which are optimized for lower climate impact. Dahlmann et al. (2016b) showed that an aircraft designed for lower flight altitudes and speed could reduce the climate impact by 32% without additional COC or by 54% with an increase of COC by 10%.

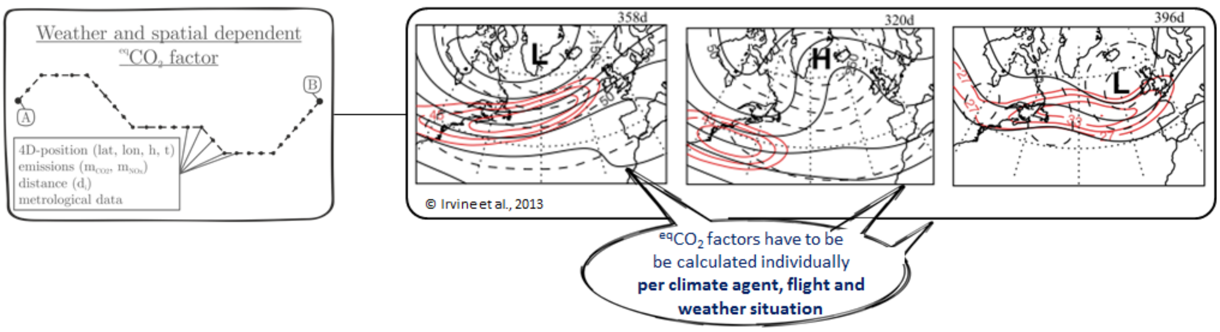
This calculation method includes different weather situations not explicitly, but only as climatological means. This might produce false incentives for special days: if for example airlines accept detours to avoid regions in which contrails often occur, although no contrails can form on this special day, the impact through additional fuel consumption can increase the climate impact. But this is only the fact for several days. In an annual mean the incentives are right. The benefit of using climatological latitude-height factors is that flights with same trajectories can be combined reducing the administrational effort.

To ensure that airlines do not withhold waypoint profile or emission data on purpose, the system must generate a financial incentive for airlines to provide them. This means that the calculation of $CO_2$ equivalents based on rough assumptions should lead to (insignificantly) higher ${}^{eq}E_{CO_2}(\boldsymbol{x})$ values.

## 2.3 Weather and spatial dependent ${}^{eq}CO_2$ factor

To avoid misguiding incentives on single days, a weather and special dependent $CO_2$ equivalent calculation method is presented as a third option which is both more complex and more accurate. To estimate the climate change contribution due to an individual emission as function of emission location, altitude and time in a specific weather situation, four-dimensional response surfaces are used, which are called climate change functions (CCF). Beside the detailed information about emissions and location also information about the actual weather situation and their development are necessary (see Figure 6).

**Figure 6: Data required for a weather and spatial dependent ${}^{eq}CO_2$ factor**

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In this case, the non-$CO_2$ factors are calculated for each flight separately and will differ from day to day. They represent the spatial variability of the atmosphere and of the atmospheric response to a local emission best among the introduced factors and by this provide an adequate incentive to avoid climate sensitive regions on a flight-by-flight basis:

$$ {}^{eq}E_{CO_2}(x,t) = E_{CO_2} + E_i(x,t) \cdot {}^{eq}CO_2{}^{i}(x,t) + dist(x,t) \cdot {}^{eq}CO_2{}^{CiC}(x,t) \qquad (6) $$

The calculation of weather dependent CCFs is very time consuming and requires detailed calculations with a comprehensive chemistry-climate model. However, algorithmic climate change functions (aCCF) have been developed within the European project ATM4E, aiming at a numerical efficient approximation of the climate change functions (Matthes et al., 2017; Grewe et al., 2017), based on input data available in numerical weather. This would enable a provision of these aCCFs together with any weather forecast, representing weather and spatial dependent factors.

The data required for implementing a weather and spatial dependent ${}^{eq}CO_2$ factor is listed in Table 3:

**Table 3: Data required for implementing a weather and spatial dependent ${}^{eq}CO_2$ factor**

| | | |
|---|---|---|
| **Calculation method for equivalent $CO_2$ emissions:** | $^{eq}\boldsymbol{E}_{CO_2}(\boldsymbol{x},\boldsymbol{t}) = \boldsymbol{E}_{CO_2} + \boldsymbol{E}_i(\boldsymbol{x},\boldsymbol{t}) \cdot {}^{eq}\mathbf{CO_2}{}^{i}(\boldsymbol{x},\boldsymbol{t}) + \boldsymbol{dist}(\boldsymbol{x},\boldsymbol{t}) \cdot {}^{eq}\mathbf{CO_2}{}^{\mathrm{CiC}}(\boldsymbol{x},\boldsymbol{t})$ | |
| **Data required per flight:** | $\boldsymbol{x}, t$ | 4D waypoint profile per flight |
| | $dist(\boldsymbol{x}, t)$ | Flown distances per flight |
| | $E_{CO_2}$ | $CO_2$ emissions per flight |
| | $E_i(\boldsymbol{x}, t)$ | 4D emission inventory per flight for $i \in \{H_2O, NO_x\}$ |
| | ${}^{eq}CO_2{}^{i}(\boldsymbol{x}, t)$ | equivalent $CO_2$ coefficient for $i \in \{H_2O, NO_x\}$ as function of emission location and time |
| | ${}^{eq}CO_2{}^{\mathrm{CiC}}(\boldsymbol{x}, t)$ | equivalent $CO_2$ coefficient for contrail induced cloudiness (CiC) as function of emission location |
| | Meteorological data | |
| **Data to be provided by the aircraft operator:** | Airport Pairs (Origin – Destination) | |
| | Number of flights per airport pair | |
| | Aircraft type per flight | |
| | (Flown) 4D trajectory per flight | |
| | Fuel consumption per flight | |
| | 4D emission inventory ($CO_2$, $NO_x$) per flight | |
| **Data to be collected by the authority:** | Operated aircraft types per city pair | |
| | Number of flights of an aircraft type per city pair | |
| | Aircraft type per flight | |
| | (Flown) 4D trajectory per flight | |
| | (Flown) flight distances per flight $\left(dist = \sum dist_{\mathrm{GC},i} + 95km\right)$ | |
| | Distance-dependent fuel consumption per flight | |
| | 4D emission inventory ($CO_2$, $NO_x$) per flight | |
| | Individual ${}^{eq}CO_2$ factor per climate agent and flight | |
| | Meteorological data | |

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The administrative efforts associated with introducing the weather and spatial dependent ${}^{eq}CO_2$ factor can be characterized as being slightly higher than the efforts for the climatological latitude-height dependent ${}^{eq}CO_2$ factor. In this case, an accurate estimate of the $NO_X$ emissions along the flight path is required to match the accuracy of the climatologic methodologies. The exact aircraft and engine type, the combustor variant, the exact flight path and the fuel flow in sufficiently short intervals (e.g. every 5 minutes) is required for accurate $NO_X$ modeling with a fuel flow method (see Section 3.2 in Plohr et al., 2019).

Meteorological information necessary for flights according to Annex 3 to the ICAO Convention on Civil Aviation are provided by two World Area Forecast Centres (WAFC), London (Met Office) and Washington (NOAA). To contribute towards the safety, regularity and efficiency of international air navigation WAFCs prepare gridded global forecasts of:

1) upper wind
2) upper-air temperature and humidity
3) geopotential altitude of flight levels
4) flight level and temperature of tropopause
5) direction, speed and flight level of maximum wind
6) cumulonimbus clouds
7) icing and
8) turbulence

for operators, flight crew members, air traffic services units, etc.

# 3 Summary and initial recommendations

In this report, we assessed the additional, recurring (administrative) data efforts for a potential inclusion of non-$CO_2$ effects at the competent authority (CA) level. Such efforts are likely to grow significantly compared to a system which only covers $CO_2$ emissions and are hence considered to be an important criterion for the evaluation of the overall efficiency of a MBM targeted at non-$CO_2$ effects. Costs for third-party services delivered to the competent authority (like consulting or data provision), as well as one-off tasks like the implementation of a non-$CO_2$ verification system or the verification of the carriers' monitoring plans, are not considered.

If non-$CO_2$ emissions were additionally covered by a MBM like the EU ETS and/or CORSIA, be it "directly" or transformed into ${}^{eq}CO_2$, the competent authority's recurring administrative burden would increase disproportionally as it would will depend on the chosen calculation method and thus on the number, type and availability of additional values and metrics that would have to be checked. Generally-speaking, this is because non-CO2 effects, unlike $CO_2$, are not correlated with fuel consumption by a fixed factor:

- **Simple "distance dependent ${}^{eq}CO_2$ factor":**
  The consideration of non-$CO_2$ effects as a fixed (distance-dependent) factor of the $CO_2$ emissions is not recommended as the non-$CO_2$ effects will depend on factors like the actual route or weather conditions. Hence, a simple distance-related factor added to the $CO_2$ emissions may set the wrong incentives and, in addition, would fail for future, possibly $CO_2$-free or $CO_2$-neutral flight operations. Administrative-wise, however, the application of such factors would be relatively easy to handle. As distances can be directly derived from airport-pair data, no additional data from the operators would be needed to verify the non-$CO_2$ emissions (or rather ${}^{eq}CO_2$) reported by the operators. For this reason, we assume the administrative burden would rise by approximately 10-20% only, which shall mirror the additional effort ("*")estimated for the aircraft operators (see Section 6 of the report "Determination of Data required for Consideration of non-$CO_2$ Effects of Aviation in EU ETS and CORSIA").
- **"Climatological latitude-height dependent ${}^{eq}CO_2$ factor":**
  If a latitude-height dependent ${}^{eq}CO_2$ factor was applied, the CA would require 3D emission inventories to check the non-$CO_2$ emissions reported by the operator, which would require substantially more administrative effort and tools to model the emissions. In the report "Determination of Data required for Consideration of non-$CO_2$ Effects of Aviation in EU ETS and CORSIA" (Section 6), we have shown that the collection of the necessary data is already a major effort ("***") for the aircraft operators. These can generate flight trajectories and fuel flow data from the onboard systems, which allows them to calculate $CO_2$ and $H_2O$ emission inventories relatively easily, while the calculation of $NO_x$ estimates would require more effort. For the CA, it would be more difficult to verify the reported numbers as consumption and the exact waypoints are not (directly) available. A major requirement for successful verification activities by the CA would hence be a similar data basis and the availability of a modelling tool for $NO_x$ and other species along the route, which would also have to consider different aircraft/engine types. If all this was available, we would still expect an increase in the administrative effort of at least 100%.
- **Detailed weather and spatial dependent ${}^{eq}CO_2$factor":**
  Here, not only 3D emission inventories but also meteorological data would be needed to check the reported figures, which would require even more administrative effort as

weather-related data would have to be retrieved and modeled, and the results would have to be compared to the reported figures. An increase in the administrative effort by more than 100% would be likely.

The following table presents these main result in a qualitative way.

**Table 4: Qualitative estimation of the additional data effort for the supervising authorities**

| $^{eq}CO_2$ factor | Additional (data) effort for the supervising authorities |
|---|---|
| Distance dependent $^{eq}CO_2$ factor | * |
| Climatological latitude-height dependent $^{eq}CO_2$ factor | *** |
| Weather and spatial dependent $^{eq}CO_2$ factor | **** |

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Generally-speaking, even if the required additional data and models were available, deviations would be much more complex to assess. This is of special importance as different competent authorities in different countries have different capabilities and manpower. For this reason, it cannot be ruled out that the CAs of certain countries would do less accurate checks than others, which could have adverse impacts on the level playing field.

Hence, we suggest taking as key criteria when deciding on a potential method to consider non-$CO_2$ emissions within a MBM not only the method's transparency, correctness, and (environmental) incentives, but also the related administrative costs and competition impacts.

### Option to simplify the administrative burden

A suitable method to tackle non-$CO_2$ emissions with reasonable administrative effort at the competent authority (and possibly also aircraft operator) level could be to make use of a public reference table, e.g. modelled and published by the EU Commision or by Eurocontrol, which would contain $^{eq}CO_2$ estimates for non-$CO_2$ emissions by airport-pair and engine/aircraft type, considering different routes, flight profiles and possibly climate tables. The tables could also be included in a software application such as Eurocontrol´s ETS Support Facility that currently already provides comparative data for $CO_2$ emissions.

Such a reference table could be made available either for verification only, or possibly also for monitoring and reporting by those (e.g. smaller) carriers for whom own data measurement and/or calculation would be too expensive.[14]

A rough proxy for additional admin effort in this case could be a 50% increase. This is based on the rough assumption that 50% of current verification efforts are actual $CO_2$ checks (which would double if the reference non-$CO_2$ values would also have to be checked), while the other 50% are related to associated administrative tasks.

As argued above, without such a central database/reference table, the administrative effort would be much higher and hardly to handle for smaller CAs.

[14] If the "published" values were used also for monitoring/reporting, there would be a certain smaller incentive to fly more efficiently, but still this option may be regarded as a good and practical solution.

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and Nuclear Safety

Project No. (FKZ) 3717 42 509 0
Report No. (UBA-FB) FB000270/ENG

# Part E:
# Integration of Non-$CO_2$ Effects of Aviation in the EU ETS and under CORSIA: Assessment of Key Design Parameters

Final report

by

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**Abstract**

The non-$CO_2$ climate effects of aviation – comprising $NO_x$, contrails, contrail-induced cloudiness (CiC), soot and water vapour – are not currently regulated to any significant extent in the EU or in other jurisdictions globally. In contrast, the sector's $CO_2$ emissions fall under the scope of the EU Emissions Trading System (ETS) since 2012 and will further be subject to the International Civil Aviation Organization's (ICAO) market-based measure CORSIA (Carbon Offset and Reduction Scheme for International Aviation) starting in 2021. Extending both schemes to non-$CO_2$ emissions could be an efficient approach to address these significant climate impacts and could potentially deliver valuable synergies for aircraft operators and competent authorities compared to developing new policies from the ground up.

The present study investigates specific design options for integrating non-$CO_2$ climate effects into the two schemes, with a primary focus on the EU ETS. Four design parameters are identified, and their impact is assessed with regards to environmental effectiveness. Distinctive features of non-$CO_2$ climate effects – such as the non-linear relationship of emissions to flight distance or the various calculation methods considered – affect the impact that design options may have on an extended scope.

In seeking to assess the feasibility of this integration in the current context of the EU ETS, a variety of technical, political and regulatory challenges are identified. Despite these, existing regulation in the EU ETS Directive already provides a path forward for a voluntary opt-in by Member States during a pilot phase, which could help build capacity, knowledge ("learning-by doing") and awareness for the costs and effort involved in regulating such a scope prior to a full EU ETS roll-out.

Regarding CORSIA, the scheme's $CO_2$ scope has yet to be launched, thus a detailed assessment of a non-$CO_2$ scope integration would be premature. Nevertheless, the international focus of the scheme inherently means that covered flights potentially have significant non-$CO_2$ emissions and thus addressing these are of high importance. One possible pathway for doing so would be to enable the use of independently certified reductions of non-$CO_2$ effects towards operators' compliance with their $CO_2$-related offsetting obligations under CORSIA.

**Kurzbeschreibung**

Die Nicht-$CO_2$-Klimaeffekte des Luftverkehrs – namentlich $NO_x$, Kondensstreifen, Kondensstreifen-Zirren (Contrail induced cloudiness, CiC), Russ und Wasserdampf – sind derzeit nicht in wesentlichem Umfang in der EU oder einer anderen Gerichtsbarkeit weltweit geregelt. Im Gegensatz dazu fallen die $CO_2$-Emissionen des Sektors seit 2012 in den Geltungsbereich des EU-Emissionshandelssystems (EHS) und unterliegen ab 2021 der marktbasierten Massnahme CORSIA (Carbon Offset and Reduction Scheme for International Aviation) der Internationalen Zivilluftfahrtorganisation (ICAO). Die Ausweitung beider Systeme auf Nicht-$CO_2$-Emissionen könnte im Gegensatz zur Entwicklung grundlegend neuer Richtlinien und Strategien ein effizienter Ansatz im Umgang mit diesen signifikanten Klimaeffekten sein und wertvolle Synergien für Luftfahrzeugbetreiber und die zuständigen Behörden bieten.

Die vorliegende Studie untersucht spezifische Ausgestaltungsmöglichkeiten der Integration von Nicht-$CO_2$-Effekten in beide Systemen, wobei der Schwerpunkt auf dem EU-EHS liegt. Es werden vier Designparameter identifiziert und ihre Auswirkungen im Hinblick auf umweltbezogene Effektivität bewertet. Alleinstellungsmerkmale von Nicht-$CO_2$-Klimaeffekten – wie das nichtlineare Verhältnis von Emissionen zur Flugdistanz oder die verschiedenen in Betracht gezogenen Berechnungsmethoden – beeinflussen die Auswirkungen, die die verschiedenen Ausgestaltungsmöglichkeiten auf einen erweiterten Betrachtungsumfang haben könnten.

Um die Durchführbarkeit dieser Integration im derzeitigen Kontext des EU-EHS zu bewerten, werden eine Reihe von technischen, politischen und regulatorischen Herausforderungen identifiziert. Trotz diesen Herausforderungen bieten die bestehenden Regelungen gemäss den EU-EHS-Richtlinien eine Basis für die Möglichkeit eines freiwilligen Opt-in für EU-Staaten während einer Pilotphase. Dies könnten zum Aufbau von Kapazität, Wissen ("learning-by doing") und Erfahrung auch bezüglich der Aufwände und Kosten der Regulierung beitragen, bevor eine Ausweitung auf die Nicht-$CO_2$-Effekte der Luftfahrt im gesamten EU-EHS erfolgt.

Die initialen Regeln des CORSIA-Systems stehen noch nicht im Detail fest. Die detaillierte Bewertung einer möglichen Ausdehnung des Systems auf Nicht-$CO_2$-Effekte wäre deshalb verfrüht. Die internationale Ausrichtung von CORSIA bedeutet jedoch grundsätzlich, dass abgedeckte Flüge potenziell erhebliche Nicht-$CO_2$-Emissionen aufweisen. Der Berücksichtigung der Nicht-$CO_2$-Effekte auch in CORSIA kommt daher aus Klimaschutzüberlegungen grosse Bedeutung zu. Ein möglicher Ansatz zur Umsetzung könnte darüber führen, dass von unabhängiger Stelle zertifizierte Minderungen von Nicht-$CO_2$-Effekten des Luftverkehrs zur Erfüllung der $CO_2$-bezogenen Minderungsverpflichtungen von Luftfahrzeugbetreibern unter CORSIA zugelassen werden.

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## List of Abbreviations

| | |
|---|---|
| **ATR** | Average Temperature Response |
| **CIC** | Contrail-Induced Cloudiness |
| **CORSIA** | Carbon Offset and Reduction Scheme for International Aviation |
| **DEFRA** | UK Department for Environment, Food & Rural Affairs |
| **DLR** | German Aerospace Centre |
| **EEA** | European Economic Area |
| **EU ETS** | European Emissions Trading System |
| **EUA** | European Emission Allowances |
| **EUAA** | European Aviation Emission Allowances |
| **GHG** | Greenhouse Gas |
| **GWP** | Greenhouse Warming Potential |
| **IATA** | International Air Travel Association |
| **ICAO** | International Civil Aviation Organization |
| **ICSA** | International Coalition for Sustainable Aviation |
| **MBM** | Market-Based Mechanism |
| **MRV** | Measuring, Reporting and Verification |
| **NDC** | Nationally Determined Contribution |
| **SARP** | Standards and Recommended Practices |
| **TFEU** | Treaty on the Functioning of the European Union |

# Summary


### Overview of current policy status

In contrast to civil aviation's $CO_2$ emission, the sector's non-$CO_2$ climate effects – namely $NO_x$, contrails, contrail-induced cloudiness (CiC), soot and water vapour – are currently not regulated in any significant way in the EU. Within the EU's Emissions Trading System (ETS), aircraft operators are required since 2012 to monitor their direct $CO_2$ emissions and annually surrender applicable allowances for flights departing and arriving within the European Economic Area (EEA). Initial discussions – starting in 2005 – around extending the scheme to cover aviation emissions emphasized the need for including non-$CO_2$ effects in the new scope as well; however, this extension proved contentious for legal and technical reasons and neither of the two options proposed – a precautionary multiplier applied to flight's $CO_2$ emissions or an effect-by-effect approach – were adopted. Subsequent revisions to the EU ETS Directive throughout Phase 3 (2013-2020) and in preparation for Phase 4 (2021-2030) have had limited impact in changing the status quo, aside from requiring the EU Commission to regularly reassess the matter.

Outside of the EU, international flights will be subject to the International Civil Aviation Organization's (ICAO) market-based measure CORSIA (Carbon Offset and Reduction Scheme for International Aviation) starting in 2021. The coverage of the planned scheme is, here as well, restricted to $CO_2$. Despite ICAO's recognition of aviation's climate impacts beyond $CO_2$ emissions, no noticeable momentum has built to extend the scope to non-$CO_2$ effects in the near future. The potential overlap between both aviation schemes – whereby inter-EU Member State flights would be subject to both offsetting requirements under CORSIA and surrendering of allowances under the EU ETS at least until 2023 – is the subject of much debate and remains to be clarified at the EU and ICAO levels. The approach recommended by certain industry groups and research institutions to address the parallel operation of both schemes and maximize environmental benefits is one of complementarity: maintain the reduced scope EU ETS for aviation and regulate all extra-EEA flights through CORSIA.

### Identification and evaluation of key design parameters for integration of non-$CO_2$ effects into EU ETS

Based on the limited developments to date in regulating climate effects from aviation beyond $CO_2$, this study investigates specific options for integrating non-$CO_2$ climate effects into the EU ETS and CORSIA. The primary focus is placed on the EU ETS given the long-standing history of debate on this topic (since 2005) as well as experience of aircraft operators with MRV-related tasks (since 2012). Assessing the scope extension of this scheme is performed qualitatively by considering a set of four key design parameters, each having a critical role in the operationalization and functioning of a potential revised scope (see Table S-1).

**Table S-1: Overview of key design parameters for integration of non-$CO_2$ scope in the EU ETS.**

| Key design parameter | Options considered |
|---|---|
| **Phasing of the integration** | **Option 1.** Instant full roll-out of non-$CO_2$ scope<br>**Option 2**. Phased roll-out of non-$CO_2$ scope: pilot phase with Member State(s) opt-in of domestic/intra-Community flights followed by full roll-out |
| **Timing of the integration** | **Option 1.** Full roll-out of non-$CO_2$ scope prior to 2026<br>**Option 2.** Full roll-out of non-$CO_2$ scope from 2026<br>**Option 3.** Full roll-out of non-$CO_2$ scope after 2026 |
| **Geographical scope of the integration** | **Option 1.** Intra-Member State flights<br>**Option 2.** Inter-Member State flights<br>**Option 3.** Flights from and to EEA |
| **Calculation methods** | **Option 1.** Distance-dependent factor<br>**Option 2.** Climate-dependent factor<br>**Option 3.** Weather-dependent factor |

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These design parameters are found to have a variety of impacts on a potential non-$CO_2$ scope under the EU ETS, namely in terms of aviation sector dynamics – consumer demand for air travel, operator behaviour in response to incentives for reducing emissions, and carbon leakage risks – as well as actual emissions baseline and cap.

The non-linear relationship between a flight's distance and non-$CO_2$ climate effect – whereby shorter routes exhibit disproportionately lower non-$CO_2$ emissions than long-haul flights due to lower cruise altitude – is a critical feature when considering a scope extension. The geographical scope of the integration is therefore a key design lever with which to influence emissions under the scheme. Integrating non-$CO_2$ climate effects at the inter-Member State level (i.e. the current reduced scope for inclusion of aviation in the EU ETS) is assessed as presenting an optimal compromise in this regard: on the one hand, the scope would include routes with flight distances relevant in terms of non-$CO_2$ effects (international EU flights), while minimizing on the other hand the carbon leakage risks associated with long-haul flights (extra-EEA flights).

The selection of calculation methods for non-$CO_2$ effects is also an important parameter as more robust approaches (namely climate- or weather-dependent factors) more effectively incentivize positive changes in operator behaviour. However, these approaches are associated with greater data requirements and likely higher costs for operators and competent authorities. In terms of implementing the scope extension, deploying it in a phased manner with an initial fixed-term opt-in phase – which current regulation already allows for through Article 24 of the EU ETS Directive – could ease the transition for aircraft operators, while avoiding delays in the timing of the integration would help in achieving greater environmental benefit. In the medium term, however, a move to a mandatory inclusion of aviation's non-$CO_2$ effects would clearly be required to ensure environmental effectiveness and avoid permanent distortion of the European aviation market.

Placing these design considerations into the broader EU political and regulatory context, it is clear that while a number of forces are acting in support of a possible integration of non-$CO_2$ climate effects in the EU ETS, critical obstacles are currently impeding the feasibility of this scope extension. The following challenges would need to be addressed to achieve further progress towards inclusion of non-$CO_2$ climate effects:

- The scientific basis for the atmospheric impacts of non-$CO_2$ species is relatively well understood for the most impactful species (i.e. $NO_x$, contrails), yet uncertainties prevail surrounding the magnitude of their effect and thus accurate estimates of additional operator costs under an extended scheme remain unavailable;
- Reference data sets – particularly if the complex climate- or weather-dependent calculation methods are to be implemented – and institutions responsible for them would need to be defined, and accepted by industry stakeholders;
- The most recent revision to the EU ETS is still relatively fresh and near-term aviation-related political priorities would likely rather revolve around resolving the CORSIA/EU ETS interface and may therefore not favour any rapid integration of non-$CO_2$ effects;
- The issue of equal treatment might be raised with a non-$CO_2$ scope extension as the financial and social impact from this integration would be unequally shared by countries depending on their geographic location as well as weather and climate cycles;
- While atmospheric and climate impact of non-$CO_2$ emissions are broadly acknowledged by government officials and experts, awareness raising on the overall climate impact of aviation would be needed in political circles and within the broader public;
- Alternative policies for reducing the global warming effects of aircraft are also under assessment (e.g. requirements for sustainable aviation fuels).

**Considerations for integration of non-$CO_2$ effects into CORSIA framework**

In the case of an integration of non-$CO_2$ climate effects under CORSIA, the absence to date of fully developed guidance on eligible emissions units and of operational experience with the scheme (pilot phase launching in 2021) makes any evaluation beyond a cursory level only speculative at this point. Nevertheless, an important relevant distinction can be noted compared to an integration under the EU ETS: the purely international scope of the scheme implies that concerned flights would tend to have, on average, longer routes and thus higher relative non-$CO_2$ impacts than would an intra-EU flight scope of the EU ETS. At first approximation, the impact on reducing consumer demand for air travel would therefore be lower than under the current EU ETS scope, while the impact on incentivizing operators to reduce their emissions – if associated with the robust climate- and weather-dependent calculation methods – would be greater.

While the current focus at ICAO is clearly on demonstrating a fully functioning $CO_2$ emissions scope, the present study discusses the option of a phased approach for integrating non-$CO_2$ climate effects that would not require any revisions to the SARP. An opt-in offsetting scheme for non-$CO_2$ climate effects would enable volunteering aircraft operators to earn carbon credits from non-$CO_2$ mitigation measures and use these towards meeting their $CO_2$ offsetting obligation. Operators would thus gain practical experience with MRV procedures. After a pre-defined pilot phase, the crediting mechanism could eventually be transitioned out in favour of full regulation by the SARP.

# Zusammenfassung

## Übersicht über das aktuelle regulatorische Umfeld

Im Gegensatz zu den Klimaauswirkungen der Luftfahrt durch $CO_2$-Emissionen sind die Nicht-$CO_2$-Effekte – namentlich $NO_x$, Kondensstreifen, Kondensstreifen-Zirren (Contrail induced cloudiness, CiC), Russ und Wasserdampf – in der EU derzeit in keiner wesentlichen Weise reguliert. Im Rahmen des Emissionshandelssystems (EHS) der EU sind die Luftfahrzeugbetreiber seit 2012 verpflichtet, ihre direkten $CO_2$-Emissionen zu überwachen und jährlich die entsprechenden Zertifikate für Flüge, die innerhalb des Europäischen Wirtschaftsraums (EWR) starten und landen, abzugeben. Erste Diskussionen – ab 2005 – über die Ausweitung des Systems auf den Luftverkehr betonten die Notwendigkeit, auch Nicht-$CO_2$-Effekte in den neuen Betrachtungsumfang einzubeziehen. Diese Erweiterung erwies sich jedoch aus rechtlichen und technischen Gründen als umstritten und keine der beiden vorgeschlagenen Optionen – ein vorsorglicher Multiplikator, angewendet auf die $CO_2$-Emissionen des Fluges oder ein Effect-by-Effect-Ansatz – wurde eingeführt. Spätere Überarbeitungen der EU-EHS-Richtlinien während der gesamten Phase 3 (2013-2020) und in Vorbereitung auf die Phase 4 (2021-2030) bewirkten abgesehen davon, dass die EU-Kommission zu einer regelmässigen Neubewertung der Angelegenheit aufgefordert wurde, nur in begrenztem Ausmass eine Änderung des Status quo.

Ausserhalb der EU unterliegen internationale Flüge ab 2021 der marktbasierten Massnahme CORSIA (Carbon Offset and Reduction Scheme for International Aviation) der Internationalen Zivilluftfahrtorganisation (ICAO). Auch hier ist der Betrachtungsumfang des geplanten Systems auf $CO_2$-Emissionen beschränkt. Trotz der Tatsache, dass die ICAO die Klimaauswirkungen des Luftverkehrs über die $CO_2$-Emissionen hinaus anerkannt hat, hat sich kein nennenswertes Momentum gebildet, um den Anwendungsbereich in naher Zukunft auf Nicht-$CO_2$-Effekte auszudehnen. Die mögliche Überschneidung zwischen beiden Systemen – wobei Flüge zwischen den EU-Mitgliedstaaten sowohl den Ausgleichsanforderungen nach CORSIA als auch der Abgabe von Zertifikaten im Rahmen des EU-EHS bis zumindest 2023 unterliegen würden – ist Gegenstand vieler Diskussionen und muss noch auf EU- und ICAO-Ebene geklärt werden. Bestimmte Industriegruppen und Forschungseinrichtungen empfehlen einen komplementären Ansatz, um Überlappungen zwischen den beiden Systemen zu vermeiden und den Umweltnutzen zu maximieren: Beibehaltung des reduzierten Betrachtungsumfangs des EU-EHS für die Luftfahrt und Regelung aller Flüge ausserhalb des EWR über CORSIA.

## Identifizierung und Bewertung der Schlüsseldesign-Parameter für die Integration von Nicht-$CO_2$-Effekten in das EU-EHS

Basierend auf den bisher begrenzten Entwicklungen bei der Regulierung der Klimaauswirkungen des Luftverkehrs, die über den Betrachtungsumfang von $CO_2$-Emissionen hinausgehen, untersucht diese Studie spezifische Optionen für die Integration von klimawirksamen Nicht-$CO_2$-Effekten in das EU-EHS und CORSIA.

Angesichts der langjährigen Diskussion zu diesem Thema (seit 2005) sowie der Erfahrung von Luftfahrzeugbetreibern mit MRV-bezogenen Aufgaben (seit 2012) liegt der Schwerpunkt auf dem EU-EHS. Die Beurteilung der Ausdehnung des Betrachtungsumfangs dieses Systems erfolgt qualitativ unter Berücksichtigung von vier Schlüsseldesign-Parametern, die jeweils eine entscheidende Rolle bei der Operationalisierung und der Funktionstüchtigkeit eines solch potenziell überarbeiteten Betrachtungsumfangs spielen (siehe Tabelle S-1).

**Tabelle S-1: Überblick über die Schlüsseldesign-Parameter für die Integration des Betrachtungsumfangs von Nicht-$CO_2$-Effekten in das EU-EHS.**

| Schlüsseldesign-Parameter | Berücksichtigte Optionen |
|---|---|
| **Phase der Integration** | **Option 1.** Sofortiger vollständiger Roll-out des Betrachtungsumfangs von Nicht-$CO_2$-Effekten<br>**Option 2**. Schrittweise Einführung des Betrachtungsumfangs von Nicht-$CO_2$-Effekten: Pilotphase mit dem/den Mitgliedstaat(en) Opt-in von Inlands-/Intra-Gemeinschaftsflüge, gefolgt von einem vollständigen Rollout |
| **Zeitpunkt der Integration** | **Option 1.** Vollständige Einführung des Betrachtungsumfangs von Nicht-$CO_2$-Effekten vor 2026<br>**Option 2.** Vollständige Einführung des Betrachtungsumfangs von Nicht-$CO_2$-Effekten ab 2026<br>**Option 3.** Vollständige Einführung des Betrachtungsumfangs von Nicht-$CO_2$-Effekten nach 2026 |
| **Geographischer Umfang der Integration** | **Option 1.** Flüge innerhalb der Mitgliedstaaten<br>**Option 2.** Flüge zwischen den Mitgliedstaaten<br>**Option 3.** Flüge aus und in den EWR |
| **Berechnungsmethoden** | **Option 1.** Distanzabhängiger Faktor<br>**Option 2.** Klimaabhängiger Faktor<br>**Option 3.** Wetterabhängiger Faktor |

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Diese Design-Parameter haben eine Vielzahl von Auswirkungen auf eine potenzielle Ausweitung des Betrachtungsumfangs auf Nicht-$CO_2$-Effekte im Rahmen des EU-EHS, namentlich in Bezug auf die Dynamik des Luftverkehrssektors – die Nachfrage nach Flugreisen, das Verhalten der Betreiber als Reaktion auf Anreize zur Emissionsreduktion und die Risiken von $CO_2$-Leakage – sowie die tatsächliche Baseline und Cap für Emissionen.

Der nichtlineare Zusammenhang zwischen der Entfernung eines Fluges und den Nicht-$CO_2$-Klimaeffekten – wobei kürzere Strecken aufgrund der geringeren Reiseflughöhe unverhältnismässig niedrigere $CO_2$-Emissionen aufweisen als Langstreckenflüge – ist eine kritische Eigenschaft in Hinblick auf eine Erweiterung des Betrachtungsumfangs. Der geografische Geltungsbereich der Integration ist daher ein wichtiger Designhebel, um die Emissionen im Rahmen des Systems zu beeinflussen. Die Integration von Nicht-$CO_2$-Effekten auf der Ebene der Mitgliedstaaten (d.h. auf Ebene des bestehenden reduzierten Anwendungsbereichs für die Einbeziehung des Luftverkehrs in das EU-EHS) wird in dieser Hinsicht als optimaler Kompromiss bewertet: Einerseits würde der Betrachtungsumfang Strecken mit Flugdistanzen umfassen, die für Nicht-$CO_2$-Effekte relevant sind (internationale EU-Flüge), andererseits aber auch die Risiken von $CO_2$-Leakage im Zusammenhang mit Langstreckenflügen (Extra-EWR-Flüge) minimieren.

Die Auswahl von Berechnungsmethoden für Nicht-$CO_2$-Effekte ist ebenfalls ein wichtiger Parameter, da robustere Ansätze (nämlich klima- oder wetterabhängige Faktoren) effektiver positive Anreize für Veränderungen im Betreiberverhalten bewirken. Diese Ansätze sind jedoch mit einem höheren Bedarf an Daten und wahrscheinlich höheren Kosten für die Betreiber und die zuständigen Behörden verbunden. Im Hinblick auf die Umsetzung der Erweiterung des Betrachtungsumfangs könnte die schrittweise Einführung einer ersten Opt-in-Phase mit befristeter Laufzeit – die die derzeitige Regelung bereits durch Artikel 24 der EU-EHS-Richtlinie erlaubt – den Übergang für

Luftfahrzeugbetreiber erleichtern und gleichzeitig durch eine Vermeidung von Verzögerungen beim Zeitplan für die Integration dazu beitragen, einen grösseren Umweltnutzen zu erzielen. Mittelfristig wäre jedoch ein Übergang zu einer verbindlichen Einbeziehung der Nicht-CO2-Effekte des Luftverkehrs erforderlich, um die umweltbezogene Effektivität zu gewährleisten und eine dauerhafte Verzerrung des europäischen Luftverkehrsmarktes zu vermeiden.

Wenn man diese Überlegungen zu Gestaltungsmöglichkeiten in den breiteren politischen und regulatorischen Kontext der EU einordnet, ist klar, dass eine Reihe von Kräften zwar eine mögliche Integration von Nicht-$CO_2$-Effekten in das EU-EHS unterstützen, dass aber derzeit kritische Hindernisse die Machbarkeit dieser Erweiterung des Betrachtungsumfangs behindern. Die folgenden Herausforderungen müssten adressiert werden, um weitere Fortschritte bei der Einbeziehung der Nicht-$CO_2$-Effekten zu erzielen:

- Die wissenschaftlichen Grundlagen für die atmosphärischen Auswirkungen von Nicht-$CO_2$-Effekten sind für die wirkungsvollsten Effektarten (z.B. $NO_x$, Kondensstreifen) relativ gut verstanden. Zugleich bestehen noch Unsicherheiten über das Ausmass ihrer Auswirkungen, so dass genaue Schätzungen der zusätzlichen Kosten für die Betreiber im Rahmen eines erweiterten Systems nicht zur Verfügung stehen;
- Referenzdatensätze – insbesondere wenn die komplexen klima- oder wetterabhängigen Berechnungsmethoden implementiert werden sollen – und die dafür zuständigen Institutionen müssen definiert und von den Interessengruppen der Branche akzeptiert werden;
- Die jüngste Überarbeitung des EU-EHS ist noch relativ frisch und die kurzfristigen luftfahrtbezogenen politischen Prioritäten würden sich wahrscheinlich eher auf die Lösung der CORSIA/EU ETS-Schnittstelle konzentrieren, was eine rasche Integration von Nicht-$CO_2$-Effekten nicht begünstigt;
- Da die finanziellen und sozialen Auswirkungen einer Erweiterung des Betrachtungsumfangs auf Nicht-$CO_2$-Effekte je nach geografischer Lage sowie Wetter- und Klimazyklen ungleichmässig auf die Länder verteilt würden, könnten Fragen bezüglich Gleichbehandlung aufkommen;
- Während die atmosphärischen und klimatischen Auswirkungen von Nicht-$CO_2$-Effekten von Regierungsbeamten und Experten weitgehend anerkannt werden, wäre eine Sensibilisierung für die allgemeinen Klimaauswirkungen des Luftverkehrs in politischen Kreisen und in der breiten Öffentlichkeit erforderlich;
- Auch alternative Politikinstrumente zur Verringerung der Klimawirkung des Luftverkehrs werden derzeit diskutiert (z.B. Vorgaben für nachhaltige Flugtreibstoffe).

**Überlegungen zur Integration von Nicht-$CO_2$-Effekten in das CORSIA-Framework**

Das Fehlen von vollständig entwickelten Leitlinien im Rahmen von CORSIA für die zugelassenen Emissionseinheiten und das Fehlen von operativen Erfahrungen mit dem System (Beginn Pilotphase in 2021) lässt zum jetzigen Zeitpunkt keine vertiefte Evaluation in Bezug auf die mögliche Integration von Nicht-$CO_2$-Klimaeffekten zu. Dennoch lässt sich ein wichtiger relevanter Unterschied zu einer Integration im Rahmen des EU-EHS feststellen: Der ausschliesslich internationale Geltungsbereich des Systems impliziert, dass betroffene Flüge im Durchschnitt tendenziell längere Flugstrecken zurücklegen und damit relative betrachtet höhere Nicht-$CO_2$-Effekte aufweisen würden als ein Intra-EU Geltungsbereich des EU-EHS. In erster Näherung wären die Auswirkungen auf die Verringerung der Verbrauchernachfrage nach Flugreisen daher geringer als im Rahmen des derzeitigen EU-EHS Geltungsbereichs, während der Einfluss auf die Anreizwirkung zur Reduktion ihrer Emissionen für die

Betreiber, – unter Voraussetzung von robusten klima- und wetterabhängigen Berechnungsmethoden – grösser wären.

Während der derzeitige Schwerpunkt der ICAO klar auf der Schaffung eines voll funktionsfähigen Mechanismus zur Anrechenbarkeit von $CO_2$-Emissionen liegt, wird in der vorliegenden Studie die Option eines abgestuften Ansatzes für die Integration von klimawirksamen Nicht-$CO_2$-Effekten diskutiert, die keine Überarbeitung des SARP erfordern würden. Ein Opt-in-Kompensationssystem für Nicht-$CO_2$-Klimaeffekte würde es den freiwillig teilnehmenden Luftfahrzeugbetreibern ermöglichen, $CO_2$-Zertifikaten für die Minderung ihrer Nicht-$CO_2$-Effekte zu erhalten und diese zur Erfüllung ihrer $CO_2$-Kompensationspflicht zu verwenden. Die Betreiber könnten so praktische Erfahrungen mit MRV-Abläufen sammeln. Nach einer vordefinierten Pilotphase könnte der Anrechnungsmechanismus schliesslich zugunsten einer vollständigen Regulierung durch das SARP ganzheitlich ausgerollt werden.

# 1 Introduction

Global civil aviation is understood to account for 4-5% of total anthropogenic climate impact [Larsson et al., 2019]. Two thirds of this impact are attributable to climate effects from species other than $CO_2$, namely $NO_x$, contrails, contrail-induced cloudiness (CiC), soot and water vapour. Whereas the direct $CO_2$ emissions of aviation are presently regulated to some extent, this is not the case for most of the climate effects of non-$CO_2$ emissions. Regulating these emissions is however critical in order to achieve global ambitions of limiting warming to 1.5° above pre-industrial levels. While proposing new and specific policies for these scopes would be an option, extending existing regulatory schemes to include non-$CO_2$ effects would potentially deliver valuable synergies for aircraft operators and competent authorities.

Adopted in 2003 as Directive 2003/87/EC, the EU Emissions Trading System (ETS) has been the subject of numerous revisions since its launch in 2005 and subsequent integration of aviation sector $CO_2$ emissions in 2012. Despite recognition in 2005 already of the importance to integrate as well non-$CO_2$ effects, these remain unregulated under the EU ETS as far as aviation is concerned. Similarly, the International Civil Aviation Organization's (ICAO) market-based measure CORSIA (Carbon Offset and Reduction Scheme for International Aviation) is currently being implemented on a $CO_2$-scope basis. To date, no noticeable momentum has built at ICAO to extend this scope to non-$CO_2$ effects in the near future.

The previous work packages of this project have defined calculation approaches for quantifying non-$CO_2$ effects, identified the data requirements of these approaches and estimated the additional administrative efforts required by airline operators and competent authorities to monitor and report this data under the EU ETS (and to a certain extent also under CORSIA). The outcomes of these work packages (AP1-AP4) form the basis for this present study aimed at investigating the integration of non-$CO_2$ climate effects into the EU ETS and CORSIA.

The approach of this study is focused on an assessment of key design parameters for the integration. The first part introduces the existing regulatory framework and ongoing developments to understand the context surrounding both schemes and their interface. Based on this situational analysis, relevant design parameters are introduced, which build on the existing specifications and technical details of the market-based mechanisms (MBM). The impact of the design parameters on the dynamics of the EU ETS is then assessed, followed by an initial assessment of the feasibility and challenges of this integration. The primary focus of this study is placed on the integration of non-$CO_2$ effects within the EU ETS. However, impact and feasibility considerations are also given to an integration in CORSIA.

# 2 Overview of the current policy status

## 2.1 EU ETS regulatory framework

### 2.1.1 Evolution of aviation sector coverage

Aviation sector activity is effectively covered by the EU ETS since January 1st, 2012, following the adoption of Directive 2008/101/EC. At first implemented on a "full scope" basis covering both flights within the European Economic Area (EEA) and those to or from the EEA (see Box 1), the scheme was quickly met with opposition from the United States and other non-EU countries, ultimately leading to the decision of the European Parliament and of the Council to "stop the clock" on the inclusion of extra-EEA flights and impose temporarily a "reduced scope" coverage. The initial decision was prolonged first until the end of 2016, and then until end of 2023, to allow time for the development of ICAO's market-based measure and the agreement of an approach to address the issues of overlapping coverage with the EU ETS. In 2018, the revised EU ETS directive for Phase 4 of the scheme was adopted, setting forth the obligations for the upcoming period 2021-2030. See Section A.1 in Annex for an overview of aviation-relevant revisions to the EU ETS Directive.

**Box 1: Distinction between full scope and reduced scope in the EU's emissions trading system.**

**Full scope:** All flights which depart from or arrive in an aerodrome situated in the territory of a "EEA Member State" minus any exempted flights.

**Reduced scope:** Intra-European flights (i.e. departure and arrival in EEA Member States) minus any exempted flights.

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While the coverage of greenhouse gas types for stationary installation operators under the EU ETS has been progressively extended, from only carbon dioxide ($CO_2$) in Phase 1 (2005-2007) to also certain nitrous oxide ($N_2O$) and perfluorocarbon (PFC) emissions in the current Phase 3 (2013-2020), the aviation sector is currently only required to monitor and surrender allowances for its $CO_2$ emissions. The cap on the aircraft operator's $CO_2$ emissions for Phase 3 is based on the years 2004-2006, and emission allowances are allocated on the basis of tonne-kilometre data collected for the year 2010. Overall, 82% of total allowances in the original aviation cap are allocated for free and the remainder is auctioned or set aside in the new entrants' reserve. However, due to the growth of the industry, the actual percentage of free allocation to aircraft operators is now lower.

No changes in the scope of aviation sector emissions covered by the EU ETS are planned in the revised directive for Phase 4 adopted in 2018. The most significant modification implemented for aircraft operators is the change from a constant emissions cap to one decreasing linearly throughout the period. As discussions progress within ICAO on the finalization of rules for CORSIA (e.g. eligible emission units, see Section 2.2 ), the EU ETS Directive will be further revised. Based on an interview held by the project team with a representative of the European Commission's DG CLIMA for aviation carbon markets, it would seem that the next review of the Directive may likely take place in 2022 or 2023 (see Section A.3 in Annex).

**Table 1: Technical aspects of the aviation sector scope under the EU ETS.**

| | **Phase 3 (2013-2020)**<br><br>Sources: [European Commission, 2015], [European Commission, 2017a] | **Phase 4 (2021-2030)**<br><br>Articles listed refer to the revised Directive 2003/87/EC. Other sources: [DEHSt, 2017] |
|---|---|---|
| Annual emissions cap & linear reduction factor | Cap set at 210'349'264 $tCO_2$ (+ 116'524 for the inclusion of Croatia in 2014) prior to "stop the clock" provision.[15] Constant annual cap (i.e. no linear reduction). | Cap carried forward (to be confirmed). As from 2021, a linear reduction factor will for the first time apply to the aviation sector, reducing the cap on aviation emissions by 2.2% annually (see Art. 28a(2)). |
| Basis for emissions cap | EEA-wide historical aviation emissions for the years 2004-2006. 95% of the annual average of these three years is taken as the annual cap | Baseline carried forward (to be confirmed). The 95% share of historical aviation emissions still applies, but subject to review per Article 30(4) (see Art. 3c(2)). |
| Allowance units | Aircraft operators can use both EU Emission Allowances (EUAs) and Aviation Allowances (EUAAs) to fulfil their compliance obligation | Similar to Phase 3 |
| Benchmark | Tonne-kilometre data reported for 2010 with the benchmark of 0.6422 allowances per 1,000 tonne-kilometre | Art. 3d(3) & Art. 3e(1): The benchmark year "shall be the calendar year ending 24 months before the start of the period". The 2010 benchmark will be carried forward for allocation until 2023 (so far). |
| Free allocation | 82 % of total EUAA allowances (i.e. original aviation emissions cap) | Art. 3e(3): calculated by subtracting number of allowances auctioned and set aside in the special reserve |
| Allowances auctioned | 15 % of total EUAA allowances (i.e. original aviation emissions cap) | Art. 3d(2): "15% of allowances shall be auctioned" |
| Reserve (for new entrants and fast-growing operators) | 3 % of total EUAA allowances (i.e. original aviation emissions cap) | Art. 3f(1): "3 % of the total quantity of allowances to be allocated shall be set aside in a special reserve" |
| Number of participating aircraft operators | 503 aircraft operators were reported to have a monitoring plan in 2016. | Likely similar as scope is currently identical to Phase 3 |

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### 2.1.2 Prior and current efforts to integrate non-$CO_2$ effects

Prior to 2008, during the revision process of the EU ETS Directive leading up to the inclusion of the aviation sector's $CO_2$ emissions in the scheme, the non-$CO_2$ climate effects of the industry ($NO_x$, contrails, CiC, soot, water vapour) were also actively considered. In its initial communication to the

[15] Following the restriction of the aviation scope to only intra-EEA flights, the cap is in practice reduced proportional to the reduction in scope.

Council and Parliament on reducing the climate impact of aviation,[16] the EU Commission emphasized the need for addressing both $CO_2$ and non-$CO_2$ effects.

However, at a technical level, the incorporation of non-$CO_2$ effects in the EU ETS proved contentious. Broadly, Member States and the European Commission discussed two different approaches: applying a precautionary fixed multiplier to aircraft operators' $CO_2$ obligations covering all non-$CO_2$ effects (Option 1), on the one hand, and following an effect-by-effect approach (Option 2), on the other hand [European Climate Change Programme II, 2006; European Commission, 2006]. Option 1 would be simple to implement; however, stakeholders saw numerous drawbacks, including:

- Uncertainty as to what the multiplier should be;
- Risk of setting wrong incentives for manufacturers and aircraft operators (that would focus on $CO_2$ instead of $NO_x$); and
- The conceptual – and potentially legal – challenge whereby the principle of equal treatment ('a tonne is a tonne') would no longer apply; instead, greenhouse gas (GHG) emissions would be allocated to polluters in a potentially arbitrary way not based on exact science and not respecting the exact degree of responsibility.

Option 2 would be more accurate in terms of estimating GHG emissions and allocating responsibility. However, the majority of stakeholders felt the scientific understanding of non-$CO_2$ effects was not strong enough.

Ultimately, the legislative proposal by the Commission did not include non-$CO_2$ effects in the broadened EU ETS scope.[17] Instead, the Commission committed to:

a) propose other legislation in 2008 wherein "emissions of nitrogen oxides will be addressed";
b) promote "research on the formation of contrails and cirrus clouds and effective mitigation measures, including operational and technical measures"; and
c) by 1 December 2014, give consideration to "developments in scientific understanding on the climate change impacts of contrails and cirrus clouds caused by aviation with a view to proposing effective mitigation measures".

As an outcome of item a) on $NO_x$ emissions, an extensive study was commissioned in 2008 on "Policies to Reduce the Climate Impact of Aviation $NO_x$ Emission" [Faber et al., 2008]. The report recommended instruments to tackle $NO_x$ emissions both outside of an emissions trading system (e.g. $NO_x$ charges for landing and take-off and/or for cruise) and within such a scheme (e.g. allowances for $NO_x$ emissions), but recognized the challenges for their development namely with respect to quantifying $NO_x$ emissions and establishing a recognized metric for their climate impact, such as a Global Warming Potential (GWP) for $NO_x$. Following from this report, it appears that the topic of regulating $NO_x$ climate impacts from aviation was not pursued further to a significant extent at the EU level. It should be noted, however, that for air quality purposes ICAO regulates $NO_x$ emissions in the landing and take-off phase for large jet engines since 1981 in the form of emissions standards (see Section 2.2.2). In addition, certain airports such as London's Heathrow airport also impose landing charges per kg of $NO_x$ emissions [Heathrow Airport, 2018].

Regarding items b) and c) on contrails and cirrus clouds, some observers have noted here as well the absence of significant progress at the EU level since the adoption of Directive 2008/101/EC [Transport & Environment, 2017].

[16] COM (2005) 459 final, September 2005
[17] Directive 2008/101/EC

In the 2017 revision to the directive, aiming at extending the application of *reduced scope* coverage until 2023, non-$CO_2$ climate effects were not a material topic. While recognizing the fact that these effects may have several times the impact of aviation's $CO_2$ emissions, the impact assessment prepared by the EU Commission did "not further consider these impacts" in its review [European Commission 2017b]. The EU's latest revision to the ETS Directive has, however, picked up the topic once again and Art. 30(4) requires the Commission to reassess the non-$CO_2$ climate effects of aviation and to develop, where appropriate, a proposal to address them by January 2020. Practically speaking, a study has been commissioned for this specific purpose with the aim of reviewing the current status of scientific understanding around quantifying non-$CO_2$ effects. Based on information obtained during an interview with a representative of the European Commission's DG CLIMA for aviation carbon markets, a preliminary draft of this study is expected prior to the January 2020 deadline (see Section A.3 in Annex for details of the interview).

Further requirements exist for the EU Commission to "biennially assess aviation's overall impact on the global climate including through non-$CO_2$ emissions or effects", as described in the monitoring and reporting regulation of the EU.[18] In its most recent communication on the matter,[19] the Commission refers to ongoing efforts in recent years to "assess the impacts of non-$CO_2$ factors on climate change" [European Commission, 2016]. Namely, the Commission highlights the EU-funded 'QUANTIFY' project (2005-2010), which estimated the overall aviation impacts at around 3.5% of total anthropogenic forcing in 2005.

## 2.2 CORSIA regulatory framework

### 2.2.1 Status of CORSIA

ICAO's market-based measure is regulated by Annex 16 (Environmental Protection), Volume IV (Carbon Offsetting and Reduction Scheme for International Aviation), to the Convention on International Civil Aviation. The Standards and Recommended Practices (SARP) contained in this document were adopted by the ICAO Council on June 27th, 2018 and became applicable on January 1st, 2019. The CORSIA SARP define the scope, compliance phases, monitoring and reporting processes, and offsetting requirements of the scheme. For an overview of the historical process and Council resolutions leading up to CORSIA's implementation, see Section A.2 in Annex.

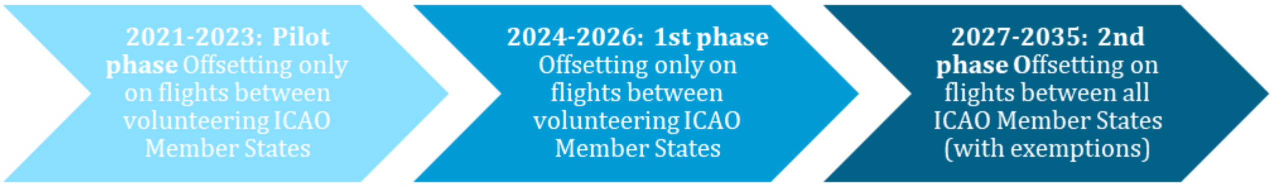
To enact the scheme's goal of ensuring carbon neutral growth of the international aviation sector after 2020, participating countries (i.e. volunteering countries until 2026 and all ICAO Member States – minus certain exclusions - from 2027) will require aircraft operators to offset their $CO_2$ emissions above the refence years (see Figure 1).[20] As of July 2019, 81 States representing close to 77% of international aviation activity have committed to participate in the voluntary phases [ICAO, n.d. a].

The baseline for offsetting is set as the average of years 2019 and 2020, for which emissions data is currently being collected. ICAO estimates global offsetting requirements in the years 2025, 2030 and 2035 to be 142-172 $MtCO_2$, 288-376 $MtCO_2$, and 443-596 $MtCO_2$, respectively [ICAO, n.d. b]. In March 2019, ICAO released the eligibility criteria that emission units must fulfil in order to be applicable under CORSIA. Offset crediting programs can apply for assessment against these criteria, a process led by a Technical Advisory Board (TAB) specially appointed for this purpose. Currently, no emission units

[18] Regulation No 525/2013
[19] COM (2016) 707 final, November 2016
[20] For further information on scope and coverage of ICAO's CORSIA and the EU ETS, refer to Section 5 of the AP2 report "Determination of Data required for Consideration of non-$CO_2$ Effects of Aviation in EU-ETS and CORSIA".

have yet been approved for use under CORSIA, creating uncertainty for aircraft operators in planning for their compliance under the scheme. A first crop of fourteen applicant programs was announced by ICAO in August 2019 and is undergoing assessment by the TAB.

**Figure 1: Phases and offsetting requirements of CORSIA**

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With the implementation of CORSIA, the international aviation sector has committed to rely heavily on offset credits to meet its climate objectives. These project-based emission reductions may likely originate from sectors covered under a country's Nationally Determined Contribution (NDC), in which case issues of double counting would need to be mitigated to avoid claiming the same reductions twice. This would require procedures to be defined under the Paris Agreement for executing corresponding adjustments in host country inventories in these cases. As the Rule Book for international transfers under the Paris Agreement is currently under development, the interface with CORSIA is still a topic of debate.

### 2.2.2 Status of integration of non-$CO_2$ effects

Only $CO_2$ emissions of the aviation sector are regulated under ICAO's market-based measure and the SARP does not refer to other greenhouse gas effects of aviation activity. In other instances, ICAO documentation acknowledges the impact of aviation's broader climate impact beyond $CO_2$ emissions. In its assessment – ahead of the ICAO Assembly's 40th session in September 2019 – of emission trends affecting the global climate, the Council highlights the climate impact of $NO_x$ emissions [ICAO Council, 2019]. Further documentation states that until consensus is reached by the scientific community on quantification methods for non-$CO_2$ effects, only $CO_2$ emissions will be addressed [ICAO, n.d. c].

With the intention to improve air quality in the vicinity of airports, ICAO established engine certification standards to limit emissions of certain species, including greenhouse gas relevant emissions such as $NO_x$. These limits are regulated by Annex 16, Volume II (Aircraft Engine Emissions) to the Convention on International Civil Aviation and have been successively tightened since their adoption in 1981. While these emission standards apply to the landing and take-off cycle, $NO_x$ emissions in these phases are positively related to cruise emissions at high altitude – where they induce ozone formation and deplete methane – in commonly available engines [Transport & Environment, 2010]. Thus, these limits, although not intended for this purpose, may have an impact in addressing GHG emissions.

## 2.3 Coexistence of EU ETS and CORSIA after 2020

### 2.3.1 Ongoing regulatory and legislative process

ICAO's final adoption of the CORSIA Standard and Recommended Practices in June 2018 has intensified the debate surrounding its implementation in the EU and the possible pathways for doing so. In its official announcement of the adopted text, the ICAO Council communicated to its Member

States a deadline of December 1st, 2018, for notifying any differences between the SARP and countries' national regulations – the so-called process of "filing of differences". Withholding from filing any such differences commits governments to adopt the ICAO market-based measure and possibly abandon existing legislation (e.g. EU ETS for aviation). The EU Member States, with pressure on one side from the airline industry and certain non-EU countries to drop the EU ETS rules on aviation in favour of CORSIA, and on the other side from partisans of maintaining the existing cap-and-trade system until at least the full CORSIA rules (i.e. eligible emission units, see Section 2.2) are decided and can be assessed, debated the matter extensively. On November 29, 2018, the EU Council agreed on a common position over filing of differences by Member States with ICAO.[21] This decision keeps open the possibility of maintaining a functioning emissions trading system for the aviation sector in the EU and buys additional time for CORSIA to be implemented in a manner compatible with the Union's climate goals.

In parallel to these formal procedures, the EU is among the first jurisdictions to have adopted binding legislative provisions to implement CORSIA [European Commission, 2018]. This includes the following revisions to Commission regulation to account for monitoring, reporting and verification (MRV) provisions in the ICAO SARP: (i) monitoring and reporting[22] and (ii) verification of greenhouse gas emission reports and tonne-kilometre reports and the accreditation of verifiers[23]. A delegated act was also adopted by the Commission in March 2019, which specifies how information reported in accordance with the aforementioned regulations will be transmitted to the ICAO Secretariat. Under Article 7 of the delegated act, the Commission is identified as bearing responsibility for transmitting verified emissions data. However, due to legal and formal concerns raised by Member States against this specific point given that the individual states – not the Commission – are parties to the ICAO Convention, the Council decided to object to the act in June 2019 [Council of the European Union, 2019; DEHSt, 2019]. The act is expected to be revised by the Commission and available in October 2019.

The terms of the actual legislative process for implementing CORSIA in the future are set out in EU Regulation 2017/2392. Included in this regulation is a requirement (Article 28b) for the Commission to regularly report to the European Parliament and to the Council on progress at ICAO in negotiating and setting up the CORSIA mechanism. As soon as the final rules are adopted by ICAO, the Article requires the Commission to conduct an assessment of all CORSIA aspects and to elaborate proposals on how these may be implemented through a revision of the EU ETS Directive. This review is to be delivered within 12 months of adoption by ICAO of the final rules and prior to the scheme actually becoming operational. In practice though, the timeline of future developments remains relatively uncertain. As mentioned in Section 2.1.1, it would seem that the next review of the Directive may likely take place in 2022 or 2023 (see Section A.3 in Annex).

### 2.3.2 Alternatives for parallel operation of EU ETS and CORSIA

In 2019 and 2020, aircraft operators with international flights in between EEA countries are required to monitor flights under both CORSIA and the EU ETS. Going forward, based on the current scopes of each scheme, CORSIA offsetting requirements would overlap with the EU ETS as of 2021 with regards to international flights within the EEA. Furthermore, should the EU ETS revert to a full scope coverage after 2023, extra-EEA flights would also be regulated twice. It is presently unknown if and to what extent the EU ETS or CORSIA would be revised to resolve these conflicts.

[21] Council Decision (EU) 2018/2027
[22] Commission Implementing Regulation (EU) 2018/2066
[23] Commission Implementing Regulation (EU) 2018/2067

To bring some clarity to the debate, scenarios have been put forth and assessed by industry groups and research institutions alike. The alternatives considered usually involve the following (see also Table2):

A. Restricting EU ETS coverage to domestic flights only and implementing CORSIA's full scope in the EU;
B. Maintaining the EU ETS reduced scope and implementing CORSIA only on international flights to and from the EEA; and
C. Reinstating EU ETS to its full scope without implementing CORSIA in the EU (but CORSIA still applied to flights with no departure or arrival in the EU.

**Table 2: Summary of commonly assessed scenarios for EU ETS and CORSIA co-existence. Source: First Climate based on [Scheelhase et al, 2018] and [Van Velzen, 2018]**

| Scenarios | Domestic flights within EEA States | International flights in between EEA States | International flights to and from the EEA |
|---|---|---|---|
| A | EU ETS | CORSIA | CORSIA |
| B | EU ETS | EU ETS | CORSIA |
| C | EU ETS | EU ETS | EU ETS |

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Given these options, Scheelhase et al. (2018) conclude that a coverage of inter- and intra-EEA flights by the EU ETS and extra-EEA flights by CORSIA would be the best alternative in terms of environmental benefits and expected political acceptance. The industry group Transport and Environment (T & E) arrives at a similar conclusion, that scenario B would contribute the most among the three to closing the gap with the EU's 2030 emissions target [Van Velzen, 2018]. In a variation to this scenario, T & E further proposes that EUAs be used – instead of offsets – in CORSIA for all flights departing from an EU airport. The attraction of this variant would be the direct emission reduction impact within the EU rather than in a third country generating the international offsets. According to the study, this modified scenario B would be the most impactful from the perspective of EU's climate goals.

# 3 Design parameters for integration of non-$CO_2$ effects into EU ETS

## 3.1 Objective of the assessment

Section 2 of this report has highlighted the limited extent to which non-$CO_2$ effects have been considered in the development of the EU ETS to date. The Aviation Working Group report and the EU Commission's impact assessment in 2006 considered the case of a fixed multiplier applied to flights' $CO_2$ emissions, but did not consider more detailed quantification options or other useful parameters [European Climate Change Programme II, 2006; European Commission, 2006]. Further, the 2017 impact assessment did not evaluate these effects altogether [European Commission, 2017b].

In this and subsequent sections, detailed options for integrating non-$CO_2$ effects in the EU ETS will be first identified, then their impact assessed. Extending the coverage of the emissions trading scheme's aviation scope implies considering at first how the scheme would be designed. Important elements include the boundary of the new scope, technical aspects regarding the functioning of the scheme, and how the extension would be implemented in practice.

A full evaluation of all design parameters is beyond the scope of this study, instead the focus will be set on a selection of design parameters. Emphasis is placed here primarily on parameters related to the technical specifications and the functioning of the emissions trading system as a whole.

## 3.2 Identification of key design parameters

### 3.2.1 Setting the scope

The set of design parameters considered in this study is listed in Table 3. Each of these parameters is a variable which may take on a range of different "values", or options. Depending on the option selected the impact on the emissions trading scheme would vary. For instance, integrating non-$CO_2$ climate effects in the EU ETS can be done at a domestic level among EU Member States or by including international flights as well. The broader the scope, the greater the environmental benefits, but the higher the costs of implementation not just for aircraft operators but for stakeholders at large

**Table 3: Overview of design parameters for the integration of non-$CO_2$ effects. Key design parameters selected for consideration in this study are highlighted.**

| Design elements | Design parameters | *Selected* |
|---|---|---|
| Scheme implementation | Phasing of the integration | ✓ |
| | Timing of the integration | ✓ |
| Scope | Non-$CO_2$ species | |
| | Geographical coverage | ✓ |
| | Aircraft operator thresholds for compliance and flight type exclusions | |
| Technical aspects | Climate metric for non-$CO_2$ effects | |
| | Non-$CO_2$ emissions quantification methodologies | ✓ |
| | Historical baseline years and linear reduction factor | |
| | Benchmarks and free allocation share | |

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### 3.2.2 Definition of key design parameters

The design parameters identified in the previous section were prioritized in consultation with the German Environment Agency and a list of *key* design parameters was selected for consideration in this study. Effort was made to focus on the most impactful parameters in terms of the functioning of the EU ETS. For this reason, parameters such as the timing and phasing of the integration as well the geographical coverage are highlighted as these are critical to operationalizing the scheme and defining the extent to which aircraft operators would be required to comply with it. Furthermore, the calculation approach would impact the complexity of the data monitoring and reporting procedures and thus is also a critically relevant parameter for both aircraft operators and competent authorities.

On the other hand, options for compliance thresholds and exemption categories are not assessed in this study as those currently in force in the existing aviation scope are assumed to be applicable as well for the extended scope. The present study also does not evaluate different options of non-$CO_2$ species coverage given the uncertainties in their effects.[24] Lastly, other technical aspects such as non-$CO_2$ climate metric historical baseline years, linear reduction factor, benchmarks and free allocation share are considered of lesser impact for the purpose of this study and are also not specifically evaluated.

The outcome of the prioritization exercise is a list of four key design parameters, which are described in the sections below along with the associated options considered in this study. Additionally, Section A.4 in Annex provides an overview of all parameters and options in tabular format.

#### 3.2.2.1 Phasing of the integration

Past experiences with the EU ETS provide useful examples of how additional sectoral or greenhouse gas scopes may be integrated into the scheme. Whereas $CO_2$ emissions from the aviation and aluminium sectors, among others, were fully introduced in 2012 and 2013, respectively, $N_2O$ emissions from nitric, adipic and glyoxylic acid production were introduced in a phased approach. In

[24] For further information on atmospheric processes and related uncertainties, refer to Section 2 of the AP1 report "Suitable climate metrics for assessing the relation of non-$CO_2$ and $CO_2$ climate effects".

Phase 2, certain Member States voluntarily included certain $N_2O$ emission sources, following which this scope was enforced for all jurisdictions starting in Phase 3 (see Box 2).

**Box 2: $N_2O$ opt-in in Phase 2 of the EU ETS.**

The EU ETS directive of 2003 enables EU Member States – subject to approval by the European Commission – to unilaterally include additional activities, greenhouse gases or operators into the scheme starting from 2008 (Article 24). This article was first invoked by the Netherlands to include $N_2O$ emissions associated with the production of nitric acid. Following an application in June 2008, the Commission approved the inclusion in December 2008 with retroactive effect from January 1st, 2008 [European Commission, 2008]. Other countries then followed suit, such as Austria and the United Kingdom, whose applications were approved in December 2009 and June 2011 with effect from January 1st, 2010, and April 1st, 2011, respectively [European Commission, 2009; European Commission, 2011]. Following the adoption in 2009 of the EU's revised directive for Phase 3,[25] the scope of the EU ETS was extended on a compulsory basis starting in 2013 to $N_2O$ emissions from production of nitric, adipic and glyoxylic acid. The opt-in of $N_2O$ emissions in Phase 2 therefore enabled early action by certain Member States to achieve emission reductions in this sector.

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The two following options are therefore considered for this design parameter:

**Option 1. Instant full roll-out**
**Option 2. Phased roll-out: pilot phase with Member State(s) opt-in of domestic/intra-Community flights followed by full roll-out**

#### 3.2.2.2 Timing of the integration

For the most part, additional compulsory sectoral or greenhouse gas coverage under the trading scheme has been integrated upon entry into force of the third phase in 2013 (sectors: e.g. aluminium, petrochemical; greenhouse gases: e.g. $N_2O$, PFC). The exception to this generality is the aviation sector, which began participating towards the end of the second phase in 2012. The EU ETS therefore provides precedents both for scope adjustment/extension upon phase launch and mid-phase.

In the upcoming Phase 4, two distinct sub-periods are planned: 2021-2025 and 2026-2030. Indeed, benchmark values for stationary operators in 2026-2030 are set to be updated from 2026 as per Article 10a of the ETS Directive. The Directive does not, however, specify whether such a benchmark update is planned for the aviation sector. It is nevertheless assumed that this mid-point provides for a useful timeframe for changes in the scope of the aviation sector as well.

Early integration of additional sectors provides obvious environmental benefits, but these must be balanced against political and practical feasibility of doing so outside of phase start dates. For the purpose of this study, options for the timing of the integration are therefore considered around this 2026 mid-point and include:

**Option 1. Full roll-out prior to 2026**
**Option 2. Full roll-out from 2026**
**Option 3. Full roll-out after 2026**

[25] Directive 2009/29/EC

#### 3.2.2.3 Geographical scope of the integration

In Section 2.3, the geographical regions of relevance for the EU ETS and its interface with CORSIA have been highlighted in detail. The debate surrounding the future of the trading scheme and how best to integrate it with ICAO's market-based measure provides a useful basis for assessing as well possible geographical scopes for non-$CO_2$ effects. Hence, the following options are identified:

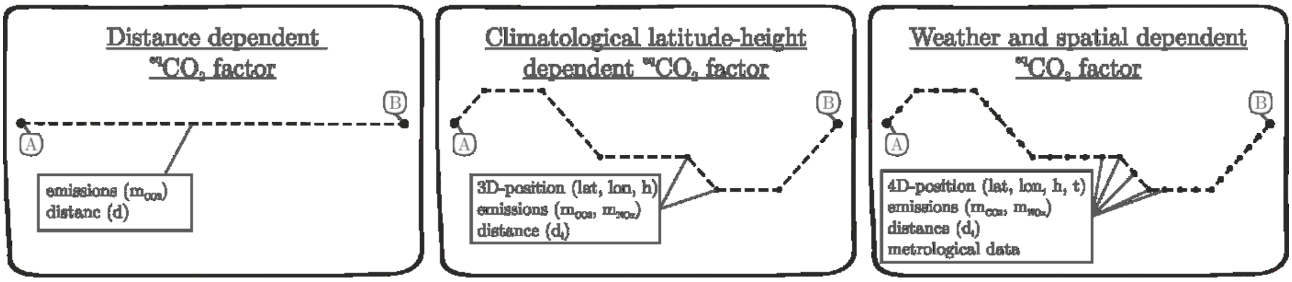
**Option 1. Intra-Member State flights**
**Option 2. Inter-Member State flights**
**Option 3. Flights from and to EEA**

Option 1 – and potentially Option 2, limited to participating Member States – would be particularly relevant, if Member States were granted opt-in choices under a pilot scheme. Option 3 would a priori run against the complementarity approach discussed in Section 2.3.2 (i.e. EU ETS for inter-EU flights and CORSIA for extra-EU flights) but will nevertheless be included in the scope of this study.

#### 3.2.2.4 Calculation methods

Previous results of this project have identified three different approaches to quantify the non-$CO_2$ effects of aviation (see Figure 2).[26] With each of these methods come varying levels of data requirements – and thus monitoring efforts – and accuracy. Greater accuracy comes at the expense of increased data requirements (weather-dependent factor), and conversely lower accuracy is associated with lower implementation efforts (distance-dependent factor).

**Figure 2: Illustration of data requirements for selected methods to calculate $CO_2$ equivalents ($eqCO_2$)**




©DLR: Niklaß and Scheelhaase

These three alternatives are factored in as options in the present study:

**Option 1. Distance-dependent factor**
**Option 2. Climate-dependent factor**
**Option 3. Weather-dependent factor**

### 3.2.3 Interdependency of key design parameters

All design parameters identified are independent from one another, with the exception of the phasing and timing of the integration. An instant roll-out is compatible with all "timing" options, however a phased integration with an initial opt-in period would not be feasible in practice with a roll-out prior to 2026 (see Table 4). Indeed, the timeframe available until the launch of such a pilot opt-in in the early 2020s would likely be insufficient for the EU to conduct the required assessments and regulatory revisions needed for implementation.

[26] For further information on the calculation methods, refer to Section 4 of the AP1 report "Suitable climate metrics for assessing the relation of non-$CO_2$ and $CO_2$ climate effects".

**Table 4: Interdependency of design parameters "phasing of the integration" and "timing of the integration".**

| | Instant full roll-out | Phased roll-out: pilot phase with Member State opt-in followed by full roll-out |
|---|---|---|
| **Full roll-out prior to 2026** | ✓ Compatible | × Not compatible |
| **Full roll-out from 2026** | ✓ Compatible | ✓ Compatible |
| **Full roll-out after 2026** | ✓ Compatible | ✓ Compatible |

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Keeping this single incompatibility in mind, all options listed in the previous sections may therefore be selected individually and without interference from others. As a result, the impact of each design parameter may be assessed separately for each individual option.

# 4 Evaluation of key design parameters on integration of non-$CO_2$ effects into EU ETS

## 4.1 Impact assessment of the key design parameter options

### 4.1.1 Criteria for assessing impact

In order to evaluate realistic pathways for integrating non-$CO_2$ effects into the EU ETS, the impacts of the various options defined in Section 3 are assessed in this section. First, the impact on aviation sector dynamics is assessed to understand how the design may affect the industry's emissions falling under the new scope. Then, the direct impact on the actual emissions baseline and cap is evaluated. The specific assessment criteria for this purpose are defined below.

**A. Impact on aviation emissions:**

Criterion 1. Demand-side: impact on consumer demand for air travel

Criterion 2. Operator-side: impact on operator behaviour through incentives to reduce emissions

Criterion 3. Unintended effects: impact on carbon leakage risk

**B. Impact on emissions baseline and cap**

Criterion 4. Baseline and cap: impact on aviation sector baseline and cap

The assessment is performed on a qualitative (at times semi-quantitative) basis focusing on those design parameters with the greatest impact on the criteria. Parameter options are mostly considered individually but, where relevant, the impact of parameter combinations is also assessed. The impact is rated on a tiered scale from low to high. The difference between impact levels (low / medium / high) is relative to each specific criterion and should not be taken as representing a standardized impact magnitude.

### 4.1.2 Results of impact assessment

#### 4.1.2.1 Criterion 1: Impact on consumer demand for air travel

Aircraft operators faced with a new and extended aviation scope under the EU ETS would incur additional costs for surrendering allowances for their non-$CO_2$ emissions and would seek to pass these through to consumers through increased ticket prices. In response, consumers in turn may reduce or modify their travel plans accordingly leading to a decrease in demand for air travel and thus a decrease in emissions. This reactive behaviour is in principle desirable from an environmental perspective[27] but must nevertheless be accounted for when the emissions cap for the new scope will be set. If not factored into the cap, the market could be faced with an excess of allowances and suffer from reduced effectiveness at curbing emissions of the sector.

Results from AP2 of this project showed that costs of administrative effort incurred by aircraft operators for monitoring and reporting their $CO_2$ emissions under the EU ETS are significantly lower (one or more orders of magnitude[28]) than the costs of the emissions themselves. In this case, the MRV

[27] For carbon leakage impacts, see Section 0

[28] For further information on current administrative effort for aircraft operators under the EU ETS and CORSIA, refer to Section 5 of the AP2 report "Determination of Data required for Consideration of non-$CO_2$ Effects of Aviation in EU-ETS and CORSIA".

costs can then be reasonably assumed to have a negligible impact on costs being passed through to consumers compared to costs associated with the emissions. When factoring in as well aircraft operators' non-$CO_2$ emissions, consideration must be given to the design parameter "calculation method" as was highlighted in AP2. For the climate- and weather-dependent factors, the estimated additional administrative effort for monitoring and reporting is significant, whereas for the distance-dependent factor it is only minor.[29] Nevertheless, and for the following reasons, this study assumes that all things considered MRV costs will remain well below actual emissions costs and that the former are therefore negligible when assessing cost pass-through to consumers:

- **Medium and large operators**: Despite the added costs – significant in the case of the climate- and weather-dependent calculation options – associated with monitoring and reporting non-$CO_2$ data, these are likely to remain overshadowed by the added costs from the non-$CO_2$ emissions themselves.
- **Small operators**: Small emitters experience disproportionately higher MRV costs compared to medium or large operators, which may be further accentuated by the added non-$CO_2$ emissions scope. This study assumes, however, that these small operators will benefit from simplified monitoring and reporting procedures for their non-$CO_2$ emissions as is the case currently for $CO_2$ emissions (i.e. use of Small Emitters tool, exemption from external verification), thereby maintaining administrative effort at acceptable levels well below the actual emissions costs.

In a perfectly competitive market, aircraft operators would pass through 100% of allowance costs for their routes through increased ticket prices [DEFRA, 2007]. Given the large number of operators in the European market, this study implicitly assumes a high level of cost past-through on all routes and does not consider effects of specific airline pricing strategies (e.g. price undercutting). On this basis, the design parameter "geographical scope of the integration" plays a critical role in determining the extent of the change in demand for air travel resulting from higher prices. Indeed, demand impacts vary depending on the flight routes that are affected by increases in ticket prices. Integrating non-$CO_2$ emissions only from domestic EU flights would have a different impact than including those emissions from international flights to and from the EEA.

Price elasticities of demand (see Box 3) for air travel were estimated and compiled by the International Air Transport Association (IATA) in 2008 for various regions. The results of the study point towards a higher price sensitivity of consumers for short-haul as opposed to long-haul flights since substitute transport means are more readily available. The study also concludes that intra-European air travel exhibits the highest price sensitivity among all regions evaluated (e.g. intra-North America, intra-Asia) due to the shorter travel distances and strong competition from other transport modes [IATA, 2008].

**Box 3: Definition of price elasticity of demand.**

Price elasticity figures capture the sensitivity of consumers' demand for a good or service in response to price variations. Elasticity figures lower than one in absolute value indicate that consumer demand is rather insensitive to price variations (inelastic), whereas figures higher than one in absolute value highlight strong price sensitivity (elastic). As an example, a price elasticity figure of -0.7 indicates that a 10% increase in price leads to a decrease in demand of 7%.

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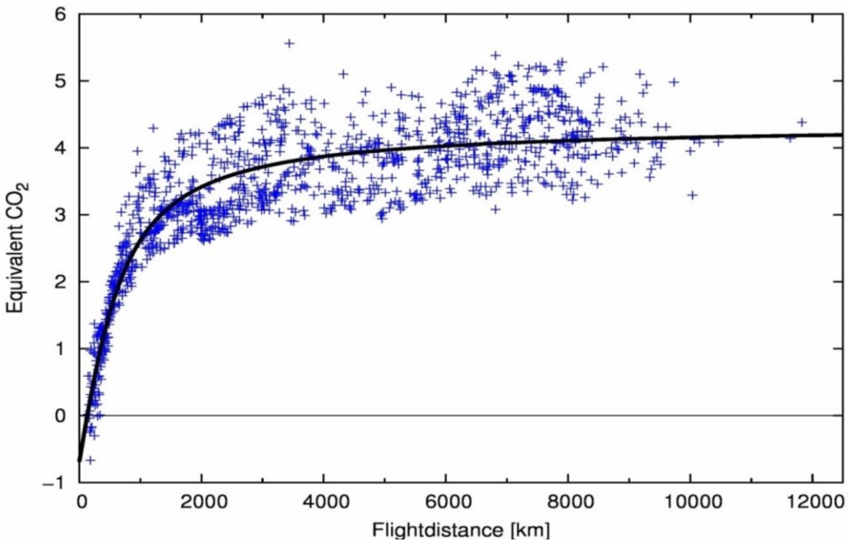
[29] For further information on estimated additional administrative effort for aircraft operators under the EU ETS and CORSIA, refer to Section 6 of the AP2 report "Determination of Data required for Consideration of non-$CO_2$ Effects of Aviation in EU-ETS and CORSIA".

From the perspective of the present study, individual price elasticities of demand can be compiled for the various geographical scope options using the IATA report. The estimates are presented in Table 5 and clearly reflect that demand for domestic EU air travel is more sensitive to ticket price hikes than international EU air travel ($E_{intra} = -1.2$ vs. $E_{inter} = -0.9$). However, in practice, shorter flights would be associated with disproportionally lower non-$CO_2$ emissions than longer flights as the impact of $NO_x$ and contrails is much lower at the lower altitudes flown on shorter routes.[30] This difference is particularly notable when comparing an international EU flight (Paris-Athens, 2090 km) with a typical domestic EU flight (Madrid-Barcelona, 480 km), whereby the latter's non-$CO_2$ emissions – relative to $CO_2$ emissions – would be approximately three times lower (see Figure 3). Therefore, ticket price increases on domestic EU flights would be expected to be disproportionally smaller than for international EU flights, thus likely levelling out the actual impact on demand between both types of flights.

**Figure 3: Equivalent $CO_2$ emissions in dependency of the flight distance (blue crosses) and according curve fit (black).**




From Dahlmann et al., 2018

When considering international flights to and from the EEA, non-$CO_2$ emissions can be considered of similar magnitude – in proportional terms – with those of international EU flights and hence the relative added costs would be small. In terms of demand impacts, the distinction between inbound and outbound flights is relevant at this level as price sensitivities were found to vary in IATA's results. Contrary to EU residents who would have no option to avoid higher prices on their flights outward of the EU ($E_{outbound} = -0.5$), overseas residents would be more sensitive to higher ticket prices as they have flexibility in selecting non-EU destinations ($E_{inbound} = -0.8$). Therefore, while the impact on extra-EEA air travel demand is overall lower than for intra- and inter-EU air travel, it is not the same across all flight routes.

[30] For further information on impacts of non-$CO_2$ species, refer to Section 4 of the AP1 report "Suitable climate metrics for assessing the relation of non-$CO_2$ and $CO_2$ climate effects.

**Table 5: Price elasticities of demand for air travel [IATA, 2008]**

| Geographical scope of the integration | Price elasticity of demand (E) |
| --- | --- |
| Intra-Member States | $E_{intra} = -1.2$ |
| Inter-Member States | $E_{inter} = -0.9$ |
| From and to EEA[31] | Inbound travel by overseas residents: $E_{inbound} = -0.8$<br>Outbound travel by EU residents: $E_{outbound} = -0.5$ |

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The impact of price elasticity of demand can be quantitatively illustrated in the example Paris-Athens flight mentioned above. As aircraft operators pass their additional non-$CO_2$ emissions costs through to consumers, demand would likely trend downwards. For aviation allowance prices between 20 and 30 EUR/t$CO_2$e – representative of the year to date – and a best-estimate non-$CO_2$-to-$CO_2$ climate effect ratio of 2.4 for this flight distance (see Figure 3), the expected decrease in consumer demand could range from 10 to 17%.[32] At industry level more complex relationships and dynamics would need to be accounted for, however the magnitude highlighted here is non-negligible.

The overall impact of key design parameters on consumer demand for air travel is summarized below for those parameters affecting this criterion the most. It should be noted here that the other two key design parameters (timing and phasing) only have minor impacts on reducing consumer demand for air travel. An early start to the new aviation scope covering non-$CO_2$ climate effects or an initial opt-in phase may potentially accelerate the effects described above but are not foreseen to affect their magnitude.

**Table 6: Summary of impacts on consumer demand for air travel.**

| | Calculation methods | | |
| --- | --- | --- | --- |
| | Distance-dependent factor | Climate-dependent factor | Weather-dependent factor |
| Evaluated impact of **calculation method** on reducing consumer demand for air travel | * | * | * |

| | Geographical scope of the integration | | |
| --- | --- | --- | --- |
| | Intra-Member States | Inter-Member States | From an to EEA |
| Evaluated impact of **geographical scope** on reducing consumer demand for air travel | ** | ** | * |

"/" no impact, "*" low impact, "**" medium impact, "***" high impact

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[31] Price elasticities for this category are estimated by the authors as the average of *Trans-Atlantic* (E = -0.7) and *Europe-Asia* (E = -0.5) regions in the IATA report. To adjust for inbound travel by overseas residents and outbound travel by domestic residents, the report recommends the multipliers 1.3 and 0.8, respectively. Hence $E_{inbound} = -0.6 \times 1.3 = -0.8$, and $E_{outbound} = -0.6 \times 0.8 = -0.5$.

[32] Calculated for a direct one-way economy-class ticket (CDG-ATH) using the myclimate flight emissions calculator (0.38 t$CO_2$), ticket price of EUR 150 and price elasticity E_inter= -0.9. The AP3 report "Practice in Voluntary Carbon Markets for Estimating CO2 and non-CO2 Effects of Air Travel" identified the myclimate tool as the most conservative for medium-haul flight emissions among the tools assessed

#### *2.1.1.1 Criterion 2: Impact on operator behaviour through incentives to reduce emissions*

As seen in the previous section, aircraft operators faced with additional operational costs from the integration of non-$CO_2$ climate effects in the EU ETS will aim – market conditions permitting – to pass through close to 100% of these allowance costs to consumers through increased ticket prices. While this is one possible pathway through which sectoral aviation emissions may be impacted, direct efforts by operators to modify their own operations for the purpose of reducing upfront the cost exposure to the scheme are another. This effect - environmentally beneficial insofar as it leads to emission reductions[33] – would depend on the incentives built into the design of the scheme.

The design parameter "calculation methods" plays here a critically important role. As described in previous work packages of this project, the three calculation methods provide varying levels of incentives to aircraft operators for reducing their non-$CO_2$ emissions.

As opposed to $CO_2$ emissions which are not dictated by location and can only be tackled through improved fuel economy, non-$CO_2$ emissions are dependent on altitude, latitude and time at which the flight occurs.[34] For this reason, a distance-dependent factor – albeit intrinsically related to altitude through a distance-altitude correlation – does not incentivize behavioural changes leading to reduced non-$CO_2$ emissions. On the contrary, to reduce the overall climate effect operators would be focused on tackling their flights' $CO_2$ emissions, which may in practice potentially increase non-$CO_2$ emissions and lead to an overall rise in emissions. Conversely, both the weather-dependent and climate-dependent factors are structured to account for spatial and/or temporal dependencies of non-$CO_2$ emissions. The former method provides the best representation of atmospheric response to local emissions and would enable aircraft operators to optimally and accurately route flights to avoid sensitive non-$CO_2$ emission-inducing regions and minimize their costs. The latter method, on the other hand, is based on climatological mean data for specific regions rather than actual weather situations and therefore also provides incentives to operators but with some limitations. Indeed, this method may provide false incentives on certain days if weather situations are avoided that may in fact generate lower non-$CO_2$ emissions than the mean climate data indicates.

The operator behaviour change fostered through these built-in incentives may comprise for instance modifications to the altitude or latitude of a given flight route. Dahlmann et al. (2016) found that reducing the mean flight altitude by 6000 ft (approx. 1800 m) would reduce the overall climate impact by 23%. These positive results depict, however, a trade-off between decreased ozone formation and contrail-induce cloudiness clouds on the one hand and increased fuel consumption and $CO_2$ emissions on the other hand.

As non-$CO_2$ climate effects do not impact all flights equally, aircraft operators would be in particular incentivized to target those routes with the disproportionally highest emissions. The design parameter "geographical scope" would thus play a role here as well, whereby higher altitude flights (i.e. medium-to long-haul) such as those in between Member States or to and from EEA would likely be prioritized. Furthermore, operator behaviour changes and their impact on sector emissions would be accelerated by an early start to the new aviation scope covering non-$CO_2$ climate effects – or by an initial pilot phase. The design parameters "timing of the integration" and "phasing of the integration" can therefore also be considered to impact this criterion, albeit only to a minor extent. The table below summarizes the most prominent impacts on operator behaviour.

[33] For carbon leakage impacts, see Section 0

[34] For further information on factors influencing non-$CO_2$ emissions, refer to the AP1 report "Suitable climate metrics for assessing the relation of non-$CO_2$ and $CO_2$ climate effects.

**Table 7: Summary of impacts on operator behaviour to reduce emissions**

| | Calculation methods | | |
|---|---|---|---|
| | Distance-dependent factor | Climate-dependent factor | Weather-dependent factor |
| Evaluated impact of **calculation method** on operator behaviour to reduce non-$CO_2$ emissions | / | * | *** |

| | Geographical scope of the integration | | |
|---|---|---|---|
| | Intra-Member States | Inter-Member States | From and to EEA |
| Evaluated impact of **geographical scope** on operator behaviour to reduce non-$CO_2$ emissions | * | ** | ** |

"/" no impact, "*" low impact, "**" medium impact, "***" high impact

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#### 4.1.2.2 Criterion 3: Impact on carbon leakage risk

The impact assessments on consumer behaviour and operator behaviour in the previous sections have highlighted the theoretically positive effects these behavioural changes may have on reducing emissions. In practice, applying an emissions trading scheme only within a defined boundary may however lead to a rise in unregulated emissions outside the scope of the system as activity – consumer- or operator-driven – is diverted there to minimize costs. This carbon leakage effect is a prevalent risk in the aviation sector as emission sources are inherently mobile, crossing international borders as part of daily business. The key design parameter "geographical scope" is therefore of critical importance in this case.

When considering the integration of non-$CO_2$ climate effects, the operational cost impact of these emissions should be recalled. Shorter, intra-Member State flights produce disproportionally lower non-$CO_2$ emissions than inter-Member State or extra-EEA flights. Hence operators would have a higher incentive to divert long-haul flights rather than domestic ones. On the other hand, as seen in Section 4.1.2.1, consumers would tend to react more to short-haul flights due to their higher price sensitivity in this market. Together, these operator- and consumer-driven effects may produce a variety of carbon leakage scenarios [Ernst & Young and York Aviation, 2008]:

- **Non-EU to EU – Foreign tourism diversion from the EU**: Price sensitivities vary on extra-EEA flights depending on whether these are to or from the EU (see Section 4.1.2.1). Overseas residents travelling to the EU are relatively flexible to select alternative travel destinations outside the EU and avoid fees associated with non-$CO_2$ emission under the EU ETS.
- **Within EU – Transport mode shift:** Due to higher price sensitivities on short-haul flights, consumers may divert to ground transport modes (i.e. train, bus, car). However, while this represents a leakage of $CO_2$ emissions, this do not represent leakage of non-$CO_2$ emissions since the other unregulated transport modes do not have any material non-$CO_2$ climate effects.
- **Non-EU to Non-EU – Transit hub diversion:** On indirect routes from non-EU origin to non-EU destination, operators (e.g. cargo), but also passengers, may opt to swap an EU for a non-EU transit airport to avoid non-$CO_2$ compliance costs under the emissions trading scheme.
- **EU to Non-EU – Connecting hub relocation:** Indirect air traffic departing from the EU through an EU connecting hub may be diverted by operators (e.g. cargo), but also passengers,

to alternatives with a non-EU connecting hub to minimize non-$CO_2$ allowance costs under the EU ETS.

The geographical scopes relevant to each carbon leakage scenario are highlighted in Table 8. While these diverted routes may present cost-advantages from avoiding compliance with the non-$CO_2$ scope of the EU ETS, these strategies should be weighed against the additional costs created. Added fuel and labour costs, as well as longer flight times, would be trade-offs to manage.

**Table 8: Correlation of carbon leakage scenarios with geographic scopes of non-$CO_2$ climate effects.**

| Carbon leakage scenario | Risk of non-$CO_2$ carbon leakage for different geographical scopes | | |
|---|---|---|---|
| | Intra-Member States | Inter-Member States | From and to EEA |
| Foreign tourism diversion from the EU | No | No | Yes |
| Transport mode shift | Limited | Limited | Very Limited |
| Transit hub diversion | No | No | Yes |
| Connecting hub relocation | No | Yes | Yes |

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Building on Table 8, the table below summarizes the impacts of the geographical scope on carbon leakage risk. Other key design parameters are not considered to have substantive impacts on this criterion.

**Table 9: Summary of impacts on carbon leakage risk.**

| | Geographical scope of the integration | | |
|---|---|---|---|
| | Intra-Member States | Inter-Member States | From an to EEA |
| Evaluated impact of **geographical scope** on leakage risk of non-$CO_2$ emissions | / | * | ** |

"/" no impact, "*" low impact, "**" medium impact, "***" high impact

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#### *2.1.1.2 Criterion 4: Impact on aviation sector baseline and cap*

The annual cap on aviation-related $CO_2$ emissions in the EU ETS – set at 95% of historical aviation emissions for the years 2004-2006— is fixed until 2020 and will decrease thereafter at an annual rate of 2.2% (see Section 2.1.1). In contrast, the non-$CO_2$ climate effects of aviation, currently not covered by the EU ETS, are generally estimated to contribute approximately twice as much to the sector's greenhouse gas emissions (see AP 1).[35] Integrating non-$CO_2$ emissions would therefore on average have a large impact in raising baseline emissions and thus the emissions cap.

This impact would however be strongly influenced by the geographical scope considered. Previous sections of this study have highlighted the dependence of non-$CO_2$ emissions on altitude and consequently on flight distance. Short-haul flights result in comparatively lower non-$CO_2$ emissions than medium- or long-haul flights (see Figure 3). The increase in capped emissions would therefore be

[35] For further information on the impact of non-$CO_2$ species, refer to the AP1 report "Suitable climate metrics for assessing the relation of non-$CO_2$ and $CO_2$ climate effects.

far smaller for a scope including only intra-Member State flights than if international flights are included.

In addition, timing of the integration would also be a relevant parameter given the strong traffic growth in the aviation sector. Assuming baseline years are selected close to the start year of the non-$CO_2$ scope, delayed action in integrating non-$CO_2$ emissions in the EU ETS would tend to result in a higher baseline and thus a possibly higher cap. In 2018, ICAO published forecasted annual growth rates in air traffic for various markets for the timeframe 2015-2035: both intra- and inter-Member State traffic is expected to grow by 2.7 %, while demand for flights to and from the EU will likely grow between 2.5% and 5.5% [ICAO, 2018]. The latter range is a representation of the different growth projections among various regional pairs such as Europe-North America or Europe-Central West Asia. Assuming a simplistic linear relationship between air traffic and non-$CO_2$ emissions, delayed integration of extra-EEA flights may have disproportionally harmful consequences on achieving the sectoral abatement goal.

The baseline and cap would inherently also be dependent on the non-$CO_2$ emission calculation method selected, albeit only to a minor extent. Indeed, to ensure operators have a financial incentive for complying with the more sophisticated and data-intensive methods (climate- and weather-dependent), these methods should result in slightly lower emissions than by using a more approximative method (distance-dependant method). In this way, operator's complying with more demanding calculation methods would have slightly lower costs than if simplistic methods are used.

The table below highlights the most impactful design parameter options for this Criterion.

**Table 10: Summary impacts on aviation sector baseline and cap.**

| | Geographical scope of the integration | | |
|---|---|---|---|
| | **Intra-Member States** | **Inter-Member States** | **From and to EEA** |
| Evaluated impact of **geographical scope** of non-$CO_2$ emission coverage on increasing capped emissions in the aviation ETS | * | *** | *** |

| | Timing of the integration | | |
|---|---|---|---|
| | **Full roll-out prior to 2026** | **Full roll-out from 2026** | **Full roll-out after 2026** |
| Evaluated impact of **timing of non-$CO_2$ scope integration** on increasing capped emissions in the aviation ETS | * | ** | *** |

"/" no impact, "*" low impact, "**" medium impact, "***" high impact

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### 4.1.3 Highlights of impact assessment

A few key results can be gleaned from the outcomes of the impact assessment of key design parameters phasing, timing, geographical scope and calculation methods (for a summary of all impacts presented, see Section A.5 in Annex).

A non-$CO_2$ scope inclusion in the EU ETS presents an additional set of challenges compared with aviation's direct $CO_2$ emissions. The inherent non-linear relationship between a flight's distance – as proxy for the cruise altitude reached – and non-$CO_2$ climate effect is a primary driver of this study's impact assessment results. Through its impact on consumer demand effects, carbon leakage risks and capped emissions, the geographical scope parameter is a key design lever with which to influence emissions under the scheme. The middle-ground option targeting integrating non-$CO_2$ climate effects at an intra-EU level (i.e. domestic and international flights within the EU) presents optimal compromises from this perspective. This scope would enable the EU ETS to address non-$CO_2$ emissions from medium-haul flights and would present a similar effectiveness as long-haul flights at incentivizing consumer behaviour, while also limiting the risk of carbon leakage compared to an extra-EEA flight scope. This outcome is aligned with the complementarity scenario for addressing the EU ETS and CORSIA interface, presented by T&E and the German Aerospace Centre (DLR) as the most optimal in terms of political feasibility and environmental benefit for the $CO_2$ scope (see Section 2.3.2).

From an ideal public policy design perspective, the geographical scope would be accompanied by a scientifically accurate quantification method of the non-$CO_2$ climate impact providing well-aligned incentives for aircraft operators to reduce their emissions. Such methods would be available in the form of the weather-dependent and, to a certain extent, the climate-dependent factors. The effectiveness of the policy measure may however need to be weighed against the practicality of its implementation and operationalization, including the political commitment in support of it. The more sophisticated the quantification methods, the greater its impact not only on operator administrative effort and costs, but also on those of the competent authority.

A key pathway for easing the transition into a future compliance scheme covering non-$CO_2$ climate effects could be an initial pilot phase over a pre-defined timeframe allowing for Member State opt-in. The case study of $N_2O$ opt-in in Phase 2 (see Box 2) – regulated by Article 24 of the EU ETS Directive – appears in fact practically applicable to non-$CO_2$ emissions from aviation. Member States may theoretically invoke Art. 24 and apply to the EU Commission to unilaterally regulate through the EU ETS "additional activities and gases", or specifically the non-$CO_2$ climate effects of their domestic aviation sector. This mechanism already in place could provide a way forward for fast implementation of a pilot scheme in order to build capacity, knowledge ("learning-by doing") and awareness for the costs and effort involved in regulating such a scope prior to a full EU ETS roll-out or under CORSIA. The environmental benefit of – and the learnings associated with –the pilot phase could be further enhanced if Member States would also opt-in flights between volunteering States, so as to integrate (longer) routes with a more meaningful non-$CO_2$ climate impact. In the medium term, however, a move to a mandatory inclusion of aviation's non-$CO_2$ effects would clearly be required to ensure environmental effectiveness and avoid permanent distortion of the European aviation market.

This phased approach also has the advantage of smoothing the introduction of the non-$CO_2$ scope and its anticipated high associated compliance costs. The previous sections of this study discussed qualitatively the cost impacts depending on different design options of the scheme. Given the over threefold increase in allowance prices since the integration of the $CO_2$ aviation scope in 2012[36] and a climate impact twice as large as for $CO_2$, the inclusion of this additional scope may come at significant cost to operators. An initial opt-in phase focused on domestic flights, coupled with other targeted design parameters (i.e. high free allocation share) would provide means to lower the financial burden on aircraft operators, at least initially.

It should be noted that qualitatively, the highlighted outcomes in this section and the impact assessment overall remain valid irrespective of the type of non-$CO_2$ species selected (i.e. $NO_x$, contrails, CiC, soot, water vapour) under an extended aviation EU ETS scope. Similarly, these are also

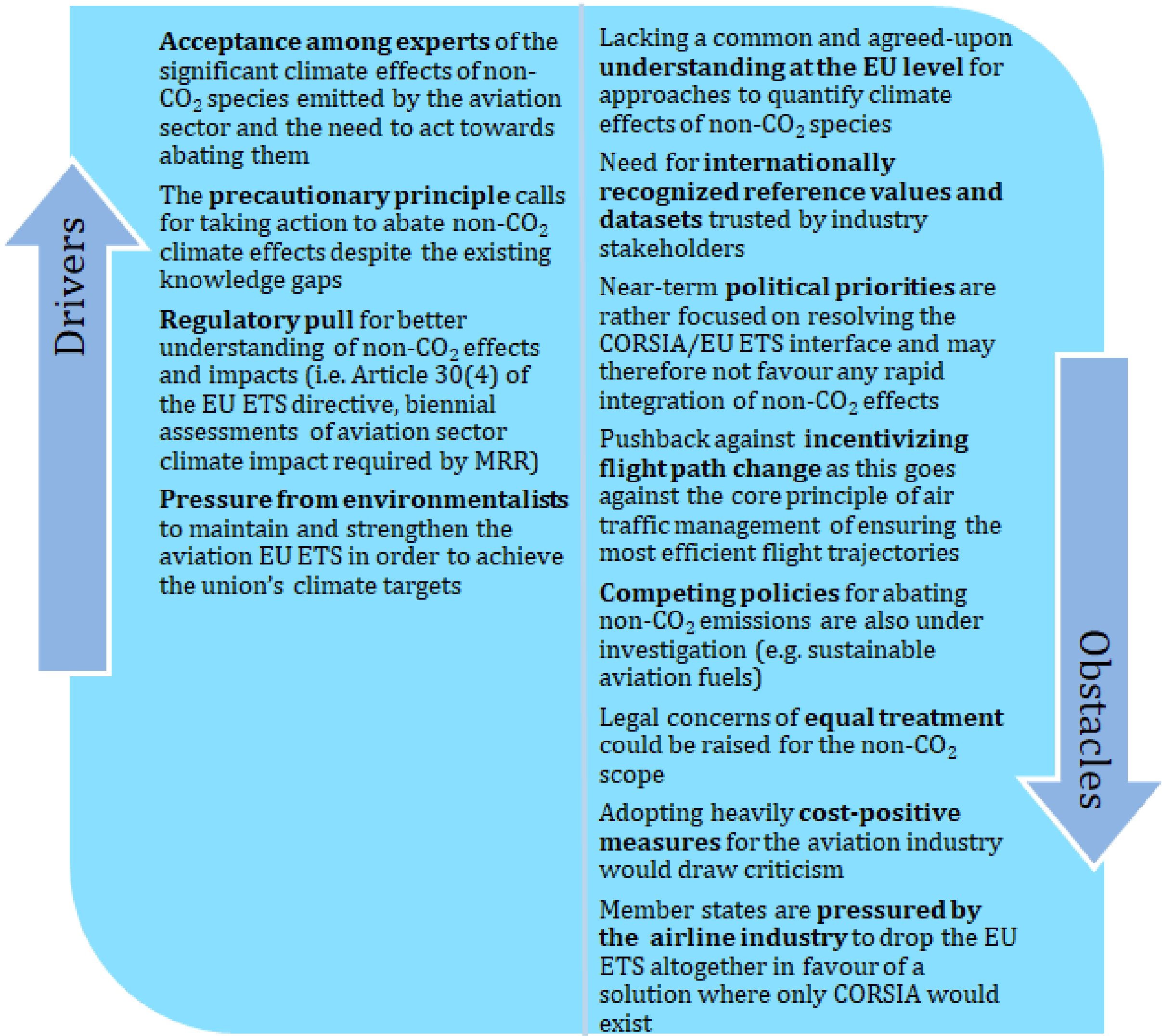
[36] Average allowance prices in 2012 and in August 2019: approx. 7.5 EUR/t and 26 EUR/t, respectively.

independent of the non-$CO_2$ climate metric selected (e.g. GWP vs. Average Temperature Response (ATR)).

## 4.2 Initial feasibility assessment of the integration of non-$CO_2$ effects into the EU ETS

Building on the outcomes of the regulatory overview and the impact assessment of this study, it is evident that the current context at the EU level is shaped by a multitude of forces acting simultaneously to influence the possible integration of non-$CO_2$ climate effects in the EU ETS. This section aims to build on the highlights of the impact assessment (see Section 4.1.3) in order to elaborate on the feasibility of this integration by taking a closer look at supporting (positive) and harming (negative) influences. Figure 4,below, summarizes identified drivers and obstacles to an inclusion of the non-$CO_2$ scope in the EU ETS.

**Figure 4: Mapping of drivers for the EU to take action on non-$CO_2$ climate effects of aviation and obstacles to the integration of this scope in the EU ETS.**

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The drivers and obstacles identified are discussed thematically in the next sections. Significant uncertainties exist at various levels which would need to be addressed to achieve further progress towards an inclusion of non-$CO_2$ climate effects.

### 4.2.1 Scientific & technical challenges:

The scientific basis for the atmospheric impacts of non-$CO_2$ species is relatively well understood for the most impactful species (i.e. $NO_x$, contrails), yet uncertainties prevail surrounding the magnitude of their effect.[37] Indeed, a common and agreed-upon understanding for approaches or models to quantify these effects is still unavailable within the scientific community. Committing to take action towards regulating these emissions would require a clear consensus on such methods as well as the metric to be used. The Commission has mandated a study to specifically review scientific developments and progress on these topics. Preliminary results of the study are expected towards late 2019.

Along with developing models to quantify these effects comes the need for defining the reference values and datasets to be used by complying operators. For the more robust – but incidentally also the most complex – quantification methods such as the climate- and weather-dependent factors identified in this project, the reference data requirements relate to global climate and weather situations and thus are far more extensive than those applicable within the $CO_2$ emissions scope (i.e. fuel emission factors). The tools and processes to manage this would have to be formalized early on, namely reputable data sources, sound data quality management and reliable IT infrastructures.

Critically, reference data sets and institutions responsible for them – whether private or public organizations – would also need to be accepted and trusted by industry stakeholders. This would present particularly prominent challenges for a scope covering extra-EEA flights, where aircraft operators in third countries and emerging economies may have less experience with adopting such European standards causing resistance to implementation. Capacity within these operators to actually implement and run sophisticated monitoring protocols may also be a limiting factor.

### 4.2.2 Political & economic challenges:

From an acceptance perspective, the atmospheric and climate impact of non-$CO_2$ emissions are broadly acknowledged by government officials and experts and so is the recognition that these should be tackled effectively by climate policy. In political circles and within the broader public, recognition of this issue is however less widespread. Awareness raising on the overall climate impact of aviation would be needed for effective political debate to take place.

Fundamental discussions about the actual type of policies best suited to tackle non-$CO_2$ impacts are currently ongoing. While incentivizing air traffic optimization (e.g. through emissions trading) is needed to tackle contrails and CiC, reducing fuel consumption or making use of better fuels (e.g. by imposing emissions charges and sustainable fuel mandates) would be effective at tackling $NO_x$ and particulates [CE Delft, 2017; Larsson et al., 2019]. Furthermore, policies promoting flight path changes are at risk of attracting criticism as this goes against the core principle of air traffic management of ensuring the most efficient flight trajectories. Clear communication around the environmental and economic benefits of emissions trading for non-$CO_2$ emissions compared to other policy options would beneficial.

[37] For further information on atmospheric processes and related uncertainties, refer to Section 2 of the AP1 report "Suitable climate metrics for assessing the relation of non-$CO_2$ and $CO_2$ climate effects".

The most recent revision to the EU ETS is still relatively fresh and aviation-related political priorities in the EU for the next revision would likely revolve around optimally resolving the interface with CORSIA by the end of 2023. In this context, pushing as well for an integration of the non-$CO_2$ scope within this short timeframe would require committed efforts and rapid mobilization of key stakeholder groups to address the existing uncertainties.

### 4.2.3 Regulatory & legal challenges:

From a legal point of view, four issues around the integration of non-$CO_2$ effects in the EU ETS Directive deserve closer attention. First, the question of equal treatment ('a tonne is a tonne'). Second, the impact on secondary legislation, namely on monitoring and registry. Third, the question of compliance with international law principles. And fourth, the potential conflict with CORSIA.

**Equal treatment**

This argument had been raised when the European Commission prepared its 2008 legislative proposal. It was then used to put in question the fixed multiplier approach: indeed, non-$CO_2$ effects are not necessarily commensurate to $CO_2$ effects (and to 'simple calculations' of fuel spent). Shorter flights will have less $CO_2$ effects than longer flights. However, in terms of non-$CO_2$ effects, the same relation does not (automatically) apply.

The issue of equal treatment might also be raised in another sense. It is not fuel and distance, but geography, weather and climate cycles that predominantly define a flight's non-$CO_2$ effects. Northern countries may end up incurring a different non-$CO_2$ footprint than countries further south. This puts countries, aircraft operators and consumers apart depending where they are (most likely to be) located; and the financial and social impact from EU ETS integration would not be equally shared.

Should the proposed measure not follow the fixed multiplier approach, but instead trace climate impacts of flights effect by effect (i.e. climate- or weather dependent calculation methods), the argument of arbitrary calculation would be less acute. The approach at hand would treat a *tonne as a tonne*. To the extent the monitoring and calculation approach does rely on default values that are generic, not specific, the Court of Justice's ruling in the case Arcelor (C-127/07) is pertinent. It also responds to the risk of social and financial discrimination. In that judgment, relying on the precautionary principle and the polluter-pays principle, the Court clarified that the Community legislator "has a broad discretion where its actions involve political, economic and social choices and where it is called on to undertake complex assessments and evaluations" (para. 57). As long as the specific choice is based on "objective criteria appropriate to the aim pursued by the legislation in question" (para. 58), the legislation passes the test of judicial control.

Such objective criteria have been identified (see results from AP1) and they represent the basis for the regulatory measure under discussion. The judicial test seems squarely met. The legal viability aside, the legislator may certainly take corrective action to accommodate countries, citizens and aircraft operators that would be impacted more than others. Such corrective action may consist in establishing a reserve to provide for additional free allocation for certain countries.

### Revisions to secondary legislation

The quantitative impact uncertainties of non-$CO_2$ climate effects translate directly into compliance cost uncertainties for operators. A comprehensive initial monitoring phase – prior to a pilot phase – would address this gap but may require modifications to implementing regulation on monitoring and reporting.[38] So far MRV is restricted to "aviation activities", i.e. "relevant data used for determining the fuel consumption and emissions" and "data used for determining the payload and distance relevant for the years for which tonne-kilometre data are reported". But initial monitoring of non-$CO_2$ effects using a climate- or weather-dependent calculation method would call for flight path monitoring rather than solely distance. Furthermore, monitoring would have to account for temporal variability in non-$CO_2$ effects – potentially the case if weather-dependent factors are used where actual meteorological conditions determine emissions. In this case, monitored emissions may vary from one year to the next for identical flight routes and a single-year monitoring would not necessarily be representative.

Depending on the metric used for non-$CO_2$ effects, registry regulation[39] may also need to be updated. Any other metric than tonnes of $CO_2$ equivalent would trigger such a revision. This is however not envisaged as being necessary under the scope studied as calculation methods proposed in this project quantify the climate impact of non-$CO_2$ species as $CO_2$ equivalents.

### Compliance with principles of international law

The inclusion of aviation emissions in the EU ETS – even though only $CO_2$ fell into its scope – was contentious from the start. A number of international airlines contested this move in the courts. The English Court referred the matter to the Court of Justice asking whether the EU ETS Directive amended in 2008 violated treaty obligations – the Chicago Convention of 1944; the Kyoto Protocol of 1997; and the Open Skies Agreement of 2007 (a treaty between the EU and the US) – as well as genuine principles of customary international law.

These issues would need to be re-examined were the EU to extend its reach on regulating aviation emissions. The Court of Justice's key findings (C-366/10)[40], though, will hardly move. The court noted that the Chicago Convention, an international treaty that exempts air fuels in transit from taxation, cannot bind the EU since it is not a party. The Kyoto Protocol – which sees the International Civil Aviation Organisation (ICAO) as a decisive venue for regulating emissions from international aviation – does not claim exclusivity. And the US-EU Open Skies Agreement bans obligatory levies on the consumption of fuel – nothing the EU ETS would entail. Integrating non-$CO_2$ climate effects is less problematic as they are not primarily linked to fuel consumption.[41] The Paris Agreement, moreover, has replaced the Kyoto Protocol as the key international treaty on climate change. Unlike the Protocol, it does not make any reference to international emissions from aviation. The question of potential exclusivity has thus faded.

[38] Commission Implementing Regulation (EU) 2018/2066
[39] Commission Regulation (EU) No 389/2013 of 2 May 2013
[40] Court of Justice: C-366/10 – Air Transport Association of America and Others, Judgment of the Court (Grand Chamber) of 21 December 2011.
[41] It is noted – in the context of the Chicago Convention – that the ICAO bodies – Council and Assembly – have long interpreted the taxation ban for fuels broadly. The Council adopted a Resolution (in 1996) that "strongly recommends that any environmental levies on air transport which States may introduce should be in the form of charges rather than taxes". This resolution was endorsed at ICAO"s 33rd Assembly in September 2001, which "Recognized the continuing validity of Council's Resolution of 9 December 1996 regarding emission-related levies".

Principles of customary international law – the Court of Justice found – were not violated from the inclusion of aviation in the EU ETS. The reasoning appears to apply irrespective of whether the EU ETS aims at $CO_2$ effects, at non-$CO_2$ effects or both: neither the principle of territoriality nor the principle of sovereignty of third States is infringed, since the EU ETS is applicable to operators only because there is a physical link between the aircraft in question and the territory of one of the Member States of the EU (departure or arrival at an aerodrome situated in a Member State).

As for the fact that the operator of an aircraft in such a situation is required to surrender allowances calculated in the light of the whole of the international flight, the Court pointed out that, as European Union policy on the environment seeks to ensure a high level of protection in accordance with Article 191(2) of the Treaty on the Functioning of the European Union (TFEU), the European Union legislature may in principle choose to permit a commercial activity, in this instance air transport, to be carried out in the territory of the European Union only on condition that operators comply with the criteria that have been established by the European Union and are designed to fulfil the environmental protection objectives which it has set for itself, in particular where those objectives follow on from an international agreement to which the European Union is a signatory, such as the Framework Convention and the Kyoto Protocol. The fact that "certain matters contributing to the pollution of the air, sea or land territory of the Member States originate in an event which occurs partly outside that territory is not such as to call into question, in the light of the principles of customary international law… the full applicability of European Union law".[42]

The inclusion of non-$CO_2$ effects does not alter these arguments. The measure appears in compliance with general principles of international law.

**CORSIA Complementarity**

The EU's legislation on aviation emissions is no longer isolated from international policymaking within ICAO. As the EU ETS articles 28a, 28b and 28c make clear, the EU is prepared – on conditions – to see ICAO's global market measure – CORSIA – prevail over the EU's 'unilateral' approach. As described in Section 2.3.1, Article 28b obliges the European Commission to present – within 12 months of ICAO's adoption of relevant instruments – a report considering "ways for those instruments to be implemented in Union law through a revision of this Directive", as well as "rules applicable in respect of flights within EEA, as appropriate".

While these are soft and fluid measures, which do not directly challenge the overlap of both regimes – EU ETS and CORSIA for intra-EEA flights – the perspective is one of complementarity, not conflict. This said, the EU ETS is clear as to the limits of the cooperative approach. The same article, 28b EU ETS, lists a number of conditions that the European Commission is to examine when presenting said report, notably "ambition and overall environmental integrity" of ICAO's scheme. A continued failure to tackle non-$CO_2$ effects – despite scientific consolidation of their impact – would certainly question the ambition of ICAO's market-based measure and make the case for a fresh 'unilateral' approach by the EU.

In fact, it may be argued that the EU ETS has worked as a trigger for action at ICAO level in the past and may do so in the future (then for non-$CO_2$ effects). Conversely, diverting regulatory attention away from emissions trading (using fees, charges, taxes or other internal policy instruments instead), may slow down ICAO's push to tackle non-$CO_2$ effects.

[42] Ibidem, para. 129.

It is noted that these are largely policy considerations. From a legal perspective, CORSIA does not block actions by countries outside its scope. ICAO may expect countries to comply with its international standards and recommended practices (SARPs) – subject to the mechanism under Article 38 of the Chicago Convention allowing the filing of differences (see Section 2.3.1) – but there is no SARP to govern non-$CO_2$ effects. The EU remains free to regulate the matter through its ETS.

## 4.3 Limitations of the assessments

The applicability of the assessment findings in the sections 4.1 and 4.2 is subject to the following limitations:

- **Significant uncertainties exist**: Among these, the uncertain actual magnitude of non-$CO_2$ impacts limits the extent and depth that can be given to an assessment around integrating non-$CO_2$ emissions in the EU ETS as fundamental considerations around capped emissions and operational cost impacts remain undefined. In addition, the currently unclear future interface between the EU ETS and CORSIA within the $CO_2$ scope is also a source of uncertainty, albeit not necessarily from a legal point of view. As pointed out just above, the SARP do not regulate non-$CO_2$ effects and the EU is therefore free to deal with the matter without conflict vis-à-vis ICAO.
- **Qualitative nature of the assessment:** This approach is applicable given the large uncertainties still present, but nevertheless more robust and targeted quantitative modelling of impacts and feasibility would be valuable in the near-term.
- **Assumptions lead to generalization:** To deliver broadly applicable conclusions, this study makes assumptions which generalize trends or behaviours and simplifies complex relationships. In this context, the specific characteristics of Member States – for example their different sizes, income levels, or aviation market size and dynamics – are not accounted for. As a result, care should be taken in applying the findings of the assessments to avoid misinterpretation.

# 5 Considerations for integration of non-$CO_2$ effects into CORSIA

The current status of CORSIA's $CO_2$ emissions scope – progressing through the first monitoring year and with guidance on eligible emission units still under development – makes any detailed evaluation of a scope extension highly speculative at this point. Instead, this section aims at presenting a cursory look into possible pathways and impacts for integrating non-$CO_2$ effects into the measure. The key design parameters selected and assessed in the EU ETS context are considered as well for CORSIA and relevant particularities of a possible inclusion of non-$CO_2$ effects in this scheme are highlighted.

## 5.1 Relevance of key design parameters under CORSIA

The four key design parameters in Section 3.2.2 were selected for their high level of impact within the EU ETS but are also relevant for CORSIA. While fundamentally different in how they operate, both schemes rely on a regulated scope, phased implementation and specific monitoring approaches. The table below describes the relevance of each parameter.

**Table 11: Relevance of key design parameters on the integration of non-$CO_2$ effects in CORSIA.**

| Key design parameter | Relevance for integration of non-$CO_2$ effects in CORSIA |
|---|---|
| Phasing of the integration | Given the early development stages of the CORSIA scheme, no precedents are available for inclusion of additional activities. The scheme's implementation does however already use a phased approach allowing ICAO Member States to voluntarily commit to the market-based measure ahead of non-volunteering States. Replicating this phased approach for a non-$CO_2$ scope under CORSIA is thus conceivable and highly relevant to promote faster adoption. |
| Timing of the integration | CORSIA's phased implementation approach for the $CO_2$ scope – pilot phase (2021-2023), 1st phase (2024-2026), 2nd phase (2027-) – provides multiple possible entry points for an additional scope. This design parameter is therefore relevant and realistic timing options for integration may be at the start of the 1st and 2nd phases, respectively 2024 and 2027. |
| Geographical scope of the integration | Integration of non-$CO_2$ emissions would likely occur for the current full international scope of the CORSIA measure. However, in an initial pilot phase, a subset of the international scope would become relevant as only volunteering Member States would have offsetting requirements. |
| Calculation methods | Similar to their role within the EU ETS, the calculation methods defined in this project (i.e. distance-dependent, climate-dependent and weather-dependent factors) would be relevant for CORSIA, namely in governing the level of incentives provided to aircraft operators to reduce their non-$CO_2$ climate impact. |

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## 5.2 Impact of relevant design parameters and distinctions compared to EU ETS

A few key design elements differentiate the CORSIA scheme from the EU ETS and these play an important role in driving the impact a non-$CO_2$ scope would have. These distinctions are highlighted for each impact assessment criterion defined in Section 4.1.1.

**Criterion 1: Impact on consumer demand for air travel**

By nature, the CORSIA scheme targets international flights but not domestic routes. This scope would therefore – at first approximation – have a somewhat lower impact on reducing demand for air travel than under the EU ETS since consumers have been found to be less sensitive to ticket price increases at this level.

**Criterion 2: Impact on operator behaviour through incentives to reduce emissions**

The international (and global) focus of the scheme inherently means that concerned flights would tend to have, on average, longer routes and thus higher relative non-$CO_2$ impacts than would an intra-EU flight scope of the EU ETS. If calculation methods such as the climate- or weather-dependent factors were applied, aircraft operators would have generally high incentives to optimize route planning.

**Criterion 3: Impact on carbon leakage risk**

ICAO's market-based measure would likely be associated with a lower carbon leakage risk than an extra-EEA scope under the EU ETS. Indeed, the full compliance phase starting in 2027 CORSIA is akin to a closed-boundary system where all international flights between ICAO Member States have an offsetting requirement. CORSIA's voluntary phase would, however, be associated with a higher leakage risk as only flights between volunteering states are included, leaving open possibilities of transit hub diversion and connecting hub relocation.

**Criterion 4: Impact on sector baseline emissions**

Growth rates of air traffic are generally higher for international flights than domestic flights, in particular to developing country regions [IATA 2008], therefore delayed action on including the non-$CO_2$ scope into CORSIA could lead to a possibly materially higher baseline. Sectoral growth – as it relates to operator-specific growth – plays a further role under CORSIA as it defines the extent of offsetting requirements.

## 5.3 Feasibility and key challenges

Extending the scheme's scope to non-$CO_2$ emissions would require an amendment of the CORSIA SARP and its approval by the ICAO Council, a process which may take up to several years. Currently still in the first year of its monitoring phase, CORSIA has yet to demonstrate a fully functioning $CO_2$ emissions scope – which is due to kick-off in 2021 with the pilot phase. A key aspect of the scheme remains also to be defined by ICAO and its international implications clarified, i.e. eligible emission units (see Section 2.2) and the double counting ramifications under international climate policy (i.e. the Paris Agreement). A process to amend the SARP to additionally cover the aviation sector's non-$CO_2$ climate effects is therefore unlikely to be launched prior to the pilot phase. This is in fact evident from the absence of related agenda items and working papers submitted ahead of the ICAO's 40th Assembly to be held in September 2019 [ICAO, n.d. d].

Developments in this direction after the pilot phase would require coordinated recognition by ICAO of aviation's non-$CO_2$ effects beyond $NO_x$ and of the particularly high non-$CO_2$ climate impact of CORSIA-compliant flights (due to long-haul flight coverage). Pressure by environmental groups for ICAO to tackle these effects – namely by pushing for long-term goals [ICSA, 2019] – may help drive productive debates going forward. Such statements must of course be caveated by the prominent uncertainties surrounding actual quantification of non-$CO_2$ effects. And ICAO messaging is clear here: until these uncertainties are resolved through a scientific consensus, non-$CO_2$ effects will be challenging to address.

Similar to an integration into the EU ETS, a phased approach should also be envisaged to raise awareness and build operator acceptance prior to a full roll-out of the extended scope in CORSIA. For this purpose, voluntary measures of aircraft operators to reduce non-$CO_2$ emissions could be accepted as way to generate carbon offsets, which could then be used to by operators towards compliance with their offsetting obligations under CORSIA. To this end, separate offset protocols or "methodologies" could be envisaged for actions targeting different non-CO2 species, such as $NO_x$ and CiC. Such a system would be aligned with the offsetting principle of CORSIA and allow for voluntary participation of ICAO Member States.

Specific methodologies could be developed under existing reputable voluntary crediting standards – and their development could be started immediately to enable fast implementation of the pilot. To the extent that the cost of generating non-$CO_2$ offsets would be lower than the market price of traditional offsets, aircraft operators could thus be financially incentivized to engage in relevant mitigation measures on a voluntary basis. Potential benefits of this approach include the possibility of gaining practical experience with relevant MRV procedures. After a pre-defined pilot phase, the crediting mechanism could eventually be transitioned out in favour of full regulation by the SARP – although this transition may come with its own set of challenges if operators have become accustomed to the interim crediting mechanism

As a last point, one of the four legal uncertainties highlighted for the EU ETS is particularly relevant for CORSIA, namely the matter of equal treatment. Indeed, the greater geographical range of CORSIA flights than those under the EU ETS reinforces this issue. Aircraft operators of similar sizes but with routes in geographically different areas may be affected unequally due the latitudinal dependency of non-$CO_2$ climate effects.

# 6 Conclusions and key findings

The complementarity approach to address the overlap from 2021 onwards of the EU ETS' and CORSIA's $CO_2$ scope – by maintaining the reduced scope EU ETS for aviation and regulating all extra-EEA flights through CORSIA – is viewed by market observers as the optimal pathway to maximize environmental benefits. For a scope extension of the EU ETS – and possibly of CORSIA – to non-$CO_2$ effects, this study finds that such an approach would optimize as well the overall impacts identified on emissions falling under the adjusted EU ETS scope.

The EU ETS would be well-suited to take a pioneering role in regard to regulating non-$CO_2$ effects. While limited progress has been made on this front till now, there is a long history of debate on this topic – starting from the EU Commission's initial communication in 2005 on reducing the climate impact of aviation up until the latest revision of the EU ETS Directive in 2018 requiring the Commission to develop a proposal by January 2020, where appropriate, to address non-$CO_2$ effects of aviation. Aircraft operators complying with the scheme are also well accustomed by now to performing MRV-related tasks since the sector's first inclusion in 2012. Furthermore, this study finds no major legal issues with an inclusion of non-$CO_2$ effects if a reduced scope were to be applied and a climate- or weather dependent calculation method is implemented

The most prominent obstacle identified to a scope extension of the EU ETS – and of CORSIA as well for that matter – is the absence of data on the quantitative impacts of non-$CO_2$ effects. This existing gap has deep ramifications from a public policy perspective as it hampers securing broad political and public support for regulating these effects since the potential additional costs for aircraft operators is currently unknown. Gathering this data is therefore of critical importance and must be a priority for policymakers.

One approach to do so under the EU ETS would be through a dedicated monitoring programme analogous to the collection of tonne-kilometre data for the $CO_2$ scope. This would require approving a calculation method, defining the needed reference datasets and selecting the entities responsible for managing them. Regulatory revisions would also have to be considered (e.g. implementing regulation on monitoring and reporting). It would be of critical importance for this monitoring programme to cover a multi-year period to account for any annual variability in non-$CO_2$ climate effects as a result of varying weather situations.

Following a monitoring phase under the EU ETS – which would very likely also benefit other jurisdictions exploring regulatory options for non-$CO_2$ climate effects of aviation, such as international aviation under CORSIA – a formal extension of the scope could be initiated through a pilot phase to build knowledge and awareness. In fact, Art. 24 of the EU ETS Directive provides a mechanism for Member States to opt-in "additional activities and gases" and regulate these domestically in addition to those already covered by the emissions trading scheme. In theory, Member States may invoke the Article for the purpose of non-$CO_2$ climate effects and apply for Commission approval. A further enhancement to the pilot could come from a coverage of – in addition to domestic flights – flights in between the volunteering Member States. Practically, however, an application to the Commission under Art. 24 would also need to demonstrate additional criteria such as "the effects on the internal market, potential distortions of competition, the environmental integrity of the EU ETS" as well as "the reliability of the planned monitoring and reporting system". The outcomes of the monitoring programme would serve here as valuable basis for addressing these criteria.

The focus placed in this study on integrating non-$CO_2$ effects in the EU ETS is by no means intended at questioning the environmental benefits of implementing the same under CORSIA. In fact, this study argues that the international nature (i.e. long-haul flights) of CORSIA inherently means that flights covered by the scheme would have a disproportionally higher non-$CO_2$ impact that flights under a reduced scope EU ETS. From a global climate perspective, a regulation of these impacts by ICAO should therefore be a priority. But based on the current status of CORSIA – whereby the first compliance phase is still over a year away and aspects of the scheme remain to be defined – and the fact that there are more voices at the ICAO table who must reach consensus, it would appear more likely that the first move would be taken under the EU ETS.

For CORSIA to effectively move forward in regulating this additional scope, a phased approach would be an optimal pathway, similarly to the EU ETS case. Here, this study discusses the option of introducing a crediting mechanism for non-$CO_2$ climate effects in a pilot phase. The benefits of such an approach would be the synergies with the existing offsetting principles of CORISA, the possibility for ICAO Member States to volunteer to take part in this phase by monitoring their non-$CO_2$ emissions and implementing measures to mitigate them, and avoiding the need for any revisions to the SARP as this would be a voluntary mechanism.

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# A Appendix

## A.1 Timeline of relevant aviation-related EU legislation and amendments to EU Directive 2003/87/EC

**Table 12: Timeline of relevant aviation-related EU legislation and amendments to EU Directive 2003/87/EC.**

| No. | Date | Description |
|---|---|---|
| Directive 2003/87/EC | 13.10.2003 | Establishing a European emissions trading system |
| COM (2005) 459 final | 27.09.2005 | Initial communication of the EU Commission to the Council and Parliament on reducing the climate change impact of aviation |
| Directive 2008/101/EC | 19.11.2008 | Inclusion of aviation activities in the EU ETS (full scope) |
| Directive 2009/29/EC | 23.04.2009 | Extension of EU ETS to other greenhouse gases and activities for Phase 3 |
| Decision 377/2013/EU | 24.04.2013 | “Stop-the-clock” decision for emissions occurring in 2012 (reduced scope) in the EU ETS |
| Regulation (EU) No 421/2014 | 16.04.2014 | Continuation of “stop-the-clock” decision in the EU ETS until December 2016 (reduced scope) |
| Regulation (EU) 2017/2392 | 13.12.2017 | Continuation of “stop-the-clock” decision in the EU ETS until December 2023 (reduced scope) to allow for further assessment and implementation of CORSIA |
| Directive (EU) 2018/410 | 14.03.2018 | Revisions for Phase 4 of the EU ETS |
| Council Decision (EU) 2018/2027 | 29.11.2018 | Position to be taken by EU Member States in respect of the ICAO SARP |
| Commission Implementing Regulation (EU) 2018/2066 | 19.12.2018 | Revision to Commission regulation on the monitoring and reporting to account for MRV provisions in the ICAO SARP |
| Commission Implementing Regulation (EU) 2018/2067 | 19.12.2018 | Revision to Commission regulation on the verification of greenhouse gas emission reports and tonne-kilometre reports and the accreditation of verifiers to account for MRV provisions in the ICAO SARP |

Source: [EPRS, 2018]

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## A.2 Timeline of regulatory development of CORSIA

**Table 13: Timeline of regulatory development of CORSIA.**

| No. | Date | Description |
|---|---|---|
| ICAO Resolution A37-19 | October 2010 | Adopted guiding principles for the design and implementation of MBMs for international aviation |
| ICAO Resolution A38-18 | October 2013 | ICAO and its Member States strive to achieve the goal of keeping the global net $CO_2$ emissions from international aviation from 2020 at the same level (so-called "carbon neutral growth from 2020") |
| ICAO Resolution A39-3 | October 2016 | Decision to implement a GMBM scheme in the form of CORSIA |
| Annex 16, Volume IV, to the Convention on International Civil Aviation | June 2018 | Adoption of the Standards and Recommended Practices for CORSIA |
| ICAO document "CORSIA Emissions Unit Eligibility Criteria" | March 2019 | Definition of eligibility criteria for carbon offset credits under CORSIA |

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## A.3 Details of interview with DG CLIMA

**Table 14: Details of interview with DG CLIMA.**

| | |
|---|---|
| **Interview date:** | 26.06.2019 |
| **Interview location:** | DG CLIMA, Brussels |
| **Interviewee:** | Cheryl Micallef-Borg<br>Policy Officer – Aviation<br>European Commission<br>Directorate-General CLIMATE ACTION<br>CLIMA.B3 International Carbon Market, Aviation and Maritime Emissions |
| **Project team conducting interview:** | Moritz von Unger, Coastlands Climate Policy<br><br>Jonathan Schwieger, First Climate |
| **Interview summary:** | • The significant impact of non-$CO_2$ effects of aviation is recognized and the focus for DG CLIMA for the next year will be on better understanding the science.<br>• In order to address the requirements of Article 30(4) of the EU ETS Directive, the EC is commissioning a study to review scientific |

| | |
|---|---|
| | developments and progress made in the last 10 years around quantification of non-$CO_2$ effects. Preliminary results of the study are expected prior to the January 2020 deadline in the Directive.<br>• On the topic of the ETS / CORSIA interface, the EC has also commissioned a study to assess the various possible permutations for the parallel operation of these two systems.<br>• For the next revision of the ETS, the main foreseen topic will likely be the alignment with ICAO's market-based mechanism. An indicative timeframe for this review would be 2022-2023. |

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## A.4 Overview of key design parameters and options considered in this study

**Table 15: Overview of key design parameters and options considered in this study.**

| Key design parameter | Options | | |
|---|---|---|---|
| **Phasing of the integration** | Instant full roll-out | Phased roll-out: Pilot phase with Member State opt-in followed by full roll-out | - |
| **Timing of the integration** | Full roll-out prior to 2026 | Full roll-out from 2026 (EU ETS benchmarks will be adapted for the 2026-2030 period using 2021-2022 as baseline) | Full roll-out after 2026 |
| **Geographical scope of the integration** | Intra-Member State | Inter-Member State | From and to EEA |
| **Calculation methods** | Distance-dependent factor | Climate-dependent factor | Weather-dependent factor |

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## A.5 Summary of major impacts of key design parameters

**Table 16: Summary of major impacts of key design parameters.**

| **Impact Assessment Criterion** | **Phasing of the integration** | | **Timing of the integration** | | | **Geographical scope of the integration** | | | **Calculation method** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Instant full roll-out | Pilot phase with Member State opt-in followed by full roll-out | Full roll-out prior to 2026 | Full roll-out from 2026 | Full roll-out after 2026 | Intra-Member State | Inter-Member State | From and to EEA | Distance-dependent factor | Climate-dependent factor | Weather-dependent factor |
| 1. Evaluated impact on reducing **consumer demand** for air travel | | | | | | ** | ** | * | * | * | * |
| 2. Evaluated impact on **operator behaviour** to reduce non-$CO_2$ emissions | | | | | | * | ** | ** | / | ** | *** |
| 3. Evaluated impact on **leakage risk** of non-$CO_2$ emissions | | | | | | / | * | ** | | | |
| 4. Evaluated impact on increasing **capped emissions** in the aviation ETS | | | * | ** | *** | * | *** | *** | | | |

"-" no impact, "*" low impact, "**" medium impact, "***" high impact

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