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Playing field for bio-jet fuels

Overview, intercomparison and verification of emission models and calculators and high-altitude impacts

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In cooperation with
SMHI and Novair

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Preface

This report is a final report in project 'Playing field for bio-jet fuels – High altitude-effects and climate efficiency' financed by Swedish Energy Agency within the program 'Sustainable fuels for aviation' which aimed to provide new knowledge and support for decision-making for long-term priorities towards sustainable aviation in terms of commercial introduction of climate effective bio-jet fuels. Results in this project were developed in collaboration between IVL, SMHI, Swedavia, Novair and SAS and the project was supported by the Fossil-Free Flight 2045 cluster in terms of valuable knowledge exchange. The project had also close collaboration with project OP-FLYKLIM (Flight-route optimisation for smaller climate impact) financed by Swedish Transport Administration and Swedish Transport Agency.

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Summary

What emissions and what climate impact does today's aviation have? It is important to create a consensus around this in order to be able to both compare the effects of different fuels and other mitigation measures and to relate the impact of aviation to e.g., other modes of transport. Emissions from aviation are inventoried and reported today at several different levels. Currently the main driver of CO_2 emission inventories are regulations targeting emissions of greenhouse gas emissions. This report provides a brief overview of the methods and data used, which stem from various regulations and initiatives. A number of emission calculators is driven by the demand for data to report climate impact from air travel and freight transport and includes emission or climate calculators that focus on emissions of CO_2 or CO_2 equivalents assigned to a passenger or to volume or mass of cargo on a given route or nominal distance. There is a number of such calculators that use different emission factors, flight parameters, aircraft occupancy and contributions from high-altitude impacts, and thus generate different results. Examples are those of ICAO (International Civil Aviation Organization, 2019), NTM (Network for Transport Measures, 2019), IATA (International Air Transport Association, 2019), Atmosfair (Atmosfair, 2019) or Flight Emission Map (Flight Emission Map, 2019). A survey of data and assumptions that form the basis for aviation greenhouse gas emissions and climate calculators and a validation of these by means of data on reported fuel consumption during flights was carried out in the project. For most of the calculators there is a good agreement with the fuel consumption data when the variability of the fuel consumption due to different aircraft types, occupancy, etc., is taken into the account. Three calculators show substantially higher emissions and an analysis indicates that the reason is that they are using obsolete emission factors. The biggest difference between calculators arise from the calculation of CO_2 equivalents in which case all use radiation forcing index (RFI) as a measure. The study also included a comparison of SMHI's air emission model with fuel consumption data.

The high-altitude effects of SLCP are crucial in minimizing the climate impact of aviation – for combustion engines these effects will remain even with use of fossil-free fuel. The first important questions associated with the high-altitude effects are their quantification and reduction of uncertainties of the climate impact of the SLCP. RFI used by many climate calculators is a blunt tool if the aim is to target the high-altitude effects as such, as it is related solely to CO_2 emissions and the relation to the SLCP radiative forcing is through impact of the historic emissions of aviation up to the date for which the FI is calculated. More appropriate are forward looking metrics considering forcing from actual SLCP species emitted during the flight as global warming potential (GWP) or global temperature potential (GTP). The most important climate forcing components are emissions of CO_2 and formation of contrails and contrail cirrus. Sustainable aviation fuels (SAF) with high hydrogen and low aromatic content emits substantially less soot particles which reduces radiative forcing of the contrails. Model simulations of full implementation of SAF in the current aviation fleet would lead to 20-50 % reduction of RF from contrails and contrail cirrus. A combination of the use of SAF, engine technology with low emissions of soot and NOx and route climate optimisation has the potential to substantially reduce the high-altitude effect.

Sammanfattning

Vilka emissioner och vilken klimatpåverkan har dagens flyg? Detta är viktigt att skapa en samsyn kring för att både kunna jämföra effekter från olika bränslen och andra åtgärder samt för att kunna relatera flygets påverkan gentemot t.ex. andra transportslag. Emissioner från flyg inventeras och rapporteras idag på flera olika nivåer. Den främsta drivkraften för detta arbete är regleringar som är inriktade mot utsläpp av växthusgaser. Föreliggande rapport ger en översikt över metoder och data som används som härrör från olika regleringar och initiativ. En typ av utsläppsberäkningar drivs av efterfrågan på data för att rapportera klimatpåverkan från flygresor och godstransporter och inkluderar utsläpps- eller klimatkalkylatorer som är inriktade på utsläpp av CO_2 eller CO_2-ekvivalenter allokerade till en passagerare och/eller volym eller vikt av gods längs en viss rutt eller nominellt avstånd. En rad sådana emissions- och klimatkalkylatorer finns idag som använder olika emissionsfaktorer, parametrar under flygning, flygplanens fyllnadsgrad och bidrag från höghöjdseffekter och de genererar därmed olika resultat. Exempel är de som tillhandahålls av ICAO (International Civil Aviation Organization, 2019), NTM (Network for Transport Measures, 2019), IATA (International Air Transport Association, 2019), Atmosfair (Atmosfair, 2019) och Flight Emission Map (Flight Emission Map, 2019). En kartläggning av data och antaganden som ligger till grund för klimatkalkylatorer och en validering av dessa med hjälp av emissionsberäkningar och data för bränsleförbrukning under flygningar genomfördes i projektet. Jämförelse av kalkylatorer med bränsleförbrukningsdata visar en bra överenstämmelse för flertalet när variation av utsläpp på grund av olika flygplanstyper, beläggning m.fl. tas i beaktning. Analys av kalkylatorer som visar betydligt högre utsläpp tyder på att orsaken är att dessa använder föråldrade emissionsfaktorer. Största skillnaden mellan kalkylatorer härrör från beräkning av CO_2-ekvivalenter där samtliga använder strålningsdrivnings index (RFI) som mått. Projektet har också omfattat en jämförelse av SMHIs flygemissionsmodell med bränsleförbrukningsdata, även där är överensstämmelse bra.

Minskning av höghöjdseffekter från kortlivade klimatpåverkande föroreningar (SLCP) och flygrelaterade cirrusmoln är avgörande för att minska klimatpåverkan från flyget – för förbränningsmotorer kommer dessa effekter att kvarstå även med användning av fossilfritt bränsle. Viktiga frågor förknippade med höghöjdseffekterna är hur de är kvantifierade och att minska osäkerheter i kvantifieringen. RFI som används av många klimatkalkylatorer är ett trubbigt verktyg för eventuella styrmedel för höghöjdseffekterna som sådana, eftersom RFI enbart är relaterat till CO_2 utsläpp som har skett historiskt. Framåtblickande mått som avser de faktiska SLCP relaterade till flygningen som GWP eller GTP skulle vara mer lämpliga. Utsläpp av fossilt CO_2 och bildning av kondensationsstrimmor är de viktigaste klimatpåverkande komponenterna. Fossilfria bränslen bildar avsevärt färre sotpartiklar vilket minskar strålningsdrivningen av kondensationsstrimmorna. Kombination av användning av SAF, motorteknik med låga utsläpp av sot och NOx och ruttoptimering för minskad klimatpåverkan har potential att i betydande omfattning minska höghöjdseffekten.

1 Introduction

The greenhouse gas (GHG) emissions from the aviation sector and its contribution to global warming has been a subject of intensive discussions in recent years. It is vital to quantify the emissions from aviation and evaluate their climate impact to select the correct measures to lower the emissions. This type of information is important to create a consensus both on being able to compare the effects of different abatement measures in aviation and to be able to relate the impact of aviation to other types of transport. Even though each commercial aircraft collects both instantaneous fuel consumption as well as fuel consumed per flight, uncertainties, or rather discrepancies between different tools for calculation of aircraft emissions are relatively large.

Today, global air traffic accounts for about 2% of total global anthropogenic emissions of fossil carbon dioxide (CO_2) (Lee et al., 2009, ATAG, 2018). Contribution of aviation to global warming in the form of radiative forcing is, however, larger. Lee et al. (2009) estimated it to be about 4.9% when the impacts of the so-called high-altitude effects are accounted. These effects are linked to emissions of substances other than CO_2, so-called short-lived climate pollutants (SLCP) including particles, water vapor and nitrogen oxides (NOx), in the upper troposphere. Their impact on the climate is very complex and dependent on local conditions. However, there is a scientific consensus that they have a net warming effect, although it is still difficult to accurately quantify it. It is also dependent on which time perspective and which metrics are applied (Moldanova et al., 2018). Contribution of the high-altitude effects implicates that climate impact of aviation is complex and cannot be directly reduced by simply replacing fossil fuel with renewables.

Emissions from aviation are frequently discussed in different context, e.g. climate and environmental impact of the entire aviation sector, impact of travel or impact of cargo transport, and it is important that these emissions, even if calculated with different approaches, are consistent. Emissions are calculated or reported with different methodologies from so-called top-down inventories based on sales of jet fuel, over summary reports of fuel consumption per individual flight reported by aviation companies to bottom-up inventories based on detailed modelling of fuel consumption during individual flights combined with air traffic data. To calculate impacts of air traffic, there are many emission and climate calculators, e.g. ICAO (International Civil Aviation Organization, ICAO, 2021), NTM (Network for Transport Measures, NTM, 2021), Atmosfair (Atmosfair, 2021), Flight Emission Map (Flight Emission Map, 2019) and the Climate Account (IVL, 2019), that use different emission factors, flight parameters, occupancy of aircraft and contributions from high altitude effects and they thus generate different results. To be able to compare the methods, it is important to conduct a survey of data and assumptions that form the basis of emission models, emission- and climate calculators along with validation of these methods using fuel consumption during flights from the flight record data. Consistent baseline emission for aviation, regardless if these consider regional emissions from the sector or emissions of passenger-km travel or of ton-km cargo transport, along with understanding of how the high-altitude effects and the climate impact metrices used contribute to the calculated overall climate impact, is of great interest to know how much the aviation industry needs to lower their emissions to reach global and national climate targets. This report provides an overview of different tools used for calculation of aviation emissions along with analysis and validation of an emission model applying methodology of EMEP/EEA air pollutant emission inventory guidebook (EMEP/EEA air pollutant emission inventory guidebook 2019 — European Environment Agency (europa.eu)) and a number of emission and climate calculators. Further it looks at the potential of sustainable aviation fuels to reduce aviation climate impact especially when high-altitude effects are considered.

2 Methodologies of calculation of CO_2 emissions and climate impact

There are several methodologies used for calculation of CO_2 emissions from aviation differing both with purpose of the emission inventory and with who is providing it. Currently the main driver of CO_2 emission inventories are regulations targeting emissions of GHGs. In this chapter we give a brief overview of the methodologies used, stemming from different regulations and initiatives. The first group of methodologies is driven by market-based instruments targeting aviation industry which is based on emission reporting of airlines, in most cases based on their own fuel consumption data. The second group is driven by reporting obligations of parties to the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement. This reporting is typically carried out by national environmental protection agencies and involves flight activity data and emission factors of different levels of complexities. The third group of emission calculations is driven by the demand of data for reporting climate impact of air travel and cargo transport and includes emission or climate calculators targeting CO_2 or CO_2-equivalent emissions assigned to a passenger or volume or mass of cargo on certain route or nominal distance.

As the fuel consumption of each aircraft is recorded continuously during the flight as well as in form of status of its fuel tanks between the flights and further, data for validation of the different emission inventories and calculation tools are plentiful. Further, reliable data on the sales of jet fuel are available at different levels of aggregation. However, even though the data exist it is often confidential. In addition, all route planning systems include accurate calculation of fuel consumption as it is central both for calculation of the mass of fuel needed for a flight as a critical safety parameter, and for optimization of the route. The route planning systems are used by airlines who combine information about the planned route, optimization preferences and number of passengers and cargo mass with information from air traffic control with information provided by the system including, among others, operational meteorological forecast and flight operation parameters of the aircraft. Examples of route planning systems are Sabre, Jeppesen (Boeing), Lido (Lufthansa systems), Navblue (Airbus), Fltplan.com or Skyplan services.

Due to the complexity of the different reporting systems and different origin of emissions or fuel consumption assumptions there, the emission inventories and calculators are not always consistent, as such large differences between their results may occur. Intercomparison and cross-validation with logged data is therefore useful. The focus of this part of the project is to evaluate and compare different calculation methods of GHGs for both airlines/air travel and reporting tools. First a presentation of the regulation surrounding aviation and calculation of GHGs will be made. Thereafter, different systems will be presented in short with the correlated method used to calculate GHGs.

2.1 Regulations for aviation - calculation of air emissions

Aviation is one of the fastest-growing sources of GHG emissions. In the recent years, new policy and technological development of the industry has led to improvement of fuel efficiency in the aviation sector; between 2005 and 2017, the average fuel burn per passenger kilometre flown for passenger aircraft, excluding business aviation, went down by 24% (https://www.easa.europa.eu/eaer/topics/overview-aviation-sector/emissions). The growth of air traffic has however eclipsed these positive results. In year 2017, passengers flew on average 60% further compared to 2005 (https://ec.europa.eu/clima/policies/transport/aviation_en). In 2017, aviation was responsible for 3.8% of the total CO_2 emissions and 13.9% of all transport-related emissions (second biggest after road traffic emissions). Before Covid-19 breakout, ICAO had predicted that in 2050, emissions from international aviation could be the triple of those in 2015. In addition to being responsible for direct CO_2 emissions, aviation impacts the climate through several non-CO_2 GHG emissions: nitrogen oxides, water vapour, sulphate and soot particles (at high altitudes). The climate effects of non-CO_2 emissions from aviation are nowadays considered at least as important as CO_2 alone (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:747:FIN).
To achieve climate neutrality, huge reductions of GHG emissions are needed in near future in all sectors and the aviation sector will have to contribute to this reduction. E.g. the European Green Deal sets out the need to reduce transport emissions by 90% by 2050 (compared to 1990-levels). As aviation is, similarly to large extent regulated on the international level, policy actions on national and regional level have limited impact and regulation through international legislation is necessary. With this said, in the at current situation the national and regional policy actions have an important role in moving the process forward and defining the ambition levels. This chapter gives an overview of international regulations for aviation and introduces important international organisations steering the sector.

2.1.1 International Civil Aviation Organization (ICAO)

ICAO is an UN agency funded and directed by 193 national governments to support their diplomacy and cooperation in air transport as signatory states to the Chicago Convention

(1944). ICAO works with the Convention's Member States and industry groups to reach consensus on international civil aviation Standards and Recommended Practices (SARPs). They also work on policies in support of a safe, efficient, secure, economically sustainable and environmentally responsible civil aviation sector.

2.1.2 Eurocontrol

The European Organisation for the Safety of Air Navigation (Eurocontrol) is a pan-European, civil-military intergovernmental organisation dedicated to support safe and seamless air traffic management across Europe. Eurocontrol supports EU Member States and air navigation service providers, civil and military airspace users, airports and aircraft/equipment manufacturers to make aviation in Europe safe, efficient, cost effective and with minimal environmental impact. The organisation was founded in 1963 and has two governing bodies: The Permanent Commission and the Provisional Council. The agency is the executive body. To be considered for membership of Eurocontrol, a country must be member of the Council of Europe and have accreditation to ICAO. Eurocontrol supports the aviation sector to ensure reporting accuracy for the two instruments designed to contribute to addressing the climate impact of aviation: the EU's Emissions Trading System (ETS) and ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).

2.1.3 CORSIA

All ICAO member states agreed in year 2010 on a resolution to manage the climate impact of aviation with three goals: improved fuel efficiency, carbon neutral growth from 2020 and a global standard for carbon dioxide emissions. In 2013, ICAO decided to develop a global market-based instrument to regulate the climate impact of international aviation and in 2016, the ICAO General Assembly decided on introduction of the global market-based instrument CORSIA. ICAO can only regulate flights between different countries and the system therefore covers international flights only. CORSIA is valid between 2021-2035 and is implemented in three phases: pilot phase (voluntary, 2021-2023), first phase (voluntary, 2024-2026); and second phase (mandatory, 2027-2035).
In short, the system means that the international aviation's carbon dioxide emissions can grow until 2020. Thereafter airlines must buy emission credits and thereby compensate for emissions exceeding the 2020 level.

The emissions that the airlines are required to compensate for are initially based initially on how emissions from international aviation develops in its whole. It is only the emission increase from the baseline that an airline company must compensate for. If emissions from international aviation grow with 4 percent between 2021 and 2022, every airline participating in the system must buy emission credits for the equivalent of 4 percent of its emissions in 2022. This regardless of whether the airline's emissions increase more or less than 4 percent. From 2032, the airlines will be committed to compensate for their emissions based on their individual emissions. The system only covers CO_2 emissions and not the high-altitude effects.

CORSIA begins with two voluntary phases: a pilot phase between 2021 and 2023 and a first phase between 2024 and 2026. CORSIA will be mandatory to participate in from 2027 for states that have a share in international aviation above 0.5% of total Revenue Tonne Kilometres (RTKs). Least developed countries, small island developing states, and developing countries without coasts are exempted from participation unless they volunteer to participate. However, the countries excluded countries must still report their emissions within the system. In July 2021, 106 states which account for almost 77 percent of international air traffic, have joined the scheme already for the first phase. When the system becomes mandatory from 2027 several other states will be joining, e.g. China, India and Russia. The system will be reviewed every three years from 2022. The review may result in new decisions on for example whether CORSIA should take the Paris Agreement's goals into account. A special review will be conducted in 2032 to decide if the system should discontinue or continue with the current or a new design.

In June 2020, ICAO Council decided that, in response to the Covid-19 pandemic, during CORSIA's pilot phase (2021-2023), 2020 baseline emissions would be replaced by 2019 emissions (https://www.icao.int/environmental-protection/CORSIA/Pages/corsia-newsletter-may21.aspx).

2.1.4 EU ETS

The European Green Deal states the need to reduce transport emissions by 90% before 2050 (compared to 1990 levels) in order to achieve climate neutrality. In the Nationally Determined Contribution (NDC), the EU and its Member States committed to an overall target to achieve in 2030 a 40% reduction of GHGs emission relative to the year 1990. In order to achieve this reduction, the European Commission has calculated and proposed to cap 2030 emissions from flights departing from the EU at 111 Mt CO_2 (https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets).

The purpose of the European Union emissions trading system (EU ETS) is to provide emitters with incentives to reduce their fossil emissions. Aviation was included in the EU emission trading system in 2012, initially covering all flights to and from EU airports. Due to significant international and industry pressure, the scope of the system was reduced to cover only intra-EU flights and flights within the European Economic Area (EEA) in order to give time to for ICAO to agree on a global measure. The global offsetting scheme CORSIA was adopted by ICAO in 2016. In Sweden, CORSIA has been received by environmental NGO's with scepticism and the Swedish Environmental Protection Agency (SEPA) is critical as the aviation industry does not need to lower their emissions over time, having severe doubts about its potential effectiveness (https://www.dn.se/nyheter/sverige/oklart-om-sverige-protesterat-mot-flygets-klimatkompensation/). The exclusion of flights to and from Europe in the ETS was extended until 2024. By that time, it is decided that EU ETS for aviation will be subject to a new review in the light of the international developments related to the operationalisation of CORSIA (https://ec.europa.eu/clima/eu-action/transport-emissions/reducing-emissions-aviation_en). There are several different possible scenarios for the future coexistence of CORSIA and EU ETS in Europe, but the situation is still unclear.

EU ETS is based on the principle that each year, polluters have to submit a number of emissions permits equal to the amount of CO_2 they emitted in the previous year. Polluters acquire permits through an annual allocation system, and a part of these permits are issued by member states for free. If an airline company (or any company included in the system) does not have enough allowances to clear its previous year's emission, it can purchase additional permits at auction from the surplus of other companies. The EU decides a maximum cap for the CO_2 that can be emitted by restricting the number of permits available on the market. The available permits are limited and progressively decreasing due to an annual reduction of the maximum cap. In this way, when the price of the permits goes up, companies have an economical incentive in reducing their emission since doing so would be cheaper than buying emission permits.

Until 2019, the ETS has not resulted in a reduction of CO_2 emissions from aviation. One of the main reasons for this is thought to be the over-allocation of permits which caused a price decrease of the allowances. With cheap permits, airlines have unlimited access to ETS allowances resulting in no growth limitations. In the year 2017 reforms to the ETS were introduced resulting in price increase. Still in 2019, unlike other sectors included in the EU ETS, aviation emissions had a growth rate estimated around 1.5 %. This can be explained by that the market price is still far from the price level that could drive significant reductions. It is also because the number of allowances that annually is removed is insufficient. The Covid-19 crisis resulted in a decrease of emission in 2020 but emissions are expected to grow again if stringent measures will not be put in place once the crisis will be overcome. The European Commission is now proposing to revise the ETS aviation rules to help ensure that the sector contributes to the more ambitious target of achieving net emission reductions of at least 55% by 2030, compared to 1990 levels. The number of free allowances allocated to aircraft operators is planned to be reduced progressively to reach full auctioning by the year 2027 (https://www.transportenvironment.org/what-we-do/flying-and-climate-change/aviation-ets).

After the implementation of CORSIA (from the year 2021 onwards), the question will be if and how the EU ETS for aviation might be adjusted. The international intra-EEA flights, which are now covered by the EU ETS, will in principle also be included in CORSIA. Under the proposal, the Commission will apply CORSIA to flights that are outside the EU ETS and depart or arrive in countries which apply CORSIA. Emissions from these flights will be offset once collective international emissions exceed 2019 levels. Domestic intra-EEA flights can only be subject to the EU ETS, because CORSIA can only cover international aviation.

2.1.5 Emission reporting of airline operators

The airline operators have administrative domicile in the country in which they are registered. Airline operators registered in Sweden report to the Swedish Environmental Protection Agency. Since CORSIA and EU ETS have several common features EU has chosen to use the framework for reporting that already exists for EU ETS with some adaptations towards what has been decided within CORSIA agreements.

Swedish based airline operators that are covered by the obligation to monitor emissions must have a monitoring plan approved by SEPA. The template for the monitoring plan is common to the EU ETS and CORSIA and is an excel file available in the national EPAs' websites. The emission report template is common to the EU ETS and CORSIA. SEPA provides a unique template for reporting emission for ETS and CORSIA. The reporting is based on real gate to gate fuel consumption data that airline companies collect. Small airlines that emit less than 25 000 tonnes of CO_2 per year can use Eurocontrol's Small emitters tool (SET) in order to calculate their fuel consumption and CO_2 emissions.

2.2 Models and tools for calculation of aviation emissions

For many years the International Civil Aviation Organisation (ICAO) has been involved in establishing procedures and setting standards to control aircraft engine emissions. Nowadays there are several other UN policy-making bodies with a legitimate interest in the emissions generated by civil aviation. These are UN Framework Convention on Climate Change (UNFCCC), the Montreal Protocol on Substances that Deplete the Ozone Layer and the Convention on Long-range Transboundary Air Pollution (LRTAP convention) accessed by member states of the UN Economic Commission for Europe (ECE). Each of these agreements seeks to address specific environmental problems caused by certain man-made emissions including aviation as one of the many sources of such emissions and maintain an ongoing interest in the amount of emissions produced by civil air traffic. For the UNFCCC and the UNECE, this interest is expressed in the obligation for Member States to report their domestic emissions from aviation to these bodies. Guidelines have been developed to assist States in compiling their national inventories (ECAC, 2003).

Within the UNECE a methodology has been developed to support countries that participate in the European-wide emission inventory programme EMEP/CORINAIR. Aviation is part of Group 8 “Other mobile sources and machinery”. The convention deals with the following pollutants: SO_2, NOx, NMVOC, CH_4, CO, CO_2, N_2O, NH_3, heavy metals and persistent organic pollutants (POPs). For the UNECE (LRTAP convention), emissions from landing and take-off operations (LTO, below 3 000 ft = 914 m) are considered being a part of the national inventory of the country concerned. Emissions from cruise are considered international emissions. The only exception is CO_2, which must be reported according to UNFCCC requirements. The UNFCCC requires all Parties to develop national inventories of GHG emissions. It deals with the same pollutants as UNECE with exception of NH3 and additionally with HFC's, PCF's and SF6. The IPCC has established guidelines for producing national inventories for emissions (Revised 1996 IPCC Guidelines for Greenhouse Gas Inventories, Vol 1, 2, 3; 1997). The methodology in the IPCC Guidelines has been further elaborated in the IPCC report “Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories” For the UNFCCC, emissions of domestic flights are considered to be part of the national inventory of the country concerned. With respect to emissions of international flights (often referred to as 'emissions from aviation bunker fuels'), there is ongoing discussion on how to allocate these emissions to national inventories. Currently the practice recommended to Parties is to collect information on international aviation emissions and submit it to the UNFCCC along with their national inventory, but not included in their national totals of GHG emissions.

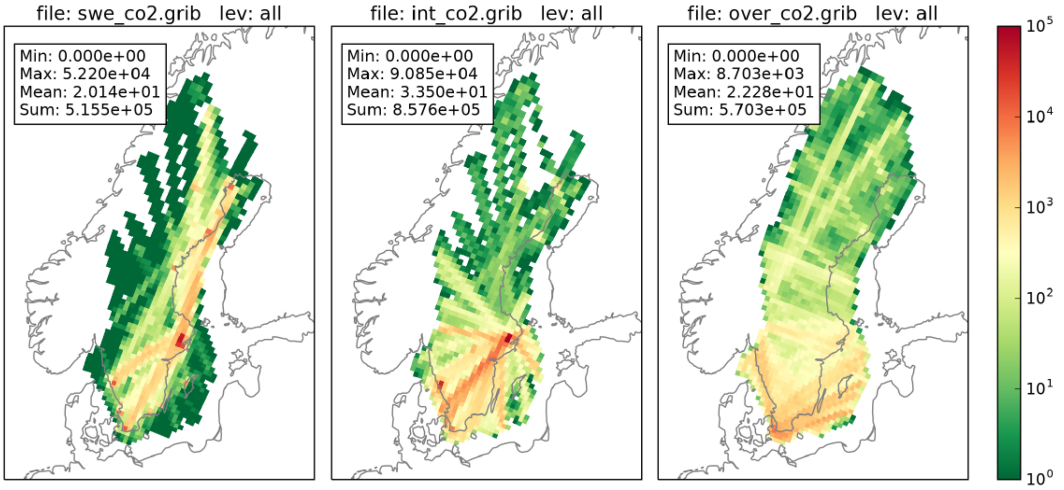
Depending on the methodology chosen for reporting (Tier 1 - Tier 3) the emission reporting can be based on fuel sales and average emission factors without distinguishing technology used or at which altitude the emissions were inserted (Tier 1 methodology with single emission factor and 10% fuel used in the LTO cycle), or on more accurate Tier 2 methodologies where emissions below and above 1000 m (3000 feet) are calculated separately, either with aggregated mean emission factors or calculated with an aircraft-based method deploying model calculations utilising flight activity data and emission factors for different aircraft types, flight phases, aircraft weight etc. The most accurate Tier 3 methodology is then based on actual aircraft movements, either between the airports or as actual flight trajectories. The reporting is typically carried out by national environmental protection agencies under the EU Climate Monitoring Mechanism according to the Emissions inventory guidebook and further compiled by European Environmental Agency (EEA). To harmonize the national emissions the EU emissions have also been recently calculated by Eurocontrol utilizing real flight data and its Advanced Emissions Model.

In Sweden aviation emission calculation for the UNFCCC reporting is commissioned by Transport Administration to the Swedish Defense Research Agency (FOI) which applies its own FOI3-method (Mårtensson and Hasselrot, 2013) for these calculations. This method uses the software Piano (www.lisys.uk) for parametrical studies of aircraft design containing a database with technical data for the majority of aircraft operating in Sweden as a basis for emissions calculation. Emissions are calculated for a variety of simplified flight trajectories where Piano utilizes emission factors from ICAO's engine exhaust emission database (EASA, 2021) and other sources, considering also the cabin factor. The calculations are combined with air Swedish air traffic data in a database tool called Hurdy-Gurdy to calculate total and LTO-cycle aviation emissions of CO_2, CO, SO_2, NOx, CH_4, NMVOC, and N2O from aviation in Sweden.

2.3 Gridded aviation emissions in Swedish air space – SMHI flight emission model

The SMHI flight emissions model, Leung et al. (2018) was developed in order to report yearly gridded flight emissions for the Swedish national emission inventory (SMED). The model is used to calculate the vertical distribution as well as geographical distribution of emissions from both domestic and international flights for various chemical components. The SMHI model is complementary to the FOI3-method which does not provide a spatial distribution of the emissions. For consistency in the reporting, total emissions from the SMHI model are scaled to the results from the FOI3-method on a yearly basis.

The SMHI model considers not only flight statistics from each Swedish airport; for example, the number of flights flying to and from each Swedish airport, but also detailed information on the movements of various aircrafts on different routes using position data from Flightradar24. The model distinguishes between three flight 'nationalities'; whether the flight is domestic (both departs and arrives at Swedish airports), international (departs and arrives at one Swedish and one foreign airport) or overflight (both departs and arrives at foreign airports). The model then categorizes the emissions by which altitudes they are emitted; landing and take-off (LTO) below 1000 m, low cruise between 1000 and 10,000 m, and high cruise at above 10,000 m. Emission factors are extracted from the EMEP/EEA air pollutant emission inventory guidebook (European Environment Agency, 2019, 1.A.3.a Aviation). Further details about the methods used in the SMHI flight emission model are given in Appendix I. As an example, Figure 2.1 shows gridded CO_2 emissions from aviation in Swedish air space for year 2014 calculated using the SMHI flight emission model.



(a) Domestic *(b)* International *(c)* Overflights

Figure 2.1. Gridded CO_2 emissions from aviation in Swedish air space for 2014 aggregated for all vertical levels for a) Domestic, b) International and c) Overflights. Units: t/yr.

2.4 Passenger- or freight-specific emissions

To assess the impact of travel or cargo transport, emissions need to be assigned to passenger or mass unit of cargo transported on the route or per transported distance. Occupancy of the cabin by passengers and/or cargo is an important parameter when calculating this type of emission numbers. A specific emission is the total emissions divided by number of passengers or mass of cargo transported. As described in section 2.2 the load factors are also used in calculation of total fuel used during the flight with more sophisticated calculation methods, in this case the correlation is positive and non-linear.

The passenger load factor is a metric used in the airline industry and indicates the percentual share of the available seats in an aircraft that has been filled with passengers. A high value is preferred over a low load factor since it lowers single passenger CO_2

emissions, and it implies that the airline has sold most of the available seats. According to the International Air Transport Association (IATA)[1], the average load factor in Europe in pre-covid 2019 was around 85% (https://www.iata.org/en/pressroom/pr/2020-02-06-01/).

The methodology to calculate and allocate CO_2 emissions to passengers has been developed by ICAO. This methodology is also recommended by IATA for its Carbon Offset Program (https://www.iata.org/contentassets/34f5341668f14157ac55896f364e3451/rp-carbon-calculation.pdf). To assess the passenger's aviation emissions, it is necessary to subtract the flight emissions associated with the freight and mail carried on the flight from the total, the so-called Passenger to Cargo Factor. With ICAO's methodology this calculation is performed on a revenue mass basis using historic freight and mail numbers specific to the city-pair being considered, proportion between the cargo- and passenger-assigned emissions being based on proportion of the cargo mass to the mass of passengers plus their luggage and passenger-related infrastructure (seats, galleys, cabin crew e.c.t.) which according to ICAO is 150 kg.

In ICAO's methodology the cabin class correction factor includes consideration that premium seats on long-haul flights occupy a larger space than economy seats. To define the cabin class correction factor, to each representative type of aircraft that support such differentiation has been assigned a standard all-economy class layout so that the reduced capacity resulting from the larger space occupied by premium seating and the associated increase in per-passenger emissions is accounted for. While it is not possible to account for all possible configurations of a given aircraft, generic cabin class factors have been estimated to educate the users about the environmental effect of their travel decisions. The methodology employs a simplified approach by using two cabin class factors ("economy" and "premium") when allocating emissions to passengers, with a ratio of 1:2 on long-haul flights. This means that for flights longer than 3 000 km, CO_2 emissions per passenger in premium cabin are twice the CO_2 emissions per passenger in economy class cabin (ICAO, 2018).

2.5 Sensitivity of emissions to different parameters

This section provides a short description of the principal factors that define the carbon footprint of an individual and that compose an aviation emission model striving for accuracy.
The reasoning is partially based on ICAO Carbon Calculator's methodology (ICAO, 2018)

Great Circle Distance (GCD)
The flown distance is an essential parameter when calculating fuel consumption of a specific flight. GCD is a way for of calculating flight distance as if the distance between

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[1] IATA is the trade association for the world's airlines, representing c.a. 290 airlines

two airports was equal to the shortest distance between two points on the surface of a sphere. Despite being an approximation, since air travel does not occur along a straight line between two points on the Earth surface, the lack of a statistic database or the access to more accurate flown distance data make this method necessary and still relevant.

Representative Aircraft – Calculators (such as ICAO's carbon calculator) draw from a database the most common aircraft flying a specific route and then match the resulting models to the performances of similar representative aircraft model(s). This assumes that aircraft designed for a similar operation also have similar performance characteristics. Due to the large amounts of details and the complexity level of the technical specifications of aircraft the adoption of representative aircraft is a reasonable approach when looking at performance characteristics of models designed for similar operation. Factors such as age, airline specific configuration of the aircraft and engine model can have a further impact on the fuel consumption within aircraft belonging to the same aircraft type variant.

Cabin Class Factor
An airline can choose to customise the seat configuration of an aircraft offering more or less space to its passengers and different classes of service. Calculators generally do not use specific aircraft seat-configuration, and tackle this issue using the "equivalent aircraft approach". Most of the calculators offer in fact the possibility to select among a simplified list of cabin classes (most commonly economy or business, but in some cases also premium-economy and first). The choice of the cabin factor has an impact on the allocation of the space per passenger, influencing the total number of seats and hence the passengers' share of fuel consumed per flight.

Passenger Load Factor
In section 2.4 was mentioned the importance of the passenger load factor on the allotment of a passenger's emissions. Emissions calculators use average passenger load factors calculated on a route group basis for international flights and on a regional basis for domestic flights. The values are obtained from the reported data sent by member states to ICAO or collected from the industry by IATA and tend to evolve with every annual update.

Passenger to Cargo Factor
Since cargo and mail freight can occur on commercial passenger flights (especially on long-haul designed aircraft), when assessing passengers' aviation emissions, it is necessary to deduce the share of the fuel consumption (or flight emissions) that are associated with the cargo (carried freight or mail) from the total fuel consumption. This in order to avoid attributing the extra fuel consumption to the passengers. This can be done by calculating *pax-to-freight factors*, which are ratios calculated from ICAO statistical database based on the number of passengers and the tonnage of mail and freight transported in a given route group. The pax-to-freight-factor is applied to the weight of the total fuel consumed in order to deduct the share of the fuel that is allocated to the freight. If a calculator does not have this adjustment, the fuel consumption is distributed entirely among the passengers, resulting in possible overestimations.

Fuel consumption per aircraft type

Detailed information about different airlines fuel consumption and efficiency performance are generally not publicly available. Due to this, calculators have to compute a flight emission choosing the aircraft fuel efficiency from database containing estimated aircraft performances. ICAO's calculator is based e.g. on publicly available information and can estimate fuel consumption from a pool of 312 aircraft groups currently on duty. An outdated or an obsolete calculator, based on dated fuel efficiency statistics could result in possible overestimations if the actual aircraft used is compared to an older model that used to fly the same route. The aircraft choice is one of the most important factors that influences the most the fuel consumption figures. The most modern aircraft are 15-20% more fuel efficient of compared to the models built 10-15 years ago.

Weather and wind conditions

As it will be shown in chapter 4, especially wind conditions can have a significant impact on the fuel consumed during a flight. This variation is not considered when calculating emission with a regular aviation carbon footprint calculator specifically, however, in some calculators the specific fuel consumption has been verified with actual and in that case the mean influence of weather conditions is included. An important part of route planning is optimisation of the route to save fuel and time, hence each commercial flight is planned utilizing weather forecast to get favourable winds and avoidance of dangerous weather conditions.

Other influences

The fuel consumption on a flight is affected also by choices of the operator during the route planning and execution. Even though time of the flight and fuel consumption are highly correlated, route optimisation prioritising to lower the flight time results in use of more engine power and hence higher fuel consumption comparing to optimisation for minimum fuel consumption. Here the driver of the choice is the relation between the operational cost of the aircraft per time unit and the fuel cost. There are additional factors influencing the route planning including differentiated costs for use of airspace and flight restrictions.

2.6 Climate impact of a flight – CO_2 or CO_2e

In addition to emissions of fossil CO_2, aviation affects the climate through other mechanisms that involve emissions of water vapour, soot and other particles, formation of contrails and NOx emissions. These other effects are often shortly called high-altitude effects and the radiation-forcing compounds have got a common name short-lived climate-forcing pollutants (SLCP). SLCP are emitted by both land-based emission sources, shipping and aviation; effects of SLCPs emitted from aviation are, however, particularly important as their impact in the tropopause region, where most of the aviation emissions occur, is much higher than at the Earth surface. An important reason for this - but not the only one - is that aviation emissions take place above the surface mixed layer, which means that they reside longer in the atmosphere and are not included in the natural water cycle with fast turnover rate. Below is an overview of processes associated with impact of aviation on climate:

- CO_2 emissions (warming).
- Emissions of water vapor at high altitude (warming).
- NOx emissions leading to ozone formation in the troposphere (warming).
- Emissions of NOx which via atmospheric chemical processes lead to the decomposition of methane in the atmosphere (cooling), which in turn causes a reduction of tropospheric ozone over a long-time horizon (cooling); reduction of methane also leads to reduction of water vapor over the same time horizon (cooling, Grewe et. al., 2014).
- Emissions of soot particles cause direct positive radiation forcing (warming)
- Formation of sulphate particles from the sulphur in the jet fuel causes direct negative radiation forcing (cooling).
- Formation of persistent contrails after the aircraft contributes with both positive (warming) and negative (cooling) radiation forcing, but the overall effect is positive (warming).
- The formation of cirrus clouds from scattered contrails contributes, like contrails, with both positive and negative radiation forcing with a net warming effect.
- Soot particles from aircraft can affect cirrus clouds also by seeding the clouds, i.e., particles act as extra condensation nuclei for cloud droplets, the magnitude and also the direction of impact of that effect is however very uncertain. A recent study (Kärcher et al., 2021) rules out importance of this impact.
- Soot particles from aviation contribute to warming also indirectly, through deposition on ice and snow in the Arctic (Jacobsson et al., 2012).

For climate systems that are in equilibrium, i.e., if the concentration of greenhouse gases is constant or increases at a steady rate, a linear relationship between global mean temperature change at the earth's surface ΔTs and radiation forcing perturbation ΔF applies:

$$\Delta Ts = \lambda * \Delta F$$

Where λ is the climate sensitivity parameter that for long-lived greenhouse gases was earlier assumed to have a constant value (which can differ between different climate models). Later research has shown though that λ varies with the type of radiation forcing, especially if it is inhomogeneous. This also applies to radiation forcing from aviation-related ozone, contrails and cirrus clouds, and a review by Lee et al. (2010) presented differences in climate sensitivity for these aviation-related compounds (*i*) in terms of their efficacies, i.e. ratio $\lambda_i / \lambda_{CO2}$. More recent studies adopted the concept of Effective Radiative Forcing (ERF) where the radiative forcing of the compound is adjusted for changes in the troposphere that occur directly due to the changes in radiative forcing without mediation by the global mean temperature change (Sharewood et al., 2015). Due to this adjustment the climate sensitivity of the system does not differ between the different compounds. Figure 2.2 presents ERF of the different compounds related to emissions from aviation released to atmosphere between years 1940 and 2018 published in a recent review of Lee et al. (2021). Their estimate of the 2018 ERF from aviation is 100.9 (70 – 229) mW/m^2 (with 5–95% confidence interval) and ERF of aviation CO_2 only (equal to RF) is 66.6 (21 – 11) mW/m^2.

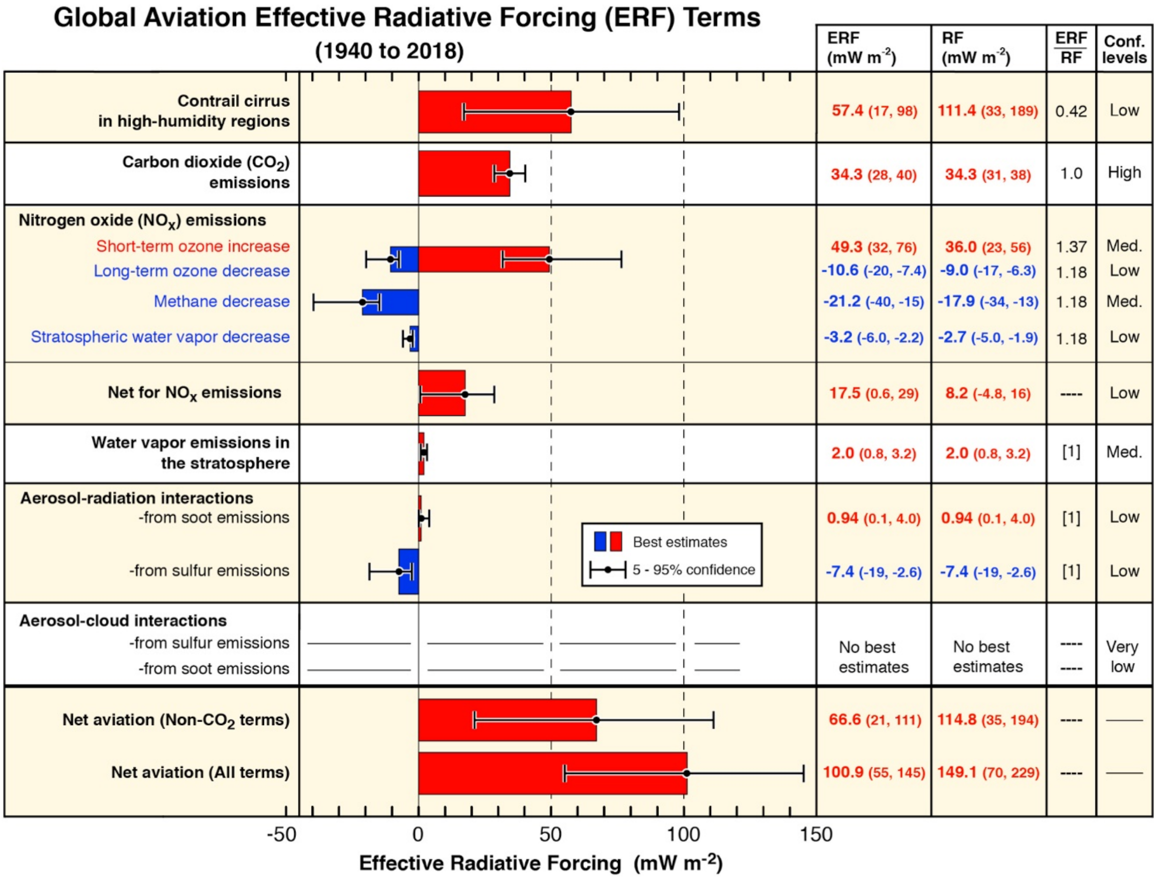

Figure 2.2. Best-estimates for climate forcing terms from global aviation from 1940 to 2018. The bars and whiskers show ERF best estimates and the 5–95% confidence intervals, respectively. Red bars indicate warming terms and blue bars indicate cooling terms. Numerical ERF and RF values are given in the columns with 5–95% confidence intervals along with ERF/RF ratios and confidence levels. RF values are multiplied by the respective ERF/RF ratio to yield ERF values. ERF/RF values designated as [1] indicate that no estimate is available yet and the arbitrary value of ERF/RF = 1 is used. From Lee et al., 2021, their Figure 3.

Different metrics are used to assess the climate impact of emissions. The Kyoto Protocol uses Global Warming Potential (GWP) with several time horizons as metric. GWP is RF of a greenhouse gas normalized with RF from the same mass of CO_2, both accumulated over the time horizon in question. Given the complex relationship between radiation forcing and temperature for different radiation forcing compounds, GWP has occasionally been criticized, but the general acceptance and further development of the concept means that it is today widely used even for SLCP. To capture impact of emissions on global mean temperature, the metric Global Temperature Potential (GTP) has been developed. This metric, in similarity with GWP, also uses different time horizons, the impact, however, shows the final impact at the end of the horizon. Even though the temperature response reflects a cumulative impact of RF over the time horizon, GWP and GTP for SLCP are very different. Both GWP and GTP can be expressed both as values relative to the corresponding mass emission of CO_2 or as absolute values in mW/m^2 and K, respectively. GTP can in some cases also address temperature response of the entire scenario instead of pulse emission of certain mass. Table 2.1 shows GWP and GTP on different time horizons and corresponding CO_2-equivalent emissions for the ERF components of 2018 aviation emissions and cloudiness, and in the bottom part also the CO_2-equivalent emissions based on these metrics.

Table 2.1. Emission metrics GWP and GTP with different time horizons Δt and corresponding CO_2-equivalent emissions for the ERF components of 2018 aviation emissions and cloudiness. E^*CO_2e arises from a simpler GWP method which defines the average annual rate of CO_2-warming-equivalent emissions (E^*CO_2e) over a period of Δt years arising from a particular component of ERF as a rate of CO_2 emission that would, alone, create the same rate of global temperature increase as the combined effect of aviation climate forcing's (from Lee et al., 2021)

Metrics						
ERF term	GWP_{20}	GWP_{50}	GWP_{100}	GTP_{20}	GTP_{50}	GTP_{100}
CO_2	1	1	1	1	1	1
Contrail cirrus (Tg CO_2 basis)	2.32	1.09	0.63	0.67	0.11	0.09
Contrail cirrus (km basis)	39	18	11	11	1.8	1.5
Net NOx	619	205	114	-222	-69	13
Aerosol-radiation						
Soot emissions	4 288	2 018	1 166	1 245	195	161
SO_2 emissions	-832	-392	-226	-241	-38	-31
Water vapor emissions	0.22	0.1	0.06	0.07	0.01	0.008

CO_2-eq emissions (Tg CO_2 yr^{-1}) for 2018							
ERF term	GWP_{20}	GWP_{50}	GWP_{100}	GTP_{20}	GTP_{50}	GTP_{100}	GWP^*_{100} (E^*CO_2e)
CO_2	1 034	1 034	1 034	1 034	1 034	1 034	1 034
Contrail cirrus (Tg CO_2 basis)	2 399	1 129	652	695	109	90	1 834
Contrail cirrus (km basis)	2 395	1 127	651	694	109	90	1 834
Net NOx	887	293	163	-318	-99	19	339
Aerosol-radiation							
Soot emissions	40	19	11	12	2	2	20
SO_2 emissions	-310	-146	-84	-90	-14	-12	-158
Water vapour emissions	83	39	23	27	4	3	42
Total CO_2-eq (using km basis)	4 128	2 366	1 797	1 358	1 035	1 135	3 111
Total CO_2-eq/CO_2	4	2.3	1.7	1.3	1	1.1	3

Concept of RF of aviation emissions as instantaneous RF caused by historic emissions (from year 1940 onward) in certain year has been introduced by the IPCC report 'Aviation and the Global Atmosphere' (IPCC, 1999). This concept is also used for the metric used by many climate calculators for air travel – the Radiation Forcing Index (RFI), in which the RF from all aviation emissions is normalized with RF of aviation CO_2. RFI is a relevant metrics that is separate from GWP, it is, however, often confused with GWP for aviation's SLCP. An important property of RFI is that the denominator, RF of CO_2, would change over time as the emitted CO_2 accumulates in atmosphere even if emissions would keep constant. When used for assessment of concrete travel or flight, one also needs to be aware of that RFI reflects impact of the global aviation fleet and doesn't have a connection to the mass of SLCP on an individual level. Figure 2.3 shows ERF of different aviation forcing terms calculated by a climate model for the period 2000-2018 from Lee at al. (2021).

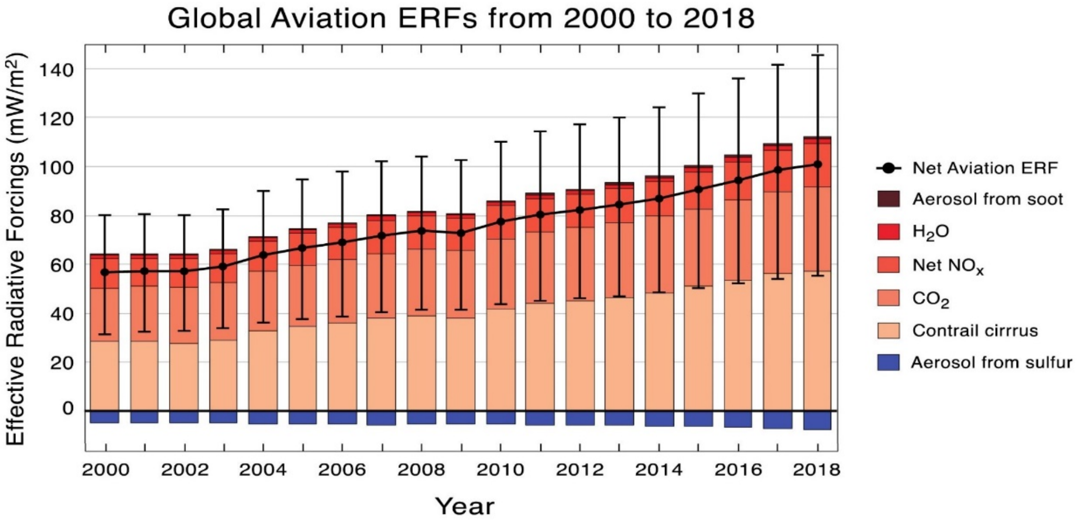

Figure 2.3. Timeseries of calculated ERF values and confidence intervals for annual aviation forcing terms from 2000 to 2018. The net values are not arithmetic sums of the annual values because the net ERF requires a Monte Carlo analysis that properly includes uncertainty distributions and correlations (from Lee et al, 2021, their Figure 6, upper panel).

2.7 Climate impact of a flight with sustainable aviation fuels (SAF)

Table 2.1 shows that regardless of the metric used, the contrail cirrus is the aviation's major climate forcing agent. The magnitude of the forcing depends on its optical thickness. For a given supersaturation level important parameters affecting the optical thickness is the number of emitted soot particles which serve as condensation nuclei for ice crystals (Kärcher and Voigt, 2017; Kleine et al., 2018). Kärcher and Voigt (2017) have shown that large decrease in emissions of soot particles' number is needed to achieve significant reductions in RF while smaller decreases are compensated by background particles and do not show proportional decreases in RF. Several measurement campaigns have shown that combustion of sustainable aviation fuels (SAF) with higher content of hydrogen and lower content of aromatic hydrocarbons produce significantly lower (by 50-70%) number concentrations of soot and ice particles in plume and ice crystals with increased size than standard jet fuels (Schripp et al., 2017, Voigt et al., 2021). In a modelling study, Burkhardt et al. (2018) have shown that 80% decrease in initial ice crystal number concentrations leads to a decrease in contrail cirrus RF by 50%, whereas

50% reduction leads to a decrease in RF by approximately 20%. Use of SAF has thus potential to successfully mitigate large part of the RF from aviation.

The second mitigation option is route optimisation for minimum climate impact avoiding flying in regions with high and stable ice supersaturation having a high potential for formation of persistent contrails. To mitigate contrail induced warming of the climate, it is not efficient to avoid all persistent contrails as some are even causing cooling. Avoiding only those ones that produce individually the largest warming would be sufficient to largely eliminate the overall climate effect of persistent contrails. For instance, in a study using data from six weeks of air traffic in Eastern Asia, Theo et al. (2018) demonstrated that only about 2% of all flight distances contribute 80% to the total EF of all flights together. Use of SAF will reduce RF of the contrails which will have impact on climate optimisation, combination of both mitigation options has a potential to largely decrease climate impact of aviation.

In the project OP-FLYKLIM a methodology for identification of regions with potential for formation of persistent contrails with high radiative forcing was developed, based on meteorological forecast data and route planning system of Novair. Original and climate optimised routes are calculated by Novair on days with occurrence of potential for contrails with high RF along the route. The RF calculation involves calculation of contrail optical thickness and thus allows for calculation of alternative RF for SAF based e.g., on data from Voigt et al. (2021). To date, the system has been tested during several months in spring 2020 for avoiding regions with ice supersaturation and only for a few routes with calculation of RF of potentially formed contrails. In the next step the route climate optimisation will be tested for a period of several weeks while also RF of contrails from aircraft using SAF will be calculated.

2.8 Overview of emission and climate calculators

In this report 15 different passenger-specific emission and/or climate calculators are described. The intention is to see what similarities and differences can be observed based on the information found in the methodology descriptions or on the websites of the emission calculators. A summary of the features of calculators is presented in Table 2.2, while a more descriptive overview of the methodologies of the analysed calculators follows in the Appendix II.

Table 2.2. Overview of the assessed flight emission calculators most common features.

Calculator / Feature	ICAO	Carbon footprint	Finnair	Lufthansa	SAS	Utsläppsrätt.se	GreenSeat	ClimateCare	Myclimate	Zeromission	South Pole	Atmosfair	Klimat kompensera.se	Vi-skogen	Flight emission map
Distance (km)	X		X		X	X			X	X		X			
Type of Aircraft	X		X		X							X			
Offsetting (€), Tax (€) and total							X	X	X	X	X	X	X	X	
Fuel consumption / person			X									X			
CO2 emissions / person (kg or ton)			X	X	X	X		X	X	X	X	X	X	X	X
Via?	X		X				X	X	X	X		X		X	X
Other pollutants?					X										
Passenger Load Factor					X										
One way/Return choice?	X	X		X	X		X	X	X	X	X	X		X	
Several passengers				X	X		X	X	X	X	X	X		X	
Class choice?				X			X	X	X	X	X	X			
High altitude effects												X	X	X	X
RFI	2	1.89				2.7		1.9	2	2	1.9	2.7 – 3*	1.9	2	1.7

* if altitude > 9 km

** if flight length > 463 km

3 Analysis of fuel consumption from on route Flight Data Recorder

Within the project, flight data recorder (FDR) data were provided by the airline's companies Novair and SAS for a selection of flights. Data were used for analysis and validation of different emission calculators and models. The FDR is a device installed on each airplane recording performance data from several sensors. Together with this data, the companies also provided information on the number of passengers on each flight. In this chapter the data are analysed in order to assess the variation of the fuel consumption to different flight parameters such as mass of the aircraft (linked to the load factor) and wind conditions. In Chapter 5, fuel consumption and CO_2 emissions for a number of selected flights are compared with results of the calculators described in chapter 3. Since the available FDR data are only for 2 types of aircrafts, both equipped with the latest engine technology, comparison is further extended with the use of 'Small Emitters Tool', a spreadsheet developed by Eurocontrol for emission reporting of small aviation companies to the EU ETS, to cover variation of emission among the different aircraft types.

From Novair, data were obtained for four round-trip routes and 25 flights per route, consisting of 4 million datapoints on 1-s resolution for an Airbus 321Neo. The aircraft, first rolled out in 2016, has two CFM Leap-1A engines, a wingspan of 35.8 m, a total length of 44.5 m, an average fuel consumption declared by Airbus of 0.0172 litre/passenger-kilometre and can carry up to 221 passengers in Novair setup (244 according to Airbus website).

The four analysed round-trip routes are the following:

- Stockholm Arlanda *Airport* (*ARN*) – Gran Canaria *Airport* (*LPA*)
- Stockholm Arlanda *Airport* (*ARN*) – Hurghada International *Airport* (*HRG*)
- Stockholm Arlanda *Airport* (*ARN*) – Chania International *Airport* (*CHQ)*
- Stockholm Arlanda *Airport* (*ARN) –* Madeira *Airport (FNC*)

SAS data, obtained for 12 flights per 7 one-way routes, consisted of about 600 000 datapoints on 1-s resolution for an Airbus A320Neo. This aircraft is smaller but otherwise similar to model A231Neo, has also two CFM Leap 1A engines, the same wingspan of 35.8 m and a total length of 37.6 m. An average fuel consumption declared by Airbus of 0.024 litre/passenger-kilometre and can carry up to 180 passengers.

The analysed one-way routes are the following:

- Stockholm Arlanda *Airport* (*ARN*) – Kiruna *Airport* (*KRN*)
- Stockholm Arlanda *Airport* (*ARN*) – London Heathrow *Airport* (LHR)
- Stockholm Arlanda *Airport* (*ARN*) – Gran Canaria *Airport* (LPA*)*
- Stockholm Arlanda *Airport* (*ARN) –* Froson Ostersund *Airport (OSD*)
- Stockholm Arlanda *Airport* (*ARN) –* Göteborg Landvetter *Airport (GOT)*
- Stockholm Arlanda *Airport* (*ARN) –* Frankfurt am Main *Airport (FRA)*
- Stockholm Arlanda *Airport* (*ARN) –* Kopenhagen Kastrup Intl *Airport* (CPH)

Average flight time for the flights belonging to each route has been calculated in minutes and are presented in Figure 3.1a together with the averages for the fuel consumed on route. Figure 3.1b shows mean fuel consumption per km of great-circle distance (the shortest distance between two airports on Earth's surface). Average time for the outbound flights often differs from the return flights. As the graph shows, within the same route, the higher consumptions correspond to the longer flying time. Flight time is one of the most determinant factors on fuel consumption of a trip.

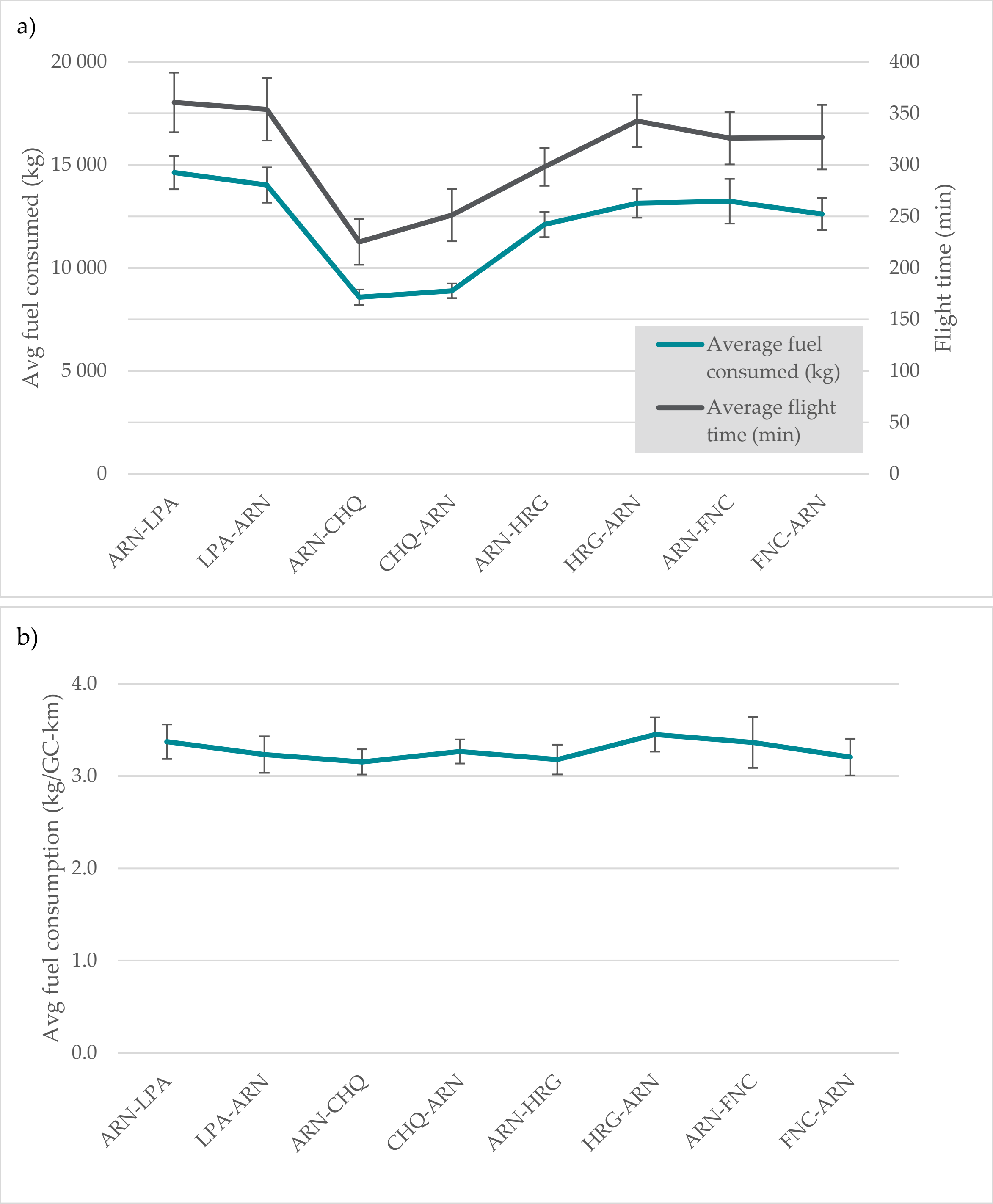

Figure 3.1 a) Average fuel consumed and flight time for the 8 routes analysed in Novair data. b) Average fuel consumption per km great-circle distance from the same dataset. Error bars represent standard deviation.

Regarding reduction of the flight time and fuel consumption, an important driver is avoidance of strong headwinds (wind blowing against the flight direction) which increase both. In many cases a longer (in time and space) route is less fuel consuming than a shorter but with stronger headwind flight. This is clearly visible in Figure 3.2 where to higher tail wind values (wind blowing in the same direction as the flight) correspond lower fuel consumption and to negative tail wind values correspond an increase in fuel consumption.

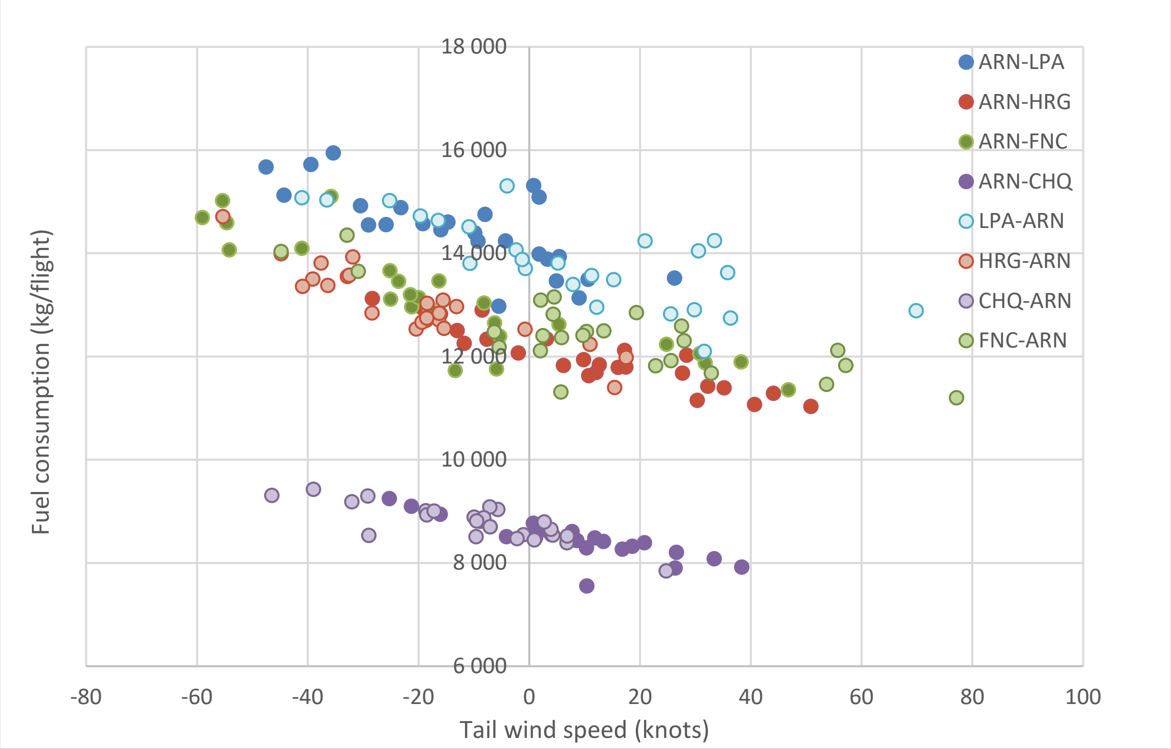

Figure 3.2. Total fuel consumption of Airbus 321NEO during flight phase 6 for all analysed flights plotted against the mean tail windspeed during the flight.

Most of the fuel consumption takes place during the cruise phase. Cruise is the longest phase of a flight and the stage in which the aircraft reaches the maximum fuel economy. An aircraft is said to be cruising when it has reached its assigned altitude for the scheduled journey which can be between 9 (but more often 11) and 12 km. Cruise altitude is set at a point where higher ground speed, increase in aerodynamic drag power, and the decrease in engine thrust meet an optimum balance. Other factors affecting optimum cruise altitude include payload, air temperature, humidity, and speed.

There are, however, more reasons for varying flight time and fuel consumption than the abovementioned factors. From the GCD between the airport pair a route is modified by the route plan in order to minimise the total cost of the flight, taking the fuel-, time- and overflight-costs into consideration. While on short routes, as e.g. ARN-OSD, ARN-GOT or ARN-CPH possibilities for optimisation are smaller, on longer routes, as e.g. all Novair routes with FDR data, possibilities are large and e.g. for the ARN-LPA route the most west-born routes go over Ireland and Madeira while the most east-born ones go over Germany, Schweiz and Eastern France. The final choice of the route for actual flight is a result of actual weather conditions, air traffic situation, overflight costs and operator’s weighing of relative importance of the fuel and time costs.

The received FDR data series were divided into 6 different operation phases, however, only data belonging to flight phases 5 (lift-off, up to 1 500 ft), 6 (climb, cruise, descent and approach), and 7 (landing, from 800 ft to touchdown) were used in the analysis of the Novair's data. Figure 3.3 shows the average fuel consumption on route ARN-LPA and LPA-ARN in phases 5, 6 and 7. Clearly, most of the fuel is combusted during phase 6. An important parameter affecting fuel consumption is the weight of the aircraft. This includes a fixed part related to the weight of the aircraft, equipment and the crew and a varying part consisting of passengers, their luggage and consumables related to their stay onboard, cargo, and fuel. Figure 3.4 shows sensitivity of fuel consumption per km of GCD on different routes to the mean gross weight of the aircraft on the route with clear decrease of average fuel consumption with lower weight of the aircraft.

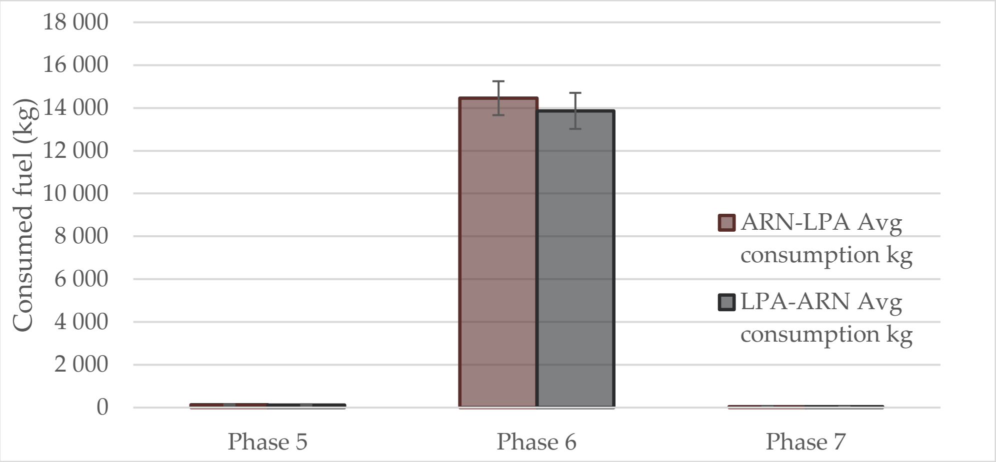

Figure 3.3. Average fuel consumption of Airbus 321Neo on the route Stockholm Arlanda Airport and Las Palmas de Gran Canaria Airport. Error bars represent standard deviation.

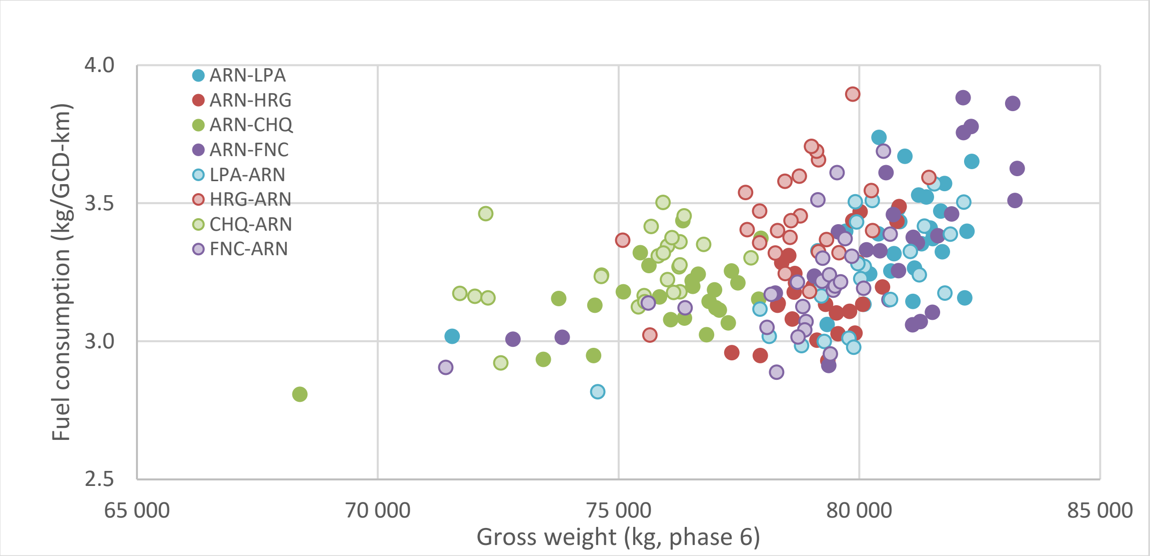

Figure 3.4. Average fuel consumption per km of GCD travelled (phase 5, 6 and 7) for Airbus 321Neo for all analysed flights plotted against the average gross mass at flight phase 6 during the flight.

4 Comparison of calculators on route and verification with FDR data

From fuel consumption values collected from the airline companies Novair and SAS, average CO_2 emissions per passenger were calculated for each one-way route. This was done first by dividing the calculated fuel consumption for each flight by the number of passengers per flight. These values were then used to calculate the average of the fuel consumption per passenger on route level. Average passenger's fuel consumption for each route was then multiplied by 3.16 in order to calculate corresponding average passenger's CO_2 emission per route.

The calculators described in Chapter 3 were used for computing CO_2 emissions resulting from the four one-way routes taking-off from Stockholm-Arlanda analysed in Chapter 4. The results were compared with the emissions obtained from FDR data.

The assessment of the calculators has been performed trying, when possible, to keep similar settings for each route throughout the different calculators. Whenever the tools allowed it, one-way trip and cabin class *economy* were chosen. Since a few calculator functions with input data in form of GCD, flight distances have been calculated by using an online tool suggested by Utsläppsrätt.se calculator (http://www.webflyer.com/travel/mileage_calculator/). An overview of the possible features of the calculators has been presented in a Table 2.2.

A few calculators (Finnair, Lufthansa, SAS and GreenSeat) computed only direct CO_2 emission from fuel consumption without considering the high-altitude effects of SLCP applying radiative forcing index (RFI). Two calculators (Carbon footprint calculator and Utsläppsrätt.se) offered the option to deselect high-altitude effects, while in the rest of the cases RFI was automatically included in the calculation. Results were hence expressed in kg (or ton) CO_2 equivalents (CO_2e).

The route ARN-LPA was chosen for the comparison since it was the only airport combination for which FDR data were made available from both from Novair and from SAS. The results of the comparison are shown in Figure 4.1. Comparison of all analysed routes can be seen in Table AII.1 in Appendix II. In order to properly compare the values from the different calculators and the FDR emissions, values resulting from the examined calculators using RFI were adjusted to express only the direct CO_2 emissions and the high-altitude impact part is shown in different colour. See Table 2.2 for the RFI values used by the calculators.

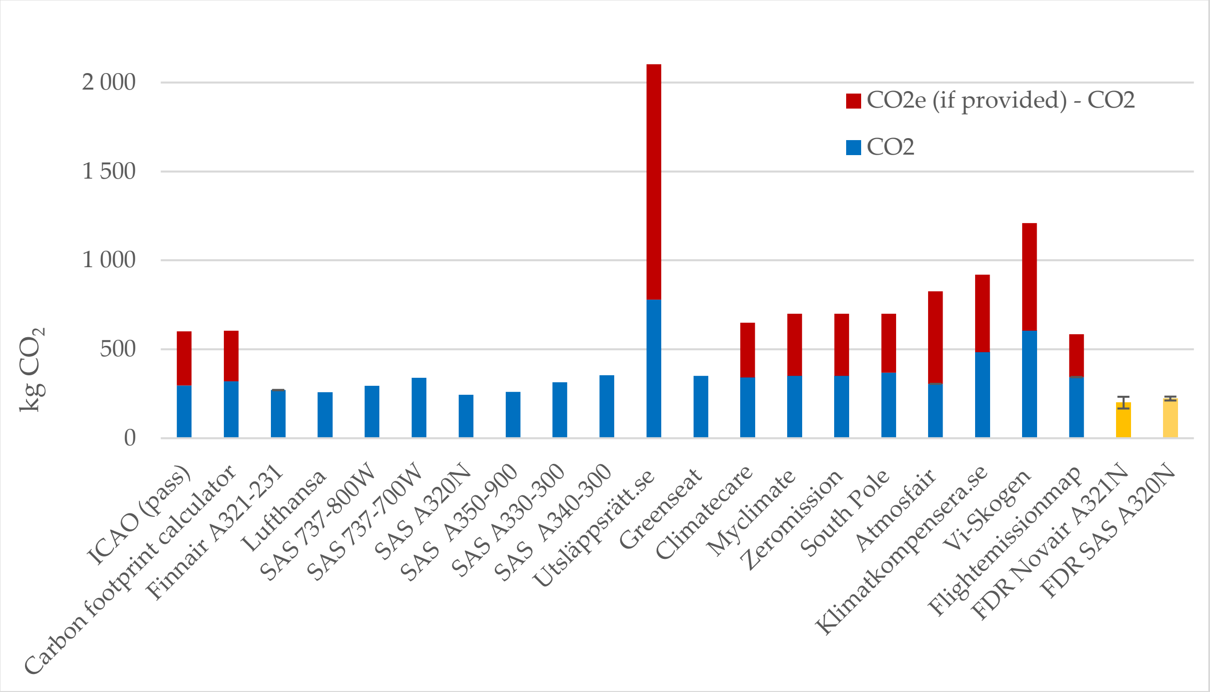

Figure 4.1. CO_2 emissions resulting from the flight calculators for the Stockholm – Las Palmas de Gran Canaria airport one-way route (ARN-LPA). Blue columns represent direct emissions in kg CO_2, red columns the additional CO_2e emissions resulted from the high-altitude effects provided by some calculators. The yellow columns are emissions calculated from FDR data analysed in this study with standard deviation.

In general, the comparison between the online based calculators and the "real-flying" data validate most of the calculator results. The assessed tools show results that are for the most in line with FDR data, with a few exceptions such as Utsläppsrätt.se, Vi-Skogen and Klimatkompensera.se that show values much above the rest of the calculators.

CO_2 emissions resulting from FDR fuel consumption data have shown to be lower than those resulting from the calculators within the same route. It is important to bear in mind that the analysed FDR data belong to the latest aircraft which have between 15-20% higher fuel-efficiency compared to the average of the aircraft models they have replaced. Not knowing the details of the composition of the aircraft fleet behind the performance assumptions of the different calculators, it is possible to presume that some might be outdated and hence resulting in overestimated emissions (e.g., Utsläppsrätt.se, Vi-Skogen). E.g. utsläpsrätt.se calculations are based on performance data older than 11 years. This can partly account for the more than three-times higher emissions of this calculator comparing to the emissions derived from the FRD data of SAS or Novair. For the SAS calculator where in which individual aircraft types can be chosen, we present results for 6 different aircraft types to illustrate the variability of emissions per passenger.

To further illustrate the impact of aircraft type on aviation emissions with independent data, the Small Emitters Tool (SET) calculator was used to compare flight emission for the ARN-LPA route for some of the most common commercial aircraft types. This calculation was performed feeding the SET with flight distance as GCD and choosing the aircraft type designators for the relevant aircrafts. The calculated CO_2 was then divided by a passenger load factor of 0.85 which was applied to the maximum amount of passenger that each aircraft can host. Results presented in Figure 4.2 show that older models belonging to same aircraft families have significantly higher emission per passenger compare to the more recent A21N and A20N. It also shows that FDR-derived CO_2 emissions per passenger are in line with those resulting from SET.

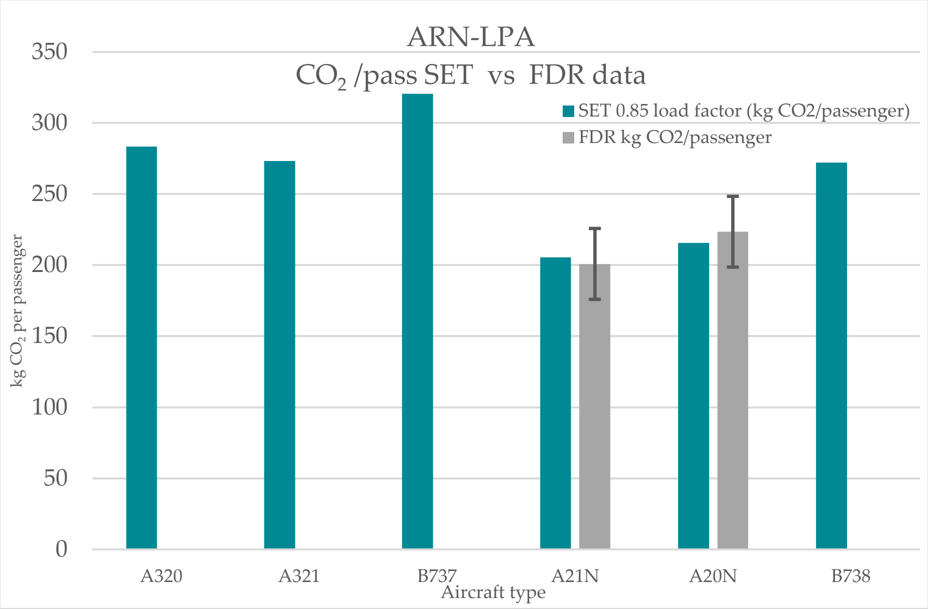

Figure 4.2. Blue bars: CO_2 emission per passenger calculated with the Small Emitters Tool for a selection of aircrafts (A320: Airbus A-320, A321: Airbus A-321, B737: Boeing 737-700 and similar, A21N: Airbus A-321neo, A20N: Airbus A320nwo, B738: Boeing 737-800) for the route ARN-LPA. Grey bars: CO_2 emission per passenger calculated from FDR data from this study.

To conclude, one can expect that a comparison between FDR data belonging to a mixture of older and new aircraft models would show closer agreement with most of the emission results obtained with the calculators in Chapter 3.

Figure 4.2 reveals also another aspect to take into consideration when looking at CO_2 emission per passenger: the passenger load factor of the flight. Novair, being a charter company with typically higher passenger load factors comparing to airlines, has reported a passenger load factor of around 94%, to be compared to the pre-Covid-19 European commercial airlines average of 83% in early 2020 (https://www.statista.com/statistics/234955/passenger-load-factor-plf-on-international-flights/). Comparison of influence of the higher load factor can be seen when the CO_2 per passenger emissions for A21N and A20N calculated from SET output with equal load factors are compared to those calculated from the FDR data.

In Figure AII.17 in the Appendix II further comparison of CO_2 emissions per passenger-km on the 4 investigated routes for different aircraft types calculated with SET, for A320Neo and A321Neo calculated from FDR data is presented along with emissions calculated with 3 emission calculators – Vi-skogen, ICAO and SAS for A320Neo.

5 Comparison of SMHI flight emission model with FDR data

In order to validate the SMHI flight emission model with the dataset from Novair the exact same routes from the Flightradar24 dataset have been extracted from the flight emission model for CO_2 emissions and fuel used comparisons. All the routes from Novair were considered to be international in the SMHI flight emission model. Since the emission model was built on Flightradar24 data that is within Swedish territory, only the part of the Novair route that is in within Swedish territory was used in the validation study. A detailed description of how the comparisons were performed as well as additional tables and figures are given in Appendix I.

The Novair dataset includes the following routes and there are 25 flights for each route:

- Arlanda to Gran Canaria, ARN – LPA
- Gran Canaria to Arlanda, LPA – ARN
- Arlanda to Hurghada, ARN - HRG
- Hurghada to Arlanda, HRG – ARN
- Arlanda to Chania, ARN – CHQ
- Chania to Arlanda, CHQ – ARN
- Arlanda to Madeira, ARN – FNC
- Madeira to Arlanda, FNC – ARN

Figure 5.1 shows results for the comparison of fuel use in the LTO cycle from Novair FDR data and from the SMHI flight emission model for the different destinations. Results from the SMHI model are shown using both default values from the EMEP LTO emission calculator for the duration of different flight phases in the LTO cycle (take off, climb out, final approach, landing) and using durations derived from the Novair FDR data. For individual airport pairs the differences reach 20%. On average the difference is 5% for the SMHI model using flight phase durations from FDR data and below 1% using the default values from EMEP LTO emission calculator.

Figure 5.2 shows the corresponding comparison for the cruise phase where most of the fuel is used. Here the comparison is limited to the part of the cruise phase within Swedish air space. The difference for the routes ARN-HRG and HRG-ARN are large due to very few routes in the Flightradar24 data used in the SMHI model for this destination (see Appendix I). For the remaining airport pairs the SMHI model overestimates the fuel use by about 12%. This difference is mainly explained by the fact that fuel burn factors for the relatively new LEAP 1A engine on the Novair A321-251N aircrafts were not available in the EMEP calculator data that is used in the SMHI emission model. Instead fuel burn factors for the older aircraft A321-131 with 3lA008 engine were used. Considering this the agreement is very good.

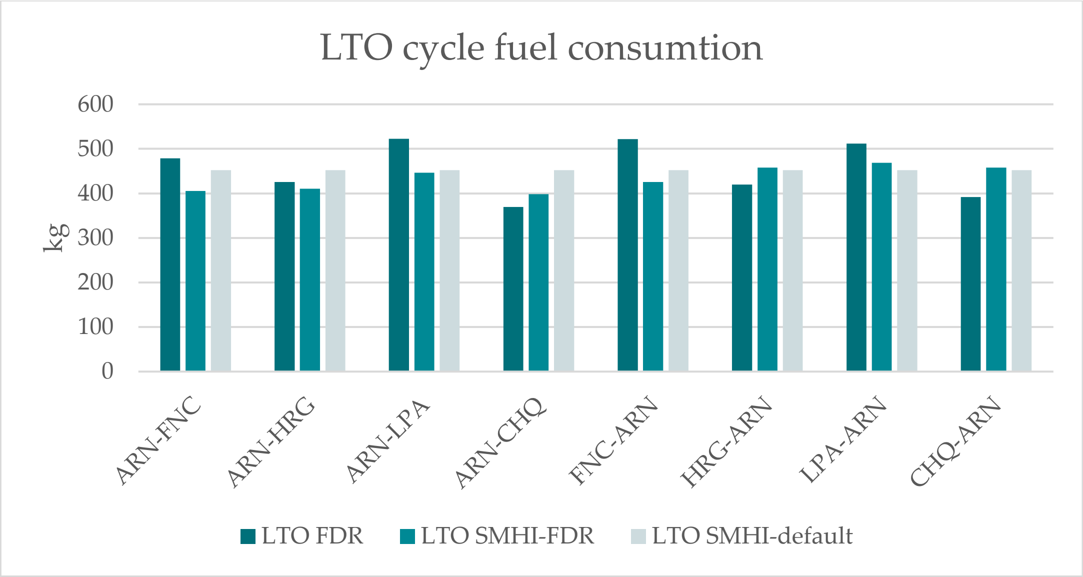

Figure 5.1. Comparison of LTO cycle fuel consumption from Novair FDR data and from the SMHI model using flight phase durations from FDR data and default values respectively. Units: kg.

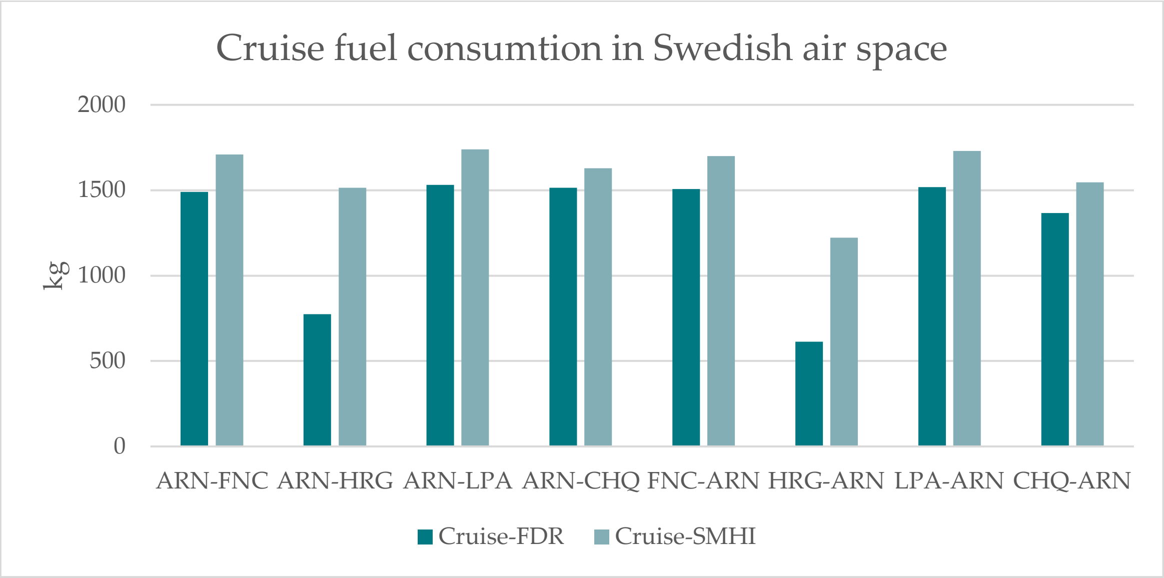

Figure 5.2. Comparison of cruise fuel consumption in Swedish air space from Novair FDR data and from the SMHI model. Units: kg

6 Conclusions and recommendations

- In aviation accurate tools exist to calculate fuel consumption on individual flights which are readily used for route planning. This methodology is also utilised in more generalised form in numerous emission calculations, e.g. ICAO's, EMEP/EEAs or FOI's. Actual fuel consumption data are recorded on each flight with high frequency by the flight data recorder as well as for the entire flight in form of so-called gate-to-gate status of the fuel tank. While the predictive methodologies are used for authorities' emission reporting to the UNFCCC and the LRTAP convention, the actual fuel consumption data are used for airlines reporting to EU ETS and CORSIA. IATA also recommends use of actual fuel consumption data for climate compensation. The actual fuel consumption data are not openly available on an individual flight level.
- Fuel consumption on individual flight level depends on flight length, aircraft type, weather conditions, aircraft load factor as well as on choices of flight operator for route optimisation. While the fuel efficiency of an aircraft is controlled by policies regulating the technological standards, the operators' choices are driven by cost optimization of the flight with respect to the cost of the fuel, flying time and the overflight costs.
- A comparison of 15 emission and climate calculators showed substantial differences in the results. The main difference was when comparing calculators that provide results in CO_2 equivalents, i.e. include high altitude effects from SLCP and those that do not, the variation of the results discourages a direct comparison of the calculators without a deeper analysis of their methodologies and assumptions. Presentation of the impact of non-CO_2 emissions in form of CO_2 equivalents might require an educated user and a transparent and easily understandable methodology available on the calcualtor website. Not all the calculators have shown the same degree of transparency or provided an easily accessible methodology.
- Among calculators computing high altitude non-CO_2 emissions, the comparison displays a variety of RFI (going from 1.7 to 3.0) and it renders an idea of how much this factor hits on the final carbon footprint and enhance the divergence between a number of calculators.
- The agreement between the calculators considering only direct CO_2 emissions was much better, with only a few calculators showing clearly higher emissions (Utsläppsrätt.se, Klimatkompensera.se, Vi-Skogen). The most likely reason for these high emissions is outdated aircraft fleet data with older, less fuel efficient technology. Comparison of emissions from the up-to-date calculators with FDR data has shown good agreement when differences between emissions of different aircraft types are considered.
- Average differences between fuel consumption from FDR data from Novair flights and the SMHI flight emission model are 1-5% for the LTO cycle, depending on the method used to estimate the duration of the LTO phase, and 12% for the cruise phase in Swedish air space. The difference for the cruise phase is mainly due to

missing emission factors in the underlying software for the newer engines used on the Novair aircrafts.

- The high-altitude effects of SLCP are crucial in decarbonisation of aviation – with use of combustion engines these efects will remain even with use of fossil-free fuel. The first important questions associated with the high-altitude effects is their quantification and reduction of uncertainties of the climate impact of the SLCP. RFI used by many climate calculators is a blunt tool if the aim would be to target the high-altitude effects as such, as it is related solely to CO_2 emissions and the relation to the SLCP radiative forcing is through the impact of the historic emissions of aviation up to the date for which the FI is calculated. More appropriate are forward looking metrics considering forcing from actual SLCP species emitted during the flight as global warming potential or global temperature potential, instantaneous or accumulated.
- The second important question related to biojet fuel in aviation is how the high-altitude effects from the use of this fuel differ from those related to fossil jet fuel. The most recent research shows that the most important climate forcing components are emissions of CO_2 and formation of contrails and contrail cirrus. SAF with high hydrogen and low aromatic content emits substantially less soot particles, which reduces radiative forcing of the contrails. Model simulations of full implementation of SAF in the current aviation fleet would lead to 20-50 % reduction of RF from contrails and contrail cirrus. Combined use of SAF, engine technology with low emissions of soot and NOx and route climate optimisation have the potential to remove a large part of the high altitude effect.

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8 Appendix I

8.1 The SMHI flight emission model

The model is based on five major sources of input data:

1. **The Swedish national emission inventory (SMED)**, compiled by SMED to be used in international reports such as the UN climate convention (UNFCCC) and the EU reporting on air quality (UNECE CLRTAP).
   The SMED database includes emission totals without geographic distribution for domestic and international flights, divided into LTO and cruise. These emissions are calculated by an aircraft emissions model developed by Mårtensson and Hasselrot (2013) and are adjusted by the statistics of fuel sold.
2. **Swedish Transport Agency airport arrival and departure statistics** is a detailed log of all arrivals and departures from all major Swedish airports (all Swedavia airports and airports that are associated to Swedish regional airport association (SRFF)) from 2005 onwards. This data includes origin and destination of each flight as well as aircraft type.
3. **Flight location data from Flightradar24** describes the movement of flights over Swedish territory.
4. **EMEP aircraft emission and fuel used factors** that are extracted from the EMEP/EEA air pollutant emission inventory guidebook (European Environment Agency, 2019, 1.A.3.a Aviation). This guidebook includes an aviation emission calculator from which emission factors from various aircraft types are separately estimated for various LTO and cruise phases.
5. **Swedish Civil Aviation Administration overflight counts** include a count of monthly overflights (aircrafts over Swedish territory, without information of e.g. location and aircraft type).

The geographically distributed fuel used, and flight emissions are calculated using the following steps:

1. Based on Flightradar24 data to calculate an average flight pattern for:
   - domestic airport pairs,
   - domestic airports to/from international airports,
   - overflight traffic.
2. Calculate geographically distributed aircraft emissions for each airport pair based on average flight patterns, number of aircraft arrivals/departures and emission factors.
3. Summation of all aircraft emissions into emissions over the Swedish territory and scaling using SMED national emission totals.

These steps are discussed in more detail in the next section.

8.1.1 Calculate average flight patterns

The model was built based on four weeks of Flightradar24 data from year 2015, split into four one-week periods in January, April, July and October, to represent the average flight patterns in winter, spring, summer, and fall, respectively. This data from Flightradar24 has been collected from ADS-B (Automatic Dependent Surveillance - Broadbast), which is similar to AIS (Automatic Identification System) for shipping, to continuously report the flight location, id, aircraft type, origin and destination. There is also data available for aircraft without ADS-B via Multilateration (MLAT), which uses the Time Difference of Arrival technique (TDOA) to triangulate positions. Data are collected over Swedish territory for aircrafts during LTO and cruise phases.

The data from these four weeks includes detailed information with time resolution of seconds to minutes of roughly 178 000 flights. Of these 178 000 flights, only 8 700 are domestic which is an extensive amount of flights even though it is only a small fraction of the total 261 000 domestic flights registered by the Swedish Transport Agency for 2015.

In order to assign geographically distributed emissions from every single flight, a generalization of the flight patterns is required. This is done by calculating an average flight pattern for each pair of airports using the Flightradar24 dataset, e.g. one pattern for Arlanda to Landvetter and one pattern for Ängelholm to Örebro.

All data points with travelled distance from Flightradar24 data are summed up over a three-dimensional grid. The pattern is then normalized, as it is used to distribute the emissions horizontally and vertically. An example of this process can be seen in Figure AI.1.

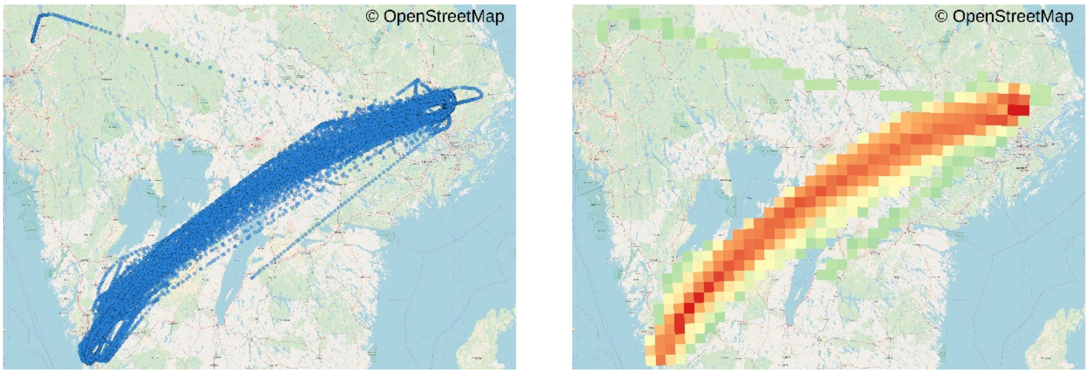


Figure AI.1. Conversion of raw Arlanda to Landvetter Flightradar24 data to average flight pattern. Background map from openstreetmap.org, © OpenStreetMap contributors.

For each airport pair, we also calculate the median distance travelled by all flights. By combining the normalized flight pattern with the distance travelled, the total emission can then be calculated for each flight, as described in the next section.

This is done for all Swedish airports with at least one flight registered in the Flightradar24 data. The pattern and average route distance between an airport pair are directional. For example, flights travelled on average 425 km and 462 km respectively from Arlanda to Landvetter and from Landvetter to Arlanda. This can be important, as wind directions can force asymmetrical departures and landings. This results in 228 flight patterns for domestic airport pairs.

Similarly, average patterns of all international arrivals and departures from each airport are obtained for international flights. This results in 29 international-domestic airport pairs. In cases where there are no matching airport pairs from the Flightradar24 data and neither a flight registered in the Swedish Transport Agency data, a fallback flight pattern is used. This fallback pattern is obtained by averaging the flight pattern for all domestic flights or all international flights. For overflights, an average flight pattern for all flights which both arrive to and depart from foreign airports is obtained.

8.1.2 Calculate aviation emissions for each airport pair

To calculate the total emissions, departure/arrival statistics from the Swedish Transport Agency which contain over 490 000 arrivals and departures at Swedish airports in 2019 are used. As both departures and arrivals are logged, each flight is counted twice. If only departures are counted, the data set has around 245 000 domestic and international flights. There is also information about the aircraft type in the data set, which allows for different emission factors to be considered. This data is aggregated into each combination of airport pairs and aircraft type. The model can then differentiate between e.g. flights from Arlanda to Landvetter done by Airbus A320 aircrafts and those travelling the same route but done by Fokker 50 aircrafts.

For the aircraft emission factors, the emission calculators supplied in the EMEP/EEA air pollutant emission inventory guidebook (European Environmental Agency, 2019, 1.A.3.a Aviation) were used. These calculators are used for calculating the total emissions for a single flight with a specified route distance and aircraft type. There are two emission calculators; one is used for calculating the total emission for the cruising phase, and the other is for calculating emissions from the LTO cycle, which is divided into taxi out, take off, climb out, landing and taxi in.

The cruise emission calculator is used to estimate emission factors given by emission per nautical mile for various route distances. These emission factors differ between routes of different distances, as emissions are affected by factors like maximum altitude and time at different altitudes. It estimates emissions factors for the 38 most common (according to Swedish Transport Agency data) aircraft types over Swedish territory.

The LTO emission calculator is used to calculate the total emission for a typical Swedish airport (affecting e.g. time on runway). The emissions for the taxi out, take off and taxi in steps are aggregated into a total emission that is distributed between 0 and 100 meters for each flight. Similarly, the emissions for the climb out and landing phases are aggregated into a total emission that is distributed between 100 and 1000 meters for each flight. These LTO emissions are generated for 15 of the most common aircraft types.

For each aircraft type, the model uses emission factors matching the exact aircraft type. Each aircraft type is also designated a template aircraft type with similar properties, so if no exact match is available, the template is used.

The total emissions and their geographical distribution are calculated for all flights at each airport pair. The flight pattern used for the geographical distribution is determined in the following order for an example airport pair Arlanda to Landvetter:

- Search for flight pattern with an exact match (Arlanda to Landvetter)
- If no match, look for flight pattern in the reversed route (Landvetter to Arlanda)
- If no match, use the general domestic flight pattern (Sweden to Sweden)

Emissions are distributed vertically according to the flight pattern. LTO emissions are divided equally into all layers between 0 and 100 meters for taxi out, take off and taxi in and equally into all layers between 100 meters and 1 000 meters for climb out and landing. Cruise emissions are distributed proportionally to the distance travelled in each layer, so that if 5% of the total distance is travelled between 5 000 and 6 000 meters, 5% of the emissions are put there.

8.1.3 Calculate and scale total emissions

In the previous section, total geographically distributed emissions were calculated for each airport pair, as well as for all international traffic from each domestic airport and overflights. The resulting calculated emission totals for the domestic flights are compared to the SMED national total flight emissions for each species. Through the comparison, a scaling factor is obtained for each emitted specie and the same scaling factor is then applied to also the emission totals for international flights and overflights.

8.2 Comparison of LTO fuel use and emissions with FDR data

In the calculation of LTO emissions using the SMHI flight emission model, a default time for each LTO flight phase is used based on the EMEP LTO emission calculator. Default time for flight phases Taxi in and Taxi out for each airport is calculated by the annual average Taxi in and Taxi out time at each specific airport. As for flight phases Take off, Climb out, and Approach, the default times are specified by ICAO (European Environmental Agency, 2019, 1.A.3.a Aviation). The definition of various flight phases can also be found in the EMEP/EEA air pollutant emission inventory guidebook 2019 (European Environmental Agency, 2019, 1.A.3.a Aviation). Table AI.2 shows the default times used in the flight emission model. Note that the EMEP LTO emission calculator only includes airports in Europe. Since Hurghada not is in Europe, there is no information about its average taxi in and taxi out time.

Table AI.1. Default times in seconds for flight phases Taxi out, Take off, Climb out, Approach and Taxi in based on EMEP LTO emissions calculator (European Environmental Agency, 2019, 1.A.3.a Aviation) for selected airports used in this validation study.

Airport	Taxi out	Take off	Climb out	Approach + landing	Taxi in
ARN	693	42	132	240	379
CHQ	817	42	132	240	230
FNC	547	42	132	240	223
LPA	681	42	132	240	243

In contrast to the standard use of the SMHI flight emission model, it is also possible to make specific time estimates for each flight phase for each flight because there is detailed flight information from the Novair and SAS datasets such as ground speed, gross weight, latitude, longitude, vertical speed, standard altitude, fuel flow in N1 engine, fuel flow in N2 engine and calculated fuel used for every second.

The EMEP calculator flight phase criteria could not be applied directly on the Novair FDR data, instead the following assumptions were used to estimate the start time for each flight phase:

- **Taxi out**: FWC flight phase is 2 and the 10 seconds rolling mean of delta latitude and delta longitude is not zero.
- **Take off**: The time right before the ground speed increases rapidly in short time.
- **Climb out**: Altitude Standard at the takeoff airport plus 40 ft (12 m).
- **Final approach**: Altitude Standard at the landing airport plus 3000 ft (914.1 m).
- **Landing**: Altitude Standard at the landing airport plus 20 ft (6 m).
- **Taxi in**: Ground speed begins to be less than 30 ms^{-1} after landing.

Table AI.2 presents the average time estimated for each LTO flight phase for various flight routes. Note that most of the Taxi in and Taxi out data is incomplete in the Novair dataset, the time estimated is therefore only based on the data available and has a large uncertainty. For this reason, the Taxi out and Taxi in flight phases are excluded in the validation.

Table AI.2. Average estimated time (s) in seconds for LTO flight phases for the Novair routes.

Flight routes	Taxi out	Take off	Climb out	Final approach	Landing	Taxi in
ARN-FNC	361.2	38.4	95.2	247.6	35.0	31.0
ARN-HRG	297.4	32.4	101.8	244.2	49.5	16.5
ARN-LPA	244.8	31.0	106.9	303.5	44.0	21.2
ARN-CHQ	234.4	36.3	101.1	220.0	40.6	19.9
FNC-ARN	239.9	32.6	115.4	240.0	39.2	26.4
HRG-ARN	416.3	39.1	119.7	258.4	39.5	26.1
LPA-ARN	488.5	52.8	106.4	260.2	47.5	17.5
CHQ-ARN	473.5	50.8	105.6	252.2	45.6	20.1

Novair has flights with CFM LEAP 1A-engines. In order to best estimate the fuel burnt and emissions of carbon dioxide (CO_2), updated emission indices for LEAP 1A35A/33/33B2/32/30 from the ICAO emissions databank (https://www.easa.europa.eu/domains/environment/icao-aircraft-engine-emissions-databank) are used in the calculation in the SMHI flight emission model for the LTO cycle. Table AI.3 shows the rate of fuel burn and rate of emissions for LEAP 1A engines used in the flight emission model. Table AI.4 compares the fuel used for LTO flight phases based on data from Flight Data Recorder in the Novair dataset with fuel use calculated by the flight emission model using the estimated time for LTO flight phases for each of the Novair flight routes in the dataset. The Table also shows emissions of CO_2 calculated by the SMHI flight emissions model based on the Novair data. Table AI.5 presents the fuel use and emissions of CO_2 calculated using default times for LTO flight phases based on the EMEP LTO emissions calculator that were assumed in the flight emission model.

Table AI.3. LEAP-1A engine rate of fuel burn and rate of emission of CO_2 (kg/s/engine) for various LTO flight phases calculated with emission indices from ICAO emission databank that is used in SMHI flight emission model for the LTO cycle.

Flight phases / Rates	CO_2	fuel
Taxi out	0.3024	0.096
Take off	3.3327	1.058
Climb out	2.7216	0.864
Landing	0.8883	0.282
Taxi in	0.3024	0.096

Table AI.4. Fuel use (in kg) and emissions of CO_2 (in kg) in LTO flight phases Take off, Climb out and Approach+landing. Fuel use (FDR data): Fuel use based on data from the Flight Data Recorder in the Novair dataset. Fuel use (SMHI): Fuel use (in kg) calculated by SMHI flight emissions model based on Novair data. Emissions of CO_2 (SMHI): Emissions of CO_2 (in kg) calculated by SMHI flight emissions model based on Novair data.

	Fuel use (FDR data)			Fuel use (SMHI)			Emissions of CO2 (SMHI)		
	Take off	Climb out	Final approach + landing	Take off	Climb out	Approach + landing	Take off	Climb out	Approach + landing
ARN-FNC	114.1	240.1	124.8	81.3	164.5	159.4	256.2	518.2	502.1
ARN-HRG	83.8	229.7	112.4	68.6	176.0	165.7	216.0	554.3	521.9
ARN-LPA	85.6	281.1	155.8	65.7	184.8	196.0	206.9	582.0	617.5
ARN-CHQ	73.8	208.4	87.4	76.8	174.7	147.0	241.8	550.2	462.9
FNC-ARN	100.3	309.4	112.1	69.0	199.4	157.4	217.3	628.1	495.9
HRG-ARN	66.6	230.1	123.1	82.7	206.9	168.0	260.5	651.7	529.3
LPA-ARN	151.2	239.3	121.5	111.6	183.9	173.5	351.7	579.4	546.6
CHQ-ARN	81.0	200.7	110.0	107.4	182.5	167.9	338.3	575.0	528.9

Table AI.5. Fuel use (kg) and emissions of CO_2 (kg) in various LTO flight phases calculated by SMHI flight emissions model using default times that are in EMEP LTO emissions calculator.

Airport	Fuel use					Emissions of CO_2				
	Taxi out	Take off	Climb out	Approach + landing	Taxi in	Taxi out	Take off	Climb out	Approach + landing	Taxi in
ARN	133.1	88.9	228.1	135.4	72.8	419.1	279.9	718.5	426.4	229.2
CHQ	156.9	88.9	228.1	135.4	44.2	494.1	279.9	718.5	426.4	139.1
FNC	105.0	88.9	228.1	135.4	42.8	330.8	279.9	718.5	426.4	134.9
LPA	130.8	88.9	228.1	135.4	46.7	411.9	279.9	718.5	426.4	147.0
HRG	-	88.9	228.1	135.4	-	-	279.9	718.5	426.4	-

By comparing the fuel use from FDR data to those calculated with estimated times according to our criteria and those calculated with default times from the EMEP LTO emissions calculator, it is concluded that using the default times in the calculation leads to fuel use that is close to that obtained from the FDR data. On average the difference is below 1% using the default values from EMEP LTO emission calculator. The difference when using flight phase durations from FDR data is 5%. For individual airport pairs the differences reach 20%.

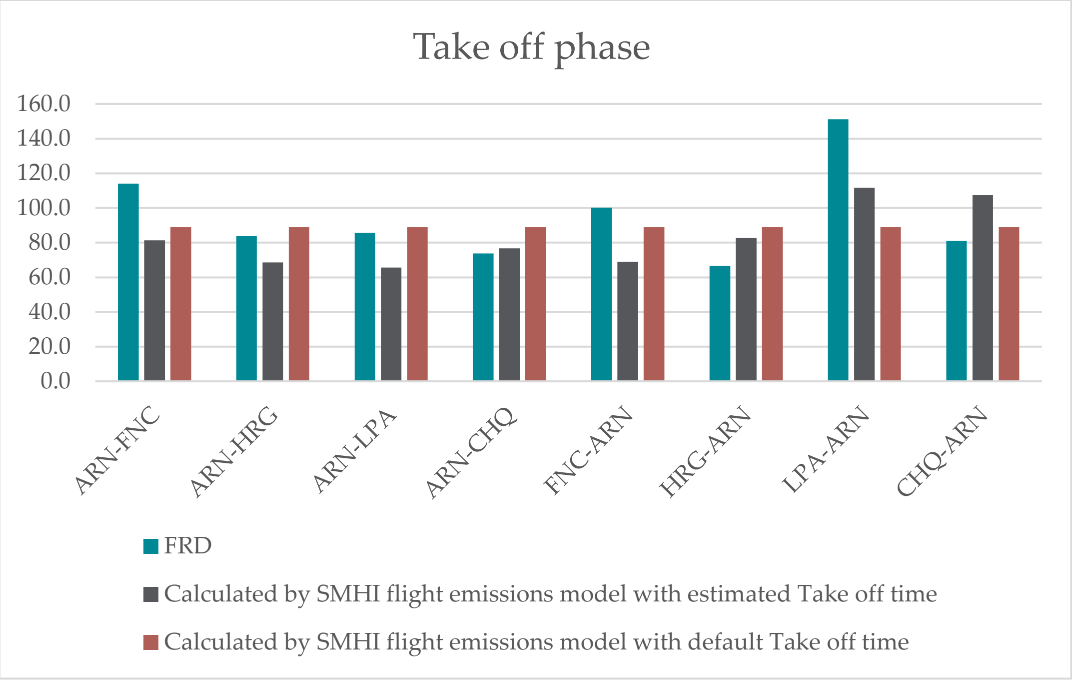
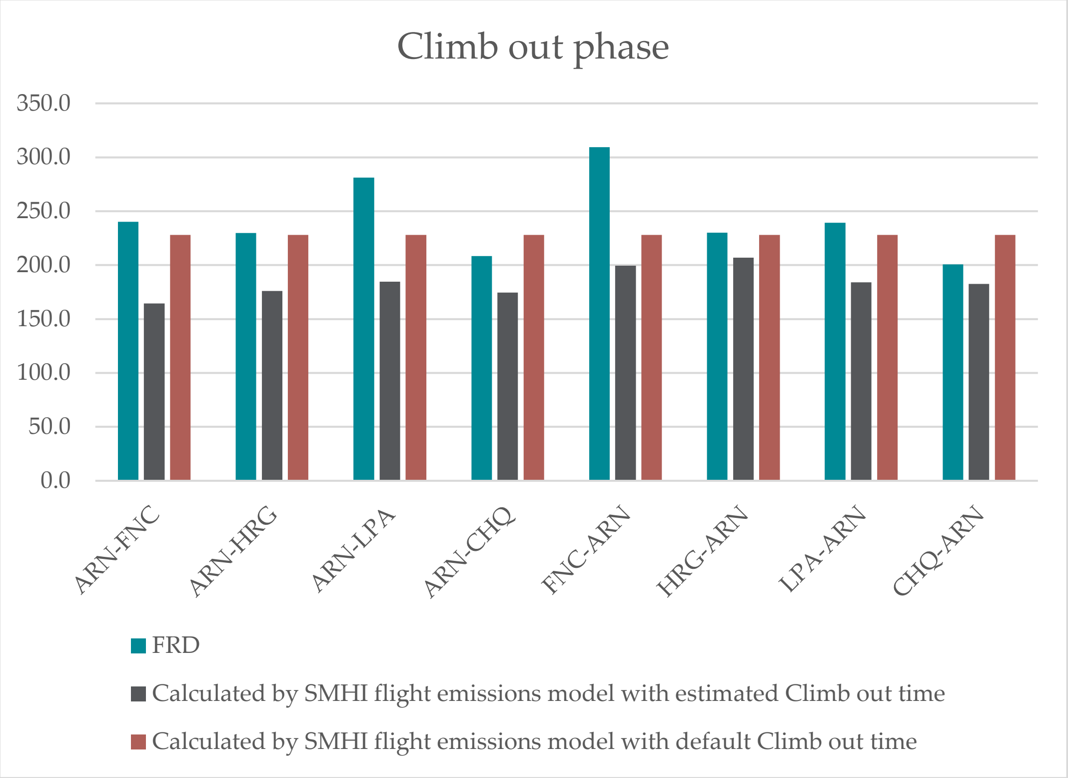


Figure AI.2. Continues on the next page.



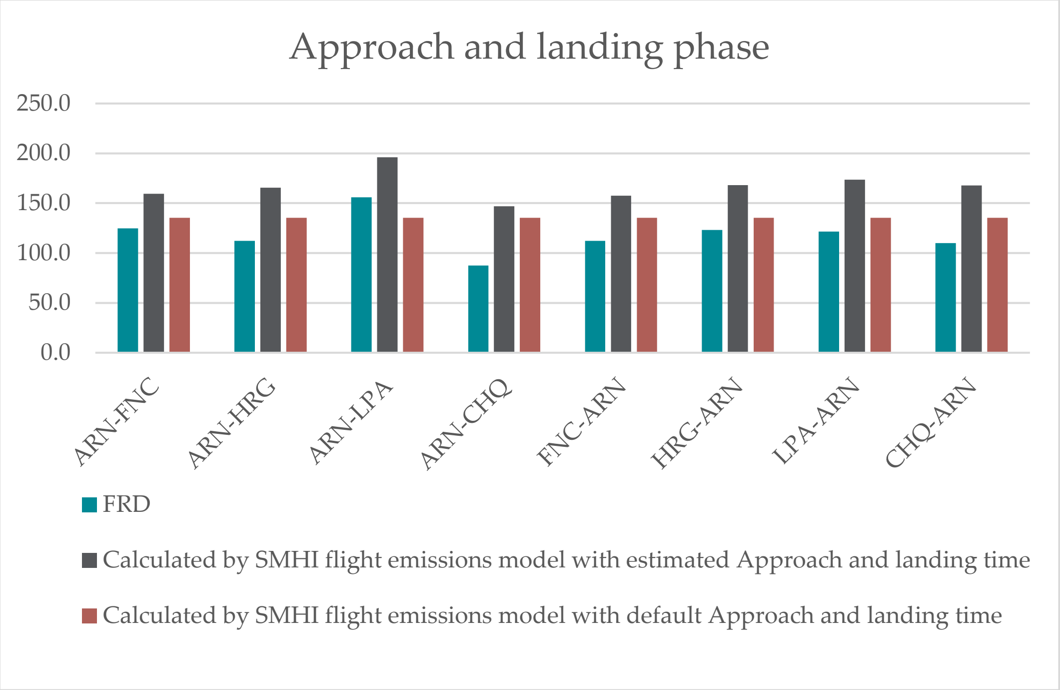


Figure AI.2. Fuel use (kg) calculated from 1. FDR in the Novair dataset, 2. SMHI flight emissions model with time estimated for various LTO flight phases based on the list of criteria, 3. SMHI flight emissions model using default time for various LTO flight phases based on the EMEP LTO emissions calculator.

8.2.1 Comparison of cruise fuel use and emissions with FDR data

The SMHI flight emissions model uses cruise emission factors based on EMEP cruise emissions calculator from 2019. However, the calculator does not include emissions factors and rate of fuel burn for the specific aircraft and engine that Novair fly with. Novair has aircrafts A321-251N with LEAP 1A engine. The closest emission factors and rate of fuel used available from the EMEP calculator are for aircraft A321-131 with 3lA008 engine.

Figure AI.3. shows the flight data from Flightradar24 and the Novair datasets between ARN to the airports of interest (HRG, FNC, CHQ, LPA) in this validation study. Flight data for all the aircraft types in the Flightradar24 dataset has been extracted and used in this comparison in order to maximize the number of flights to be compared, as there were only a limited number of flights between these specific airports in the dataset. The flight patterns from Flightradar24 in general match quite well with those in the Novair data, as seen in the overlapping flight routes in the figures. However, the Flightradar24 dataset includes some variations of the flight route that do not exist in the Novair dataset and vice versa, for example, as seen in the flight patterns for FNC-ARN and HRG-ARN.

Table AI.6 shows the calculated average route distances within Swedish territory for the Novair and Flightradar24 datasets. The route distances calculated for both datasets were comparable, except for the routes ARN-HRG and HRG-ARN. The route distance calculated in between ARN and HRG for the Flightradar24 dataset is almost twice as long as the distance calculated for the Novair dataset. This is because there were less than 10 flights in the Flightradar24 dataset between the airports ARN and HRG. Among these flights, most of them fly towards the south to exit Swedish territory and thus attain longer flight routes within Swedish territory while most of the Novair flights fly towards the southeast to exit Swedish territory and thus having much shorter flight routes.

Table AI.7 shows the average total fuel use and CO_2 emission for the different routes based on Novair FDR data and also the corresponding numbers within Swedish territory. Table AI.8 shows the corresponding numbers for the total fuel use and CO_2 emission using GCD distances along with the fuel use and CO_2 emission within Swedish territory calculated using the SMHI flight emission model. Focusing on the emissions within Swedish territory the difference between FDR data and the SMHI model is large for the routes ARN-HRG and HRG-ARN as expected due to the difference in route distance discussed above. For the remaining airport pairs the SMHI model overestimates the fuel use by about 12%. This difference can mainly be explained by the fact that fuel burn factors for the relatively new LEAP 1A engine on the Novair A321-251N aircrafts is lower than for the older aircraft A321-131 with 3lA008 engine that was used in the calculations. Considering this the agreement is very good.

Table AI.6. Average route distances in nautical miles (nm) within Swedish territory calculated from FlightRadar24 and Novair dataset.

	Route distances (nm) Novair	Route distances (nm) FR24
ARN-FNC	229.6	262.4
ARN-HRG	119	232.1
ARN-LPA	237.9	268.9
ARN-CHQ	233.6	251
FNC-ARN	232.4	261
HRG-ARN	94.4	187.2
LPA-ARN	235.8	267.3
CHQ-ARN	210.7	238.4

Table AI.7. Total average route distances in nautical miles (nm) between two airports, interpolated fuel/nm, total amount of fuel used (kg), CO_2 emissions (kg), and fuel used (kg) and CO_2 emissions (kg) within the Swedish territory calculated from the Novair dataset .

Novair	Total average route distance (nm)	Fuel (kg)/nm	CO2 (kg)/ (kg) fuel	Total fuel used (kg)	Total emission of CO2 (kg)	Fuel used within Swedish territory (kg)	Emission of CO2 within Swedish territory (kg)
ARN-FNC	2 256.4	6.488720	3.15	14 641	46 120	1 490	4 693
ARN-HRG	2 174.8	6.505040	3.15	14 147	44 564	774	2 438
ARN-LPA	2 522.6	6.440000	3.15	16 246	51 173	1 532	4 826
ARN-CHQ	1 529.3	6.483516	3.15	9 915	31 233	1 515	4 771
FNC-ARN	2 285.7	6.482860	3.15	14 818	46 676	1 507	4 746
HRG-ARN	2 220	6.496000	3.15	14 421	45 427	613	1 932
LPA-ARN	2 484.6	6.443080	3.15	16 008	50 427	1 519	4 786
CHQ-ARN	1 528.7	6.483444	3.15	9 911	31 220	1 366	4 303

Table AI.8. Great circle distance in nautical miles (nm) between two airports, interpolated fuel/nm, total fuel used (kg) and CO_2 emissions (kg), and fuel used (kg) and CO_2 emissions (kg) within the Swedish territory calculated using the SMHI flight emissions model.

FR24	Total average route distance (nm)	Fuel (kg)/nm	CO2 (kg)/ (kg) fuel	Total fuel used (kg)	Total emission of CO2 (kg)	Fuel used within Swedish territory (kg)	Emission of CO2 within Swedish territory (kg)
ARN-FNC	2 123.8	6.515240	3.15	13 837	43 587	1 710	5 385
ARN-HRG	2 058.9	6.528220	3.15	13 441	42 339	1 515	4 773
ARN-LPA	2 343.2	6.471360	3.15	15 164	47 766	1 740	5 481
ARN-CHQ	1 470.0	6.486600	3.15	9 535	30 036	1 628	5 129
FNC-ARN	2 123.8	6.515240	3.15	13 837	43 587	1 700	5 357
HRG-ARN	2 058.9	6.528220	3.15	13 441	42 339	1 222	3 850
LPA-ARN	2 343.2	6.471360	3.15	15 164	47 766	1 730	5 449
CHQ-ARN	1 470.0	6.486600	3.15	9 535	30 036	1 546	4 871

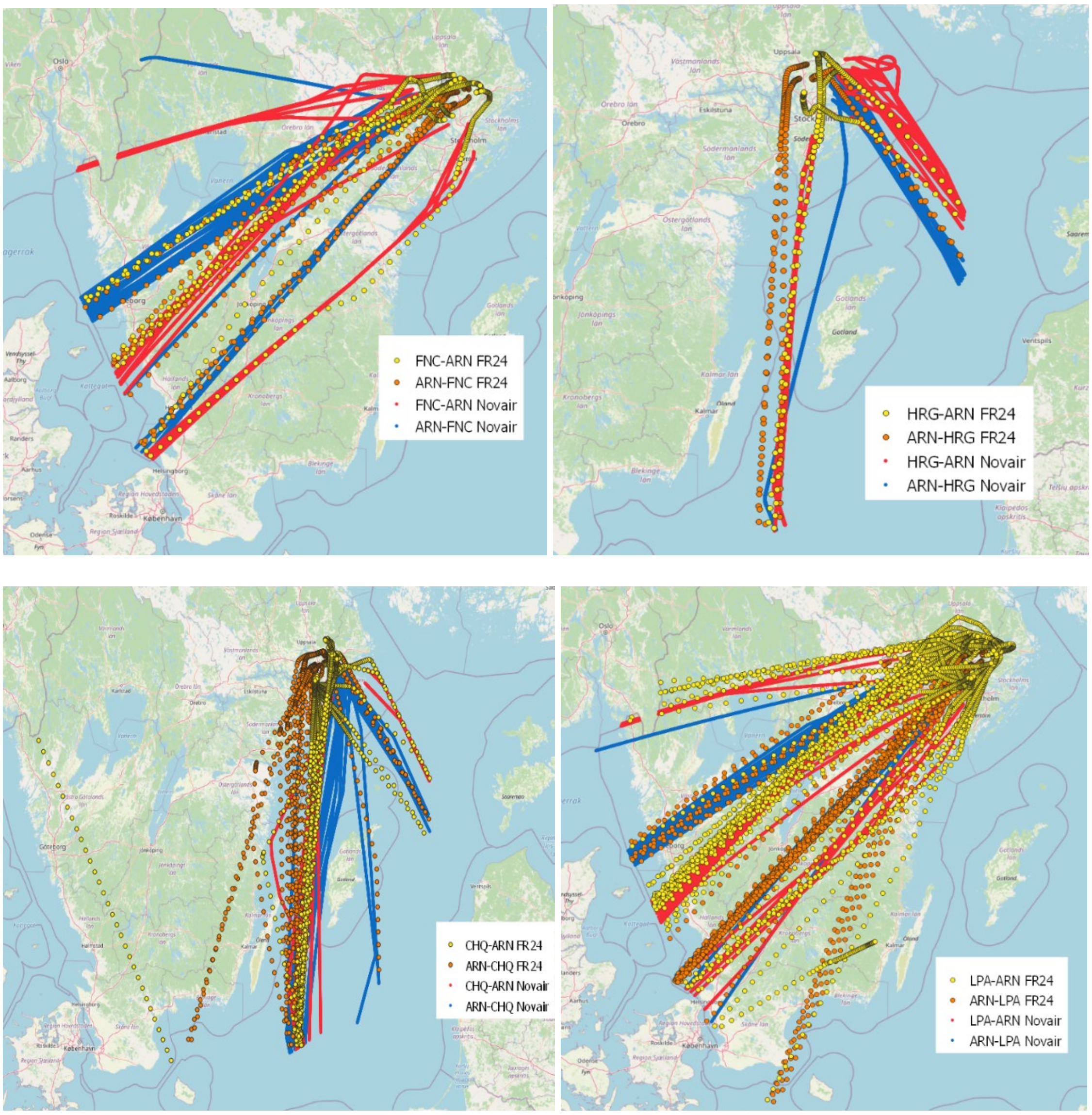


Figure AI.3. Flight routes in between FNC-ARN, ARN-FNC, HRG-ARN, ARN-HRG, CHQ-ARN, ARN-CHQ, LPA-ARN, ARN-LPA for Flightradar24 and the Novair dataset. Background map from openstreetmap.org, © OpenStreetMap contributors.

9 Appendix II

9.1 Description of the emission and climate calculators

9.1.1 ICAO for passengers

The methodology of ICAO's Carbon Emission Calculator (ICAO, 2021) is provided in an open-source format, making it possible for individual air carriers to customize it with their own data.

The ICAO Carbon Emission Calculator requires that the user inputs the airport of origin and destination for a direct through flight (i.e., a flight which does not have a change of the flight number). This is then compared with the published scheduled flights to obtain the aircraft types used to serve the two airports concerned and the number of departures per aircraft. Each aircraft is then mapped into one of the 312 equivalent aircraft types in order to calculate the fuel consumption for the trip based on the GCD between the airports. The passenger load factors, and passenger to cargo ratios, obtained from traffic and operational data collected by ICAO, are then applied to obtain the proportion of the total used fuel that can be attributed to the passengers carried. The system then calculates the average fuel consumption for the journey weighted by the frequency of departure for each equivalent aircraft type. This is then divided by the total number of economy class equivalent passengers, giving an average fuel burn per economy class passenger. The result is then multiplied by jet fuel emission factor 3.16 (kg CO_2/kg fuel) in order to obtain the amount of CO_2 footprint attributed to each passenger travelling between those two airports. The cabin class correction factor used by ICAO has been described in Section 2.4.

The steps for the estimation of CO_2 emissions per passenger:

Step 1: Estimation of the aircraft fuel burn
Step 2: Calculation of the passengers' fuel burn based on a passenger/freight factor which is derived from Revenue Tonne Kilometres data[2]
Step 3: Calculation of seats occupied (assumption: all aircraft are entirely configured with economic seats). Seat occupied = Total seats * Load Factor
Step 4: CO_2 emissions per passenger = (Passengers' fuel burn * 3.16) / Seat occupied

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[2] RTK correspond to the transport of 10 passengers for 1 kilometre or of 1 tonne gods for the same distance. A weight of 100 kg is accounted for each passenger

The passengers interested in their CO_2-footprint, must fill out a form with information on origin, destination, number of passengers, if it is a one way or round trip and what cabin class the passenger is travelling in. According to ICAO, the methodology is based on the best publicly available industry data on aircraft types, route specific data, passenger load factors and cargo carried.

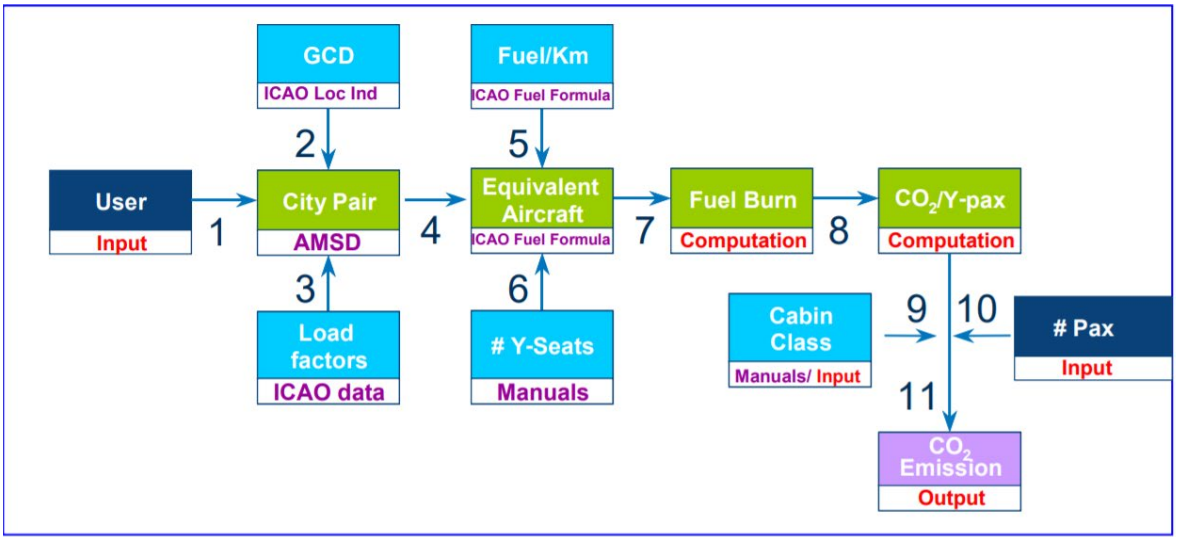


Figure AII.1. Diagram of the steps and information used in ICAO's calculator and the data sources present in the database. (from ICAO, 2018)

Figure AII.1, taken from ICAO´s Carbon Emissions Calculator Methodology (ICAO, 2018), is the schematic representation of the database and its sources used by the calculator.

City Pair: It is obtained from the airlines multilateral schedules database (AMSD). The flight schedule data are based on the latest available information and are updated annually.

GCD: The distance between origin and destination airports is derived from latitude and longitude coordinates originally obtained from ICAO Location Indicators database.

Load Factors: The average generic factors considered for the purpose of the calculation are sourced from the Traffic by Flight Stage database (TFS) which collects air carrier city-pair specific traffic data by aircraft type produced on an annual basis, and domestic traffic and operational data, both collected by ICAO, as well as data based on the flight schedules published by the air carriers.

Fuel/km: This information, per equivalent aircraft model, is obtained from the ICAO Fuel Consumption Formula.

Y-seats: It is the number of economy seats that can be fit inside the equivalent aircraft. ICAO made use of a standard cabin layout (in terms of location of galleys, toilets and exits) for each reference aircraft.

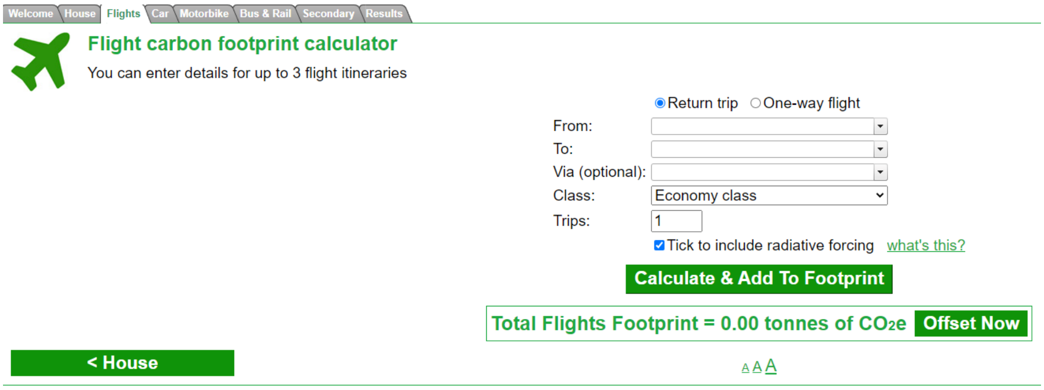
One Way/Round Trip: Round Trip
Cabin Class: Economy
Number of Passengers: 1
Leg: 1
From City/Airport:
To City/Airport:

Figure AII.2. The ICAO Carbon Calculator (ICAO, 2021)

9.1.2 Flight Carbon Footprint Calculator

The Flight Carbon Footprint Calculator is an emissions calculator provided by a private environmental consultancy firm called Carbon Footprint Ltd that also offers services such as carbon offsetting. It is based on publicly available data and estimates on GHG emissions (Carbon Footprint, 2021). According to the information available on the website, the distance between two given airports of departure and destination is first calculated by using the greater circle method. Then this distance is multiplied by the appropriate emissions factor specific to the type of flight (UK domestic, short haul or long haul) and the class of seat taken (e.g. economy class, business class etc.). Based on provided information on the website, the emissions factors include the distance uplift to compensate for planes not flying using the most direct route i.e. flying around international airspace, stacking etc.

Users of the calculator can select type of trip (return trip vs one-way flight), stop-over airport, class of flight and number of trips apart from departure and destination airports. Users can also choose radiative forcing to be included. The result of calculations is presented in the form of metric tons of CO_2e (Carbon Footprint Flight Tab, 2021).



Flight carbon footprint calculator

You can enter details for up to 3 flight itineraries

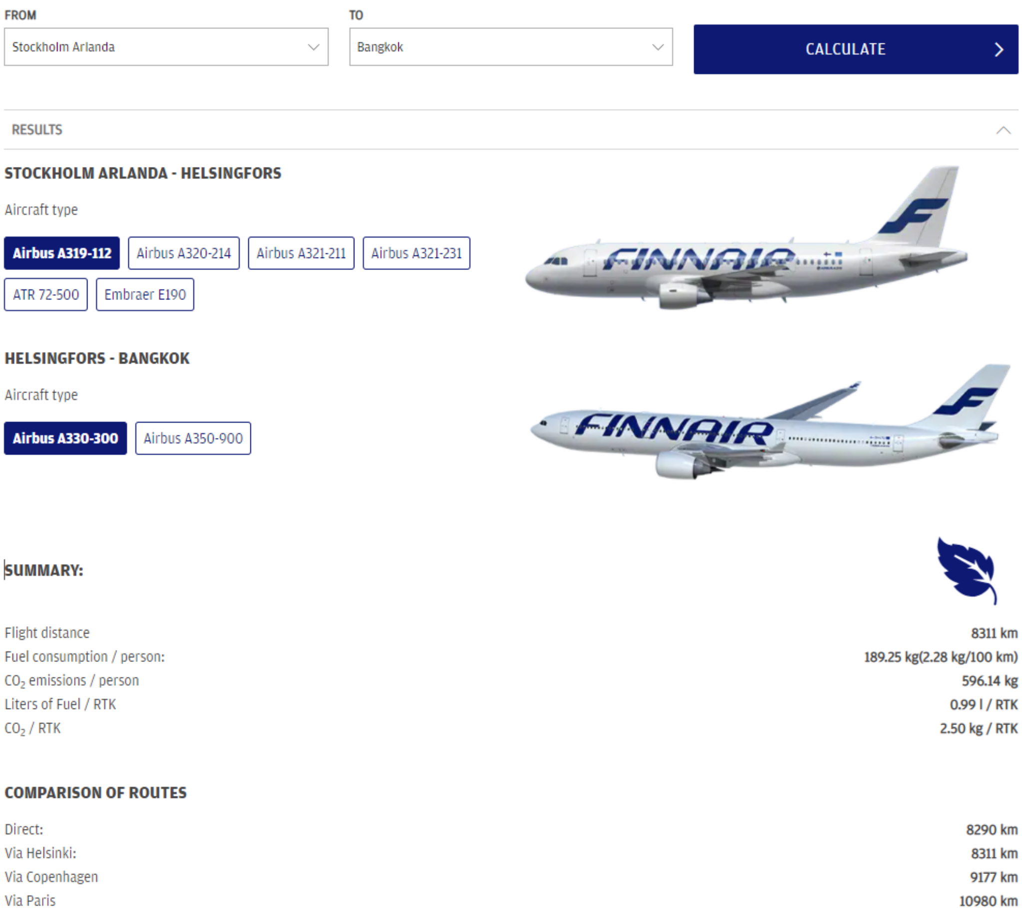
● Return trip ○ One-way flight
From:
To:
Via (optional):
Class: Economy class
Trips: 1
☑ Tick to include radiative forcing what's this?

Total Flights Footprint = 0.00 tonnes of CO_2e

Figure AII.3. Picture of starting page for the Flight Carbon Footprint Calculator (Carbon Footprint, 2020)

9.1.3 Finnair

Finnair’s calculator allows to search only for a selection of the company’s bookable routes. Calculations are based on the actual cargo, passenger, and fuel consumption data for Finnair’s air transportation in the previous financial year. The data is updated four times a year. The fuel consumed is calculated for each flight in relation to the weight of the cargo and passengers. In the calculator, the fuel allocated to the passengers’ share is shown. In the calculations, all the aircraft types flown by Finnair on the route are included. Finnair states that they report only CO_2 emissions that they can accurately verify (Finnair, 2021).



FROM: Stockholm Arlanda

TO: Bangkok

STOCKHOLM ARLANDA - HELSINGFORS

HELSINGFORS - BANGKOK

SUMMARY:

Flight distance	8311 km
Fuel consumption / person:	189.25 kg(2.28 kg/100 km)
CO_2 emissions / person	596.14 kg
Liters of Fuel / RTK	0.99 l / RTK
CO_2 / RTK	2.50 kg / RTK

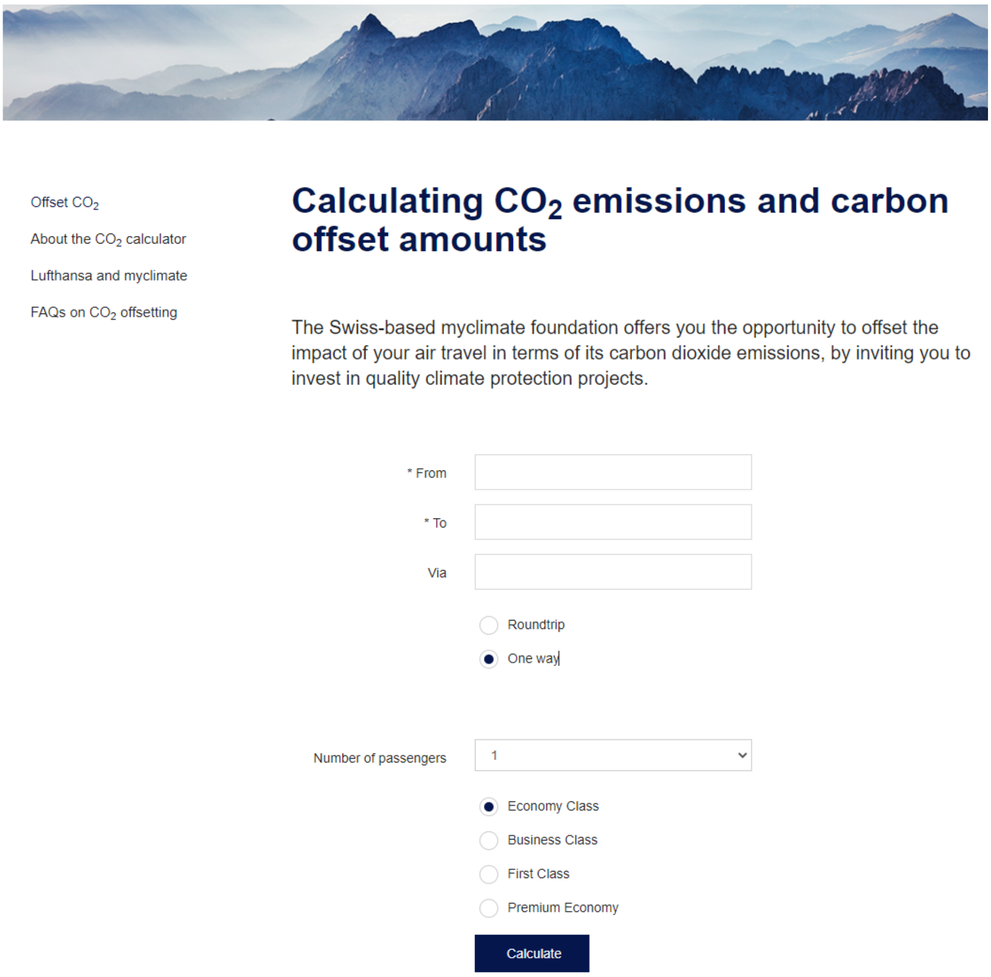
COMPARISON OF ROUTES

Direct:	8290 km
Via Helsinki:	8311 km
Via Copenhagen	9177 km
Via Paris	10980 km

Figure AII.4. Picture of the starting page for Finnair Emissions calculator with example calculation (Finnair, 2021) https://www.finnair.com/se/se/emissions-calculator

9.1.4 Lufthansa

Lufthansa has worked together with the Swiss-based foundation Myclimate since 2007 to develop a carbon calculator and use the Lufthansa emission figures in improving the carbon calculator. According to Lufthansa, the developed algorithm analyzed 43 000 flights representative for their aircraft fleets and can calculate the CO_2 emissions generated and allocated per person. There is the possibility to differentiate between travel classes business or economy. The calculator does not consider any other types of emission or radiative forcing (Lufthansa calculations, 2021). More can be read below in section 3.9 on Myclimate.



Calculating CO_2 emissions and carbon offset amounts

The Swiss-based myclimate foundation offers you the opportunity to offset the impact of your air travel in terms of its carbon dioxide emissions, by inviting you to invest in quality climate protection projects.

* From
* To
Via
○ Roundtrip
● One way

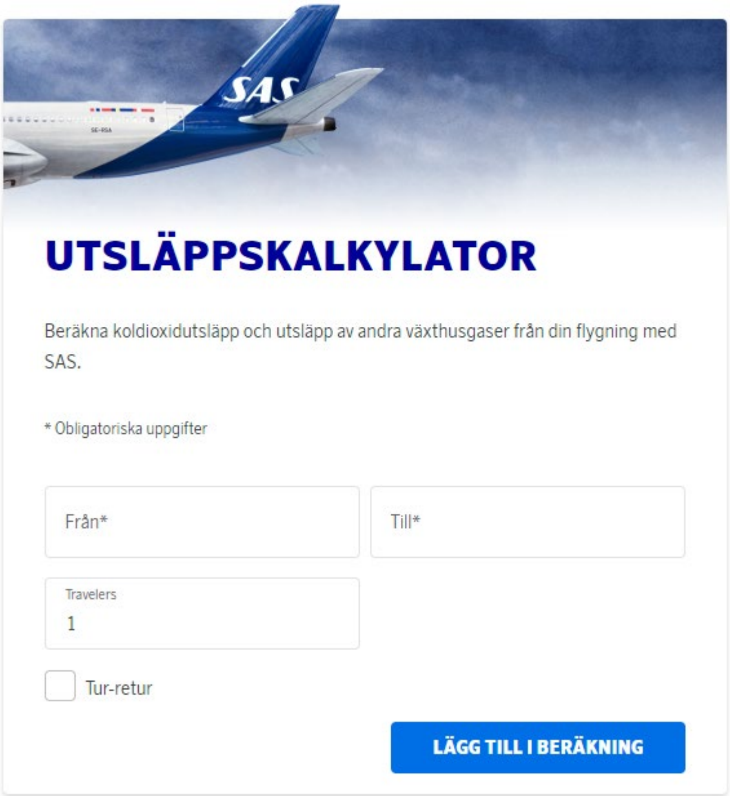
Number of passengers: 1
● Economy Class
○ Business Class
○ First Class
○ Premium Economy

Figure AII.5. Picture from Lufthansa and Myclimate CO2 emission calculator (Lufthansa, 2021) https://lufthansa.myclimate.org/en/flight_calculators/new

9.1.5 SAS Emissions calculator

There is no methodology document connected to the SAS emission calculator and not much information on the website on the methodology either. The website states that the emissions calculator calculates fuel burnt and emissions using several parameters. Not all parameters are disclosed, but it is stated that “the most important parameters are the aircraft type and distance flown”. Distance is calculated as the GCD and fuel burnt, and emissions are based on data from aircraft and engine (SAS, 2021). Probably the system also uses algorithms and information from the SAS operated aircrafts, but information on this could not be found.

In the calculator it is possible to select destination and arrival airports, the number of travelers and if the rout is round trip or not. In the result section is then possible to select between a list of possible airplanes. The most common aircraft used associated with the route is highlighted in the list. The result is displayed in kg CO_2. It is possible to select a detailed result view in which other gases emissions are accounted for the chosen route (NO_X, CO, HC, H_2O, and SO_2). The calculator does not offer the possibility to display the results in CO_2 equivalent, so the high-altitude climatic effects are not considered included in the CO_2 emissions result.


UTSLÄPPSKALKYLATOR

Beräkna koldioxidutsläpp och utsläpp av andra växthusgaser från din flygning med SAS.

* Obligatoriska uppgifter

Från*

Till*

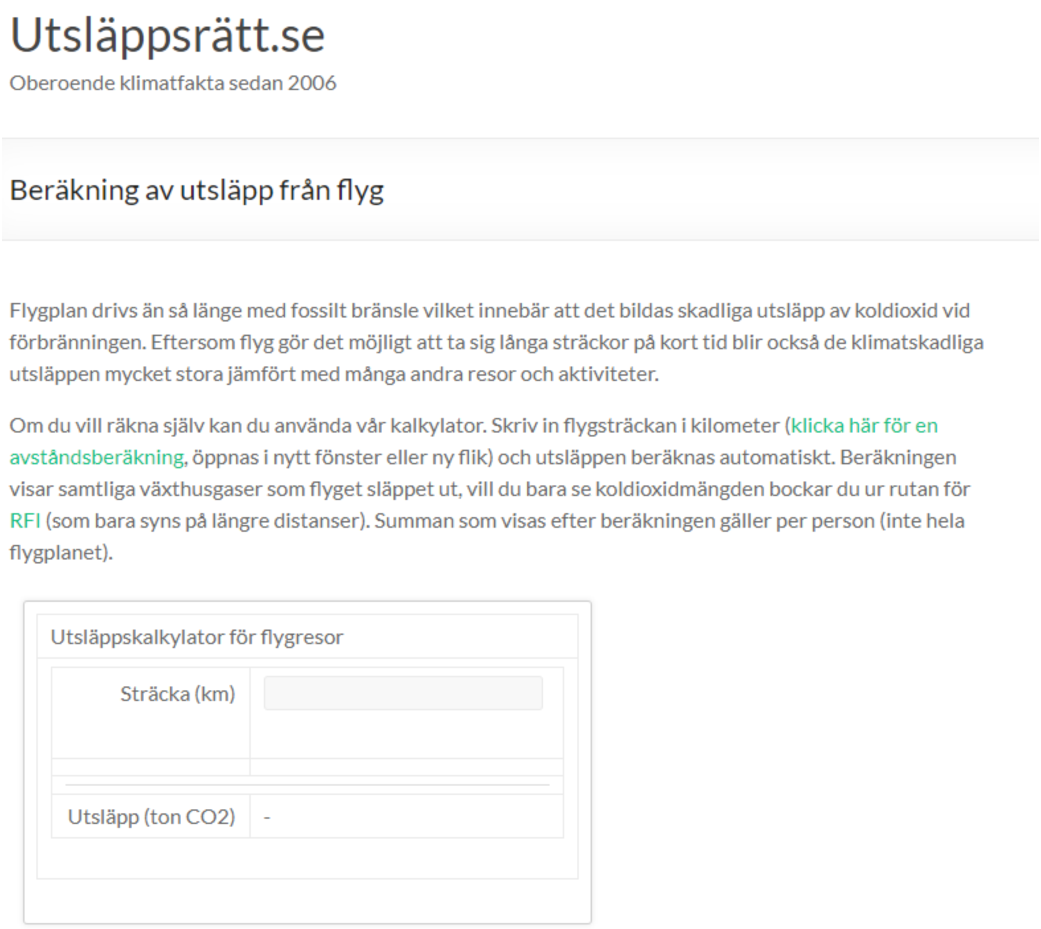
Travelers
1

☐ Tur-retur

Figure AII.6. Picture from SAS Emission calculator (SAS, 2021) https://www.flysas.com/en/sustainability/emission-calculator/

9.1.6 Utsläppsrätt.se

Utsläpprätt.se was founded in 2006 with the goal to provide "independent facts and information about climate compensation and emission licenses". Utsläppsrätt.se is run by the non-profit association Emisso. Emission for a flight can be calculated on the website by putting in its length. An external link to use a flight distance calculator is also provided in case the distance of the flight is unknown. The result of the emission calculator includes all the GHGs emitted by the flight per passenger. It is possible to select only CO_2 emissions by deselecting Radiative Forcing Index in the calculator. A second calculator box offers the possibility to calculate air freight emissions (with or without RFI) by specifying the distance in km and the cargo weight in kg. After email contacts in July 2021 with Petter Lydén, one of the creators behind utslappsatt.se, it was revealed that the calculator was developed in 2010 and the emission factors and the RFI value of 2.7 are taken from IPCC values in the same year. Average fuel consumption, load factor and cabin class factors used in the system has been calculated in year 2010 from the available airplane models.



Utsläppsrätt.se

Oberoende klimatfakta sedan 2006

Beräkning av utsläpp från flyg

Flygplan drivs än så länge med fossilt bränsle vilket innebär att det bildas skadliga utsläpp av koldioxid vid förbränningen. Eftersom flyg gör det möjligt att ta sig långa sträckor på kort tid blir också de klimatskadliga utsläppen mycket stora jämfört med många andra resor och aktiviteter.

Om du vill räkna själv kan du använda vår kalkylator. Skriv in flygsträckan i kilometer (klicka här för en avståndsberäkning, öppnas i nytt fönster eller ny flik) och utsläppen beräknas automatiskt. Beräkningen visar samtliga växthusgaser som flyget släppet ut, vill du bara se koldioxidmängden bockar du ur rutan för RFI (som bara syns på längre distanser). Summan som visas efter beräkningen gäller per person (inte hela flygplanet).

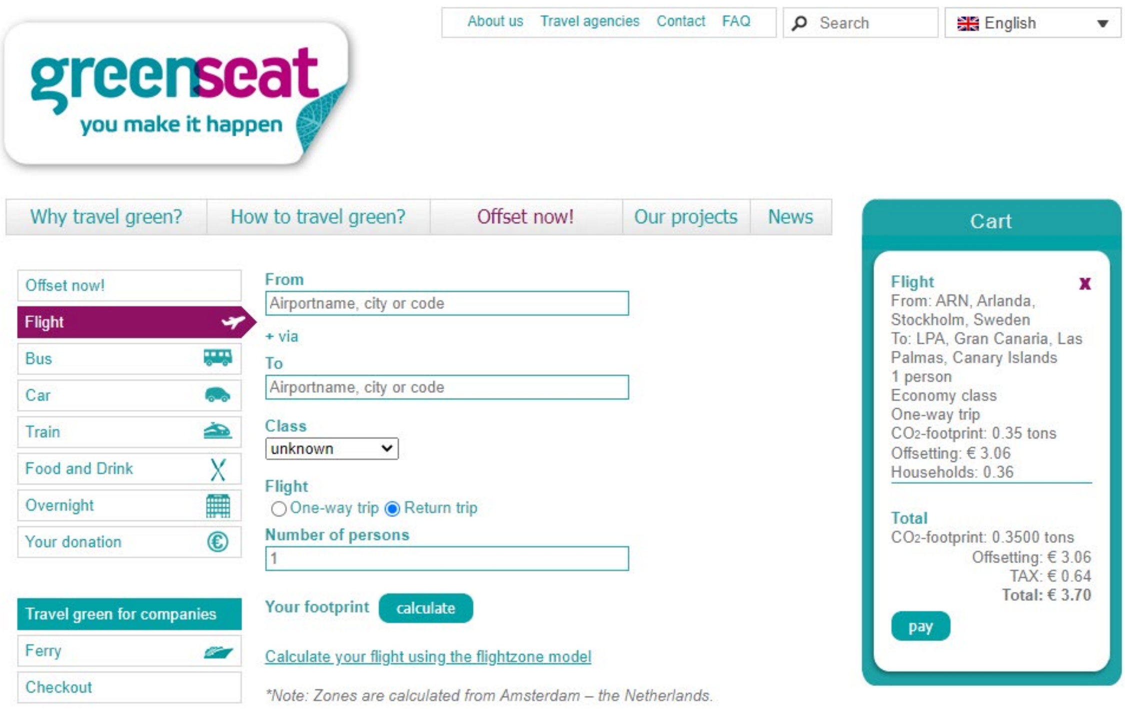
Utsläppskalkylator för flygresor

Sträcka (km)	
Utsläpp (ton CO2)	-

Figure AII.7. Picture of the emission calculator of utsläppsrätt.se (Utsläppsrätt.se, 2021)

9.1.7 GreenSeat

GreenSeat is a Dutch company that assists travelers and travel companies to offset their CO_2 emissions. Ving, which is a Nordic travel company (owned by Nordic Leisure Travel Group), uses GreenSeat since 2007 to offer their clients carbon offsetting according to the calculations done by GreenSeat and the projects that they invest in. GreenSeat have a flight CO_2 footprint calculator on their website. The user can either choose the zone in which they have travelled and get information based on distance from Amsterdam or enter the origin and destination airport, an intermediate landing, whether the flight is one-way or a return trip, the number of passengers and the class (GreenSeat, 2021). Averages are used for data such as load factors and the cargo weight of an aircraft, and they use "the most recent emission factors" (Cuijpers, 2021) Unfortunately, methodology information is not shared on the website (GreenSeat, 2021).



From: Airportname, city or code

+ via

To: Airportname, city or code

Class: unknown

Flight: ○ One-way trip ● Return trip

Number of persons: 1

Your footprint

Calculate your flight using the flightzone model

*Note: Zones are calculated from Amsterdam – the Netherlands.

Cart

Flight
From: ARN, Arlanda, Stockholm, Sweden
To: LPA, Gran Canaria, Las Palmas, Canary Islands
1 person
Economy class
One-way trip
CO_2-footprint: 0.35 tons
Offsetting: € 3.06
Households: 0.36

Total
CO_2-footprint: 0.3500 tons
Offsetting: € 3.06
TAX: € 0.64
Total: € 3.70

Figure AII.8. Picture of the emission calculator of Greenseat (greenseat.nl, 2021) https://greenseat.nl/en/

9.1.8 Climatecare

Climatecare is a privately held company located in United Kingdom (headquarter), Kenya and India. The company provides products such as a carbon calculator, carbon offsets and services such as CSR programs, supply chain and market development projects in India and Africa (Climatecare about us, 2020). The Climatecare carbon calculator methodology is based on first calculating the GCD between the two airports selected. A short haul factor is applied to flights between 0 and 3 700 km, above 3 700 km an International long-haul factor is used. First class or business class flight emit more CO_2 emissions per passenger km as the First and Business class seating takes up considerably more room in the aircraft and equipment and seating is heavier than economy seating. A Radiative Forcing Index of 1.9 is used in the calculator to take account for “the extra gases emitted in the atmosphere” when one flies at higher altitudes. According the Climatecare methodology website, the calculator complies fully with UK government flight factors (Climatecare methodology, 2020).

FLIGHTS

Calculate and offset your flight emissions here:

From: ARN - Arlanda - Stockholm -

Via: Enter airport info

To: ACE - Lanzarote - Las Palma

No. Passengers: 1

Class: Economy

Flight type: ○ Return ● One way

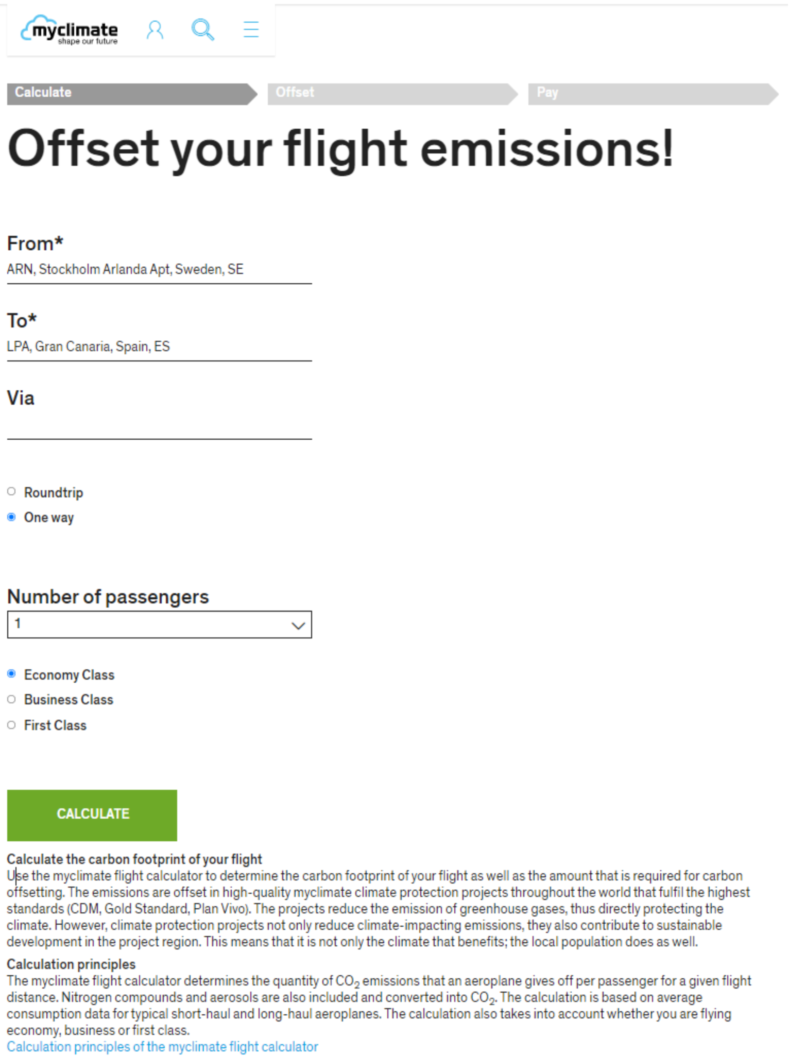
CARBON EMISSIONS

0.62
tonnes of CO_2e

Figure AII.9. Picture of the emission calculator of Climatecare (climatecare.org, 2021)
https://www.climatecare.org/calculator/

9.1.9 MyClimate

MyClimate is a non-profit climate protection organization based in Switzerland. The organization partners with industry and individuals to offer advisory services, education programs as well as carbon offsetting projects (MyClimate about, 2020). Myclimate has a climate calculator (myclimate Flight Emission Calculator) and an offsetting program. Myclimate states that "The factors used are all based on estimates in literature and recent statistics. Wherever possible emission calculations and assumptions are in line with the European standard CEN 16258 (2012)." The myclimate Flight Emission Calculator methodology includes first a calculation of the flight distance based on the GCD. An extra mileage/distance correction of 95km for all flights is added in line with CEN 16258 (2012). Myclimate differentiates between short-haul flights, which is set to less than 1,500 km and long-haul flights which is set to above 2,500 km. Myclimate uses an RFI (Radiative Forcing Index) of 2 in the calculation, which entails multiplying the estimated CO_2 emissions by a factor of 2 to account for the warming effect due to non-CO_2 aircraft emissions. (Myclimate flight emission calculator, 2020). It is used by Lufthansa (see section 3.4 above) and Zeromission, a company started in 2006 by personnel from a consulting firm, with the aim of offsetting emissions (Zeromission, 2020).



Offset your flight emissions!

From*
ARN, Stockholm Arlanda Apt, Sweden, SE

To*
LPA, Gran Canaria, Spain, ES

Via

○ Roundtrip
● One way

Number of passengers
1

● Economy Class
○ Business Class
○ First Class

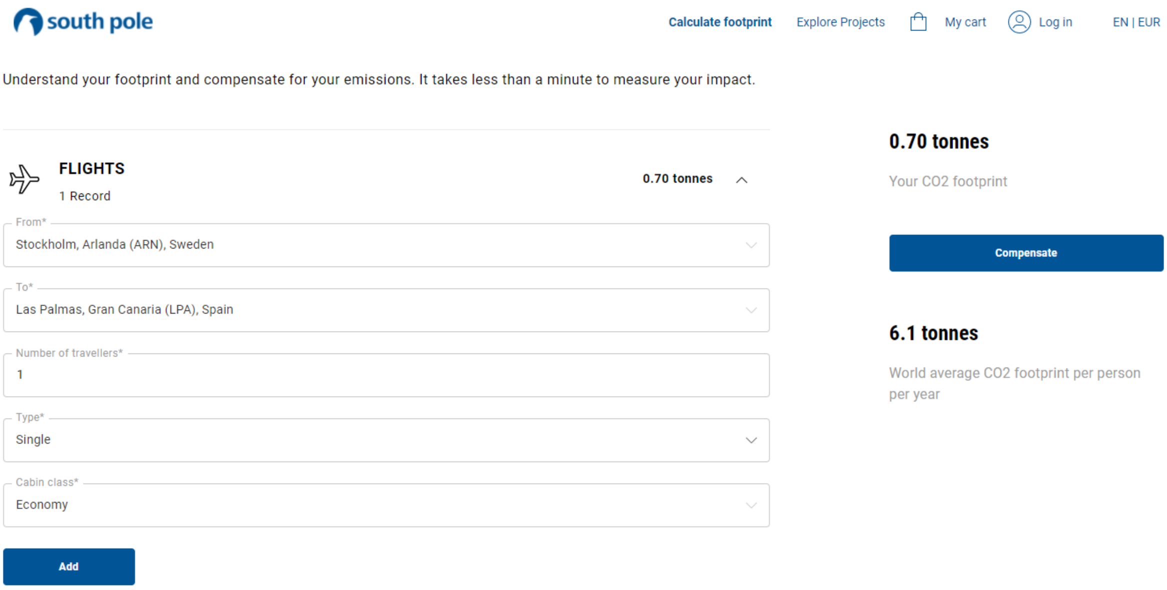
Calculate the carbon footprint of your flight
Use the myclimate flight calculator to determine the carbon footprint of your flight as well as the amount that is required for carbon offsetting. The emissions are offset in high-quality myclimate climate protection projects throughout the world that fulfil the highest standards (CDM, Gold Standard, Plan Vivo). The projects reduce the emission of greenhouse gases, thus directly protecting the climate. However, climate protection projects not only reduce climate-impacting emissions, they also contribute to sustainable development in the project region. This means that it is not only the climate that benefits; the local population does as well.

Calculation principles
The myclimate flight calculator determines the quantity of CO_2 emissions that an aeroplane gives off per passenger for a given flight distance. Nitrogen compounds and aerosols are also included and converted into CO_2. The calculation is based on average consumption data for typical short-haul and long-haul aeroplanes. The calculation also takes into account whether you are flying economy, business or first class.
Calculation principles of the myclimate flight calculator

Figure AII.10. Picture of the emission calculator of Myclimate (co2.myclimate.org, 2021)
https://co2.myclimate.org/en/flight_calculators/new

9.1.10 South Pole

South pole is a company which started in 2006 in Switzerland by the same people who started MyClimate. South pole works to realize decarbonisation pathways across industries and governments. The company provides sustainability financing solutions and services globally (South Pole, 2020). The calculation methodology of South Pole for GHG emissions from flights is based on the GHG protocol, developed by the World Resources Institute and the World Business Council for Sustainable Development. South pole also uses the UK Department for Business, Energy & Industrial Strategy (UK BEIS) methodology on the calculation of GHG emissions from flights. The distance between two airports is calculated, and then an 8 percent uplift factor is added to scale up the flight GCD. Depending on the distance travelled (short-haul < 463 km; medium-haul 463-3 700 km; long-haul >3 700 km) and type of seating (economy class, business class and first class), the emissions increase. For short-haul flights, only Economy class is considered, for medium-haul flights Business and First class is considered equal to 1.5 economy seats. For long-haul flights, the premium Economy or Economy + class is 1.6 economy seats, Business class is equal to 2.9 and First class is equal to 4 economy seats. South pole methodology also includes indirect emissions such as well-to-tank (WTT) emissions from the aviation fuel lifecycle and a Radiative Forcing Index (RFI) multiplier of 1.9 (South Pole Flight emissions calculation methodology, 2020).



Understand your footprint and compensate for your emissions. It takes less than a minute to measure your impact.

FLIGHTS
1 Record
0.70 tonnes

From*: Stockholm, Arlanda (ARN), Sweden
To*: Las Palmas, Gran Canaria (LPA), Spain
Number of travellers*: 1
Type*: Single
Cabin class*: Economy

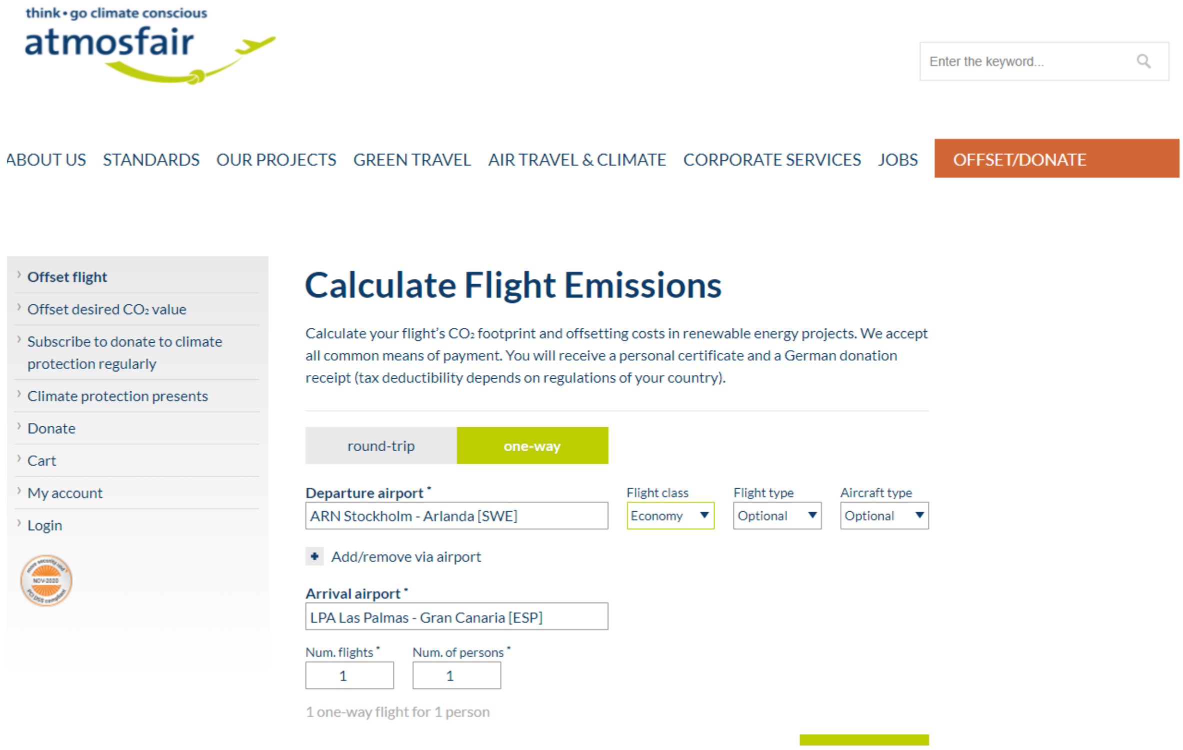
0.70 tonnes
Your CO2 footprint

6.1 tonnes
World average CO2 footprint per person per year

Figure AII.11. Picture of South Pole emission calculator (market.southpole.com, 2021) https://market.southpole.com/individual

9.1.11 Atmosfair

Atmosfair is a German non-profit organization aiming to decarbonize the world economy. The organization design software tools and assist businesses lowering the companies' impact on the climate, with focus on business travel (Atmosfair, 2021). The Atmosfair flight emissions calculator uses the method of the Atmosfair Airline Index (AAI). The Atmosfair Airline Index contains data from 32 million flights, data from more than 200 of the world’s largest airlines, 22 300 city pairs worldwide, 119 aircraft types (which covers 97 percent of the global market) and include data from 408 engines (which covers 96 percent of the global market). As of 2016 the index covered approximately 92 percent of global air traffic. The 8 percent not included is calculated using averaged values from IATA and ICAO for the respective world region. The AAI methodology is based on the carbon calculation method of ICAO. The CO_2 emissions are simulated using a computer model Piano-x (www.lissys.uk). The model uses the fuel consumption of a complete aircraft on a given route. The resulting carbon emissions are then divided by the number of passengers minus the cargo. In the Atmosfair emission calculator, carbon emissions produced during a flight at over 9 kilometers altitude are multiplied by a RFI as high as 3. Carbon emissions emitted at altitudes of less than 9 kilometers are not submitted to any alterations and are directly included in the flight’s carbon footprint (Atmosfair, 2016).



Calculate Flight Emissions

Calculate your flight's CO_2 footprint and offsetting costs in renewable energy projects. We accept all common means of payment. You will receive a personal certificate and a German donation receipt (tax deductibility depends on regulations of your country).

Departure airport *: ARN Stockholm - Arlanda [SWE]
Flight class: Economy
Flight type: Optional
Aircraft type: Optional
Arrival airport *: LPA Las Palmas - Gran Canaria [ESP]
Num. flights *: 1
Num. of persons *: 1

1 one-way flight for 1 person

Figure AII.12. Picture of Atmosfair's emissions calculator (atmosfair.de, 2021) https://www.atmosfair.de/en/offset/flight/

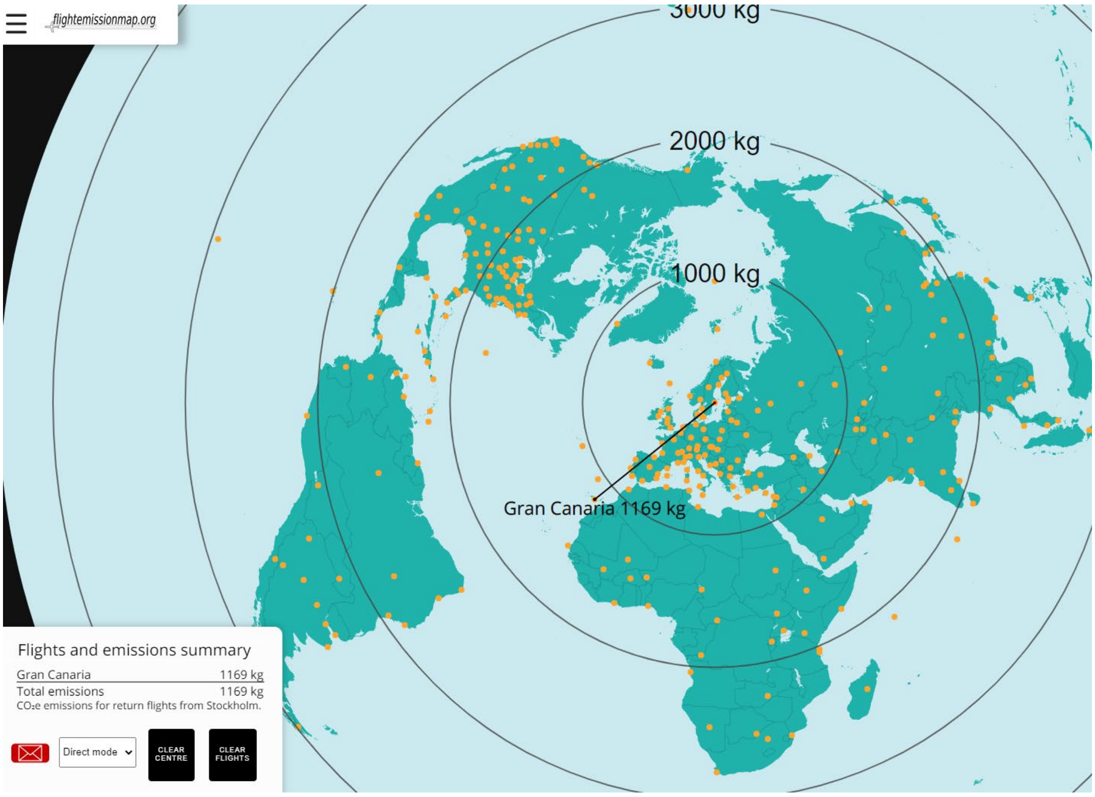
9.1.12 Flight emission map

Flight Emission Map is a GHG emission calculator developed and continuously updated by a group of professors at Chalmers University in Gothenburg. According to the author the site is intended as an educational tool.

The interface of the calculator displays a world map with yellow clickable dots representing airports for which the calculator can compute emissions. The user clicks on the airports of interest for computing the route and the result, displayed simultaneously in a corner, is expressed in kg CO_2 equivalents per passenger and it includes the return flight(s). There is the possibility to choose transit mode.

The emission presented are computed multiplying the flight distance with a fixed factor called (FEM factor) which is annually updated. FEM factor expresses CO_2-e emission per passenger km. In 2021 FEM value was 134 g CO_2-e pax/km and, besides accounting for non-CO_2 effects, it includes even emissions from production and distribution of fuel. Despite short distance flights have higher emission per passenger km, the factor is not dependent on flight distance. The reason behind this is the fact that taking into account non-CO_2 effects of flights with a longer distance, and hence with a higher average altitude, counterbalance the higher the higher passenger km emission value of shorter flights.

Flight emissions are also largely dependent on the flight class, but FEM factor represents only economy flights. The FEM factor is determined by three components: average CO2 emissions from international air travels, non-CO2 emissions (based on a RFI equal to 1.7), and upstream emission from the fuel production and distribution (ca. 20% on top of the CO_2 emission). The methodology to determine FEM factor is based on 5 peer-reviewed articles that are made available on the calculator's website.



Flights and emissions summary

Gran Canaria	1169 kg
Total emissions	1169 kg

CO_2e emissions for return flights from Stockholm.

Figure AII.13. Picture of Flight Emission Map emissions calculator (flightemissionmap.org, 2021) https://flightemissionmap.org/

9.1.13 NTM

NTM stands for Network for Transport Measures which is a non-profit association developing standards to calculate environmental performance from transportation. The NTM air emissions calculations are done in two steps, firstly calculation of the total emission of the flight, and secondly allocation of emission either to cargo or to passengers. To calculate the emission the following input is needed: distance of each flight, the vehicle used (i.e., aircraft model), the load factor and the weight of the shipment or the functional unit chosen. The NTM emission database is based on FOI-3 method already described earlier (Mårtensson and Hasseltor, 2013). Two different emission factors are used: constant emission factor and variable emission factor. Constant Emission Factor (CEF) is connected to the high fuel use during take-off and landing, and Variable Emission Factor (VEF) that is multiplied with the GCD in kilometers (emissions during cruise phase).

Emissions will differ, depending on the aircraft type and fuel used. Emission outputs are carbon dioxide, nitrogen oxides (NOx), hydrocarbon (HC) and carbon monoxide (CO).

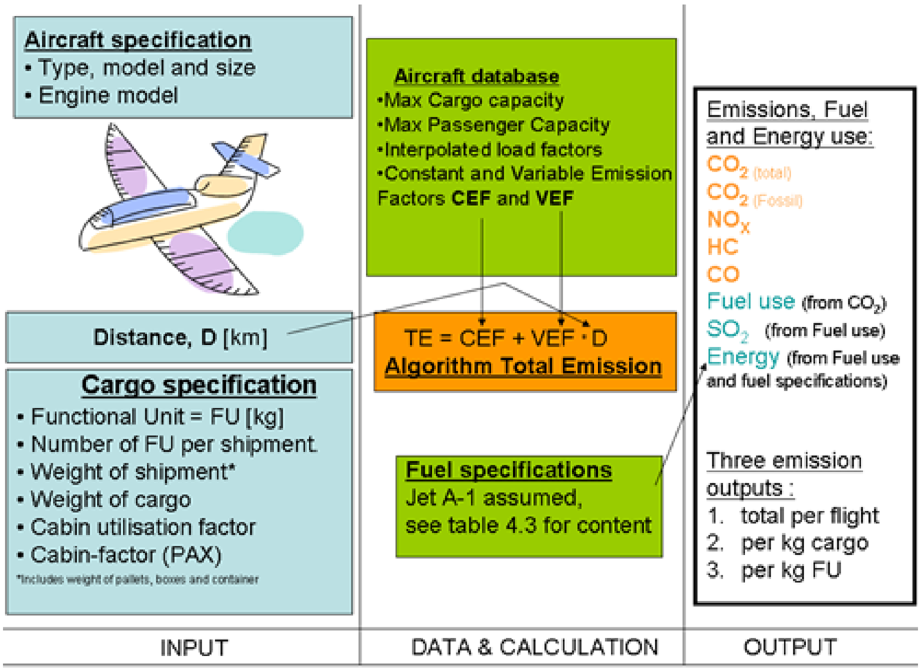


Figure AII.14. NTM-calc air transport calculations

9.1.14 Klimatkompensera.se

Klimatkompensera.se is run by Tricorona Climate Partner AB, which offers climate compensation and climate-related services to Swedish companies, organizations and authorities (Klimatkompensera, 2020). The methodology used is based on the calculation framework from NTM (Network for Transport Measures). The calculations include origin and destination of travel, airplane type and cabin factor. The cabin factor is taken from NTM standard values, which in turn is based on data from ICAO. If the flight includes a stopover, every part of the flight is calculated and added to a total value, including emissions during taxi, takeoff and landing for each time it occurs. Flights GCDs between the airports are also calculated, but there is no explanatory methodology presented on the website. Results show emissions of CO_2 per passenger multiplied with an RFI-factor of 1.9. Data can also be accessed per region or distance category: The Nordics, Europe (excluding Nordic countries) and the World (all flights excluding Europe). The values used for each region or distance category come from statistics from Swedavia[3] for all flights during the previous year to and from Swedavia's airports (Klimatkompensera.se beräkningsmetodik, 2020).

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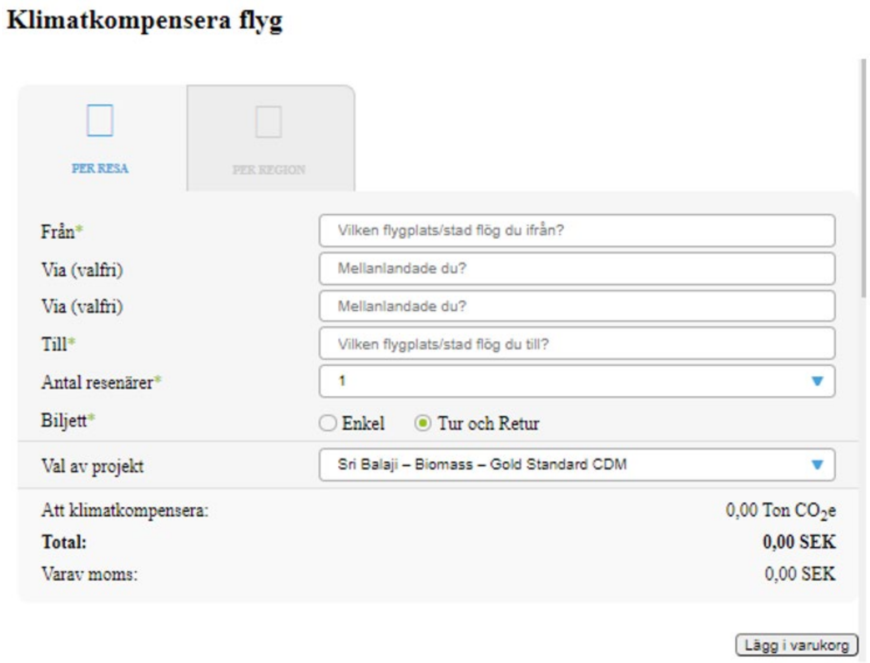
[3] Swedavia own and operates a national basic network of airports in Sweden.

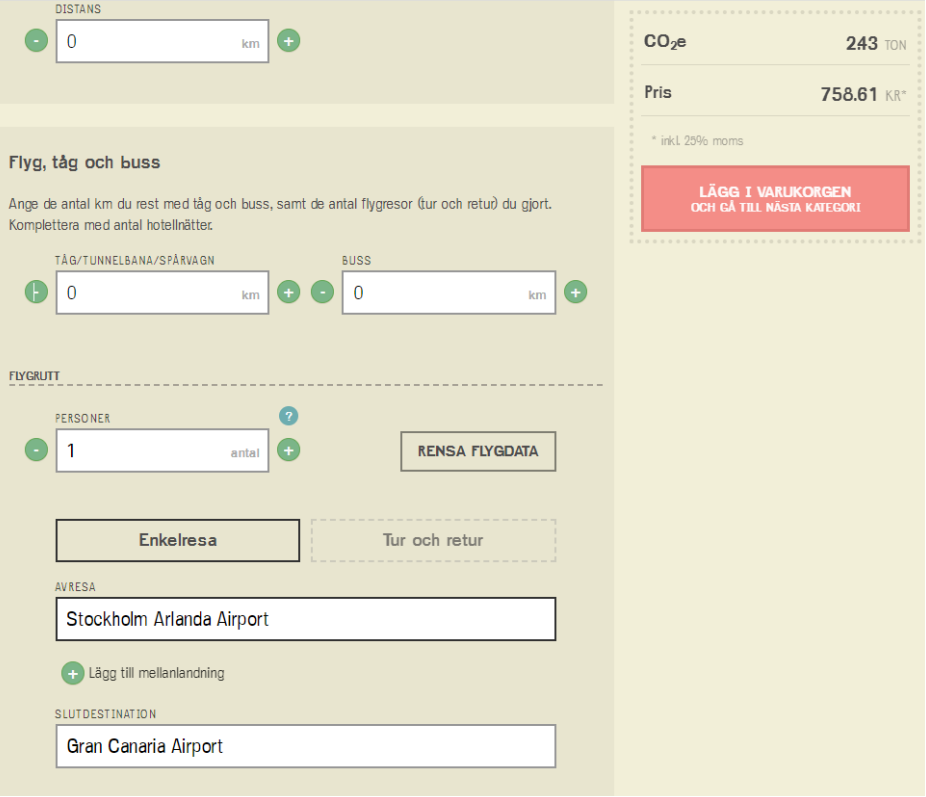

Klimatkompensera flyg

Från* Vilken flygplats/stad flög du ifrån?
Via (valfri) Mellanlandade du?
Via (valfri) Mellanlandade du?
Till* Vilken flygplats/stad flög du till?
Antal resenärer* 1
Biljett* ○ Enkel ● Tur och Retur
Val av projekt Sri Balaji – Biomass – Gold Standard CDM
Att klimatkompensera: 0,00 Ton CO$_2$e
Total: **0,00 SEK**
Varav moms: 0,00 SEK

Figure AII.15. Picture of Klimatkompensera's emissions calculator (klimatkompensera.se, 2021) https://klimatkompensera.se/produkt/klimatkompensera/

9.1.15 Vi-skogen

Vi-skogen is a Swedish foundation working with agroforestry in Kenya, Rwanda, Uganda and Tanzania. The board and chairman are elected by the Cooperative Association in Sweden and the board should include the editor-in-chief of the magazine "Vi" (Vi-skogen om oss, 2020). Emission calculation from flights is based on emission factors from NTM (Network for transport measures). Users of the emission calculator from Vi-skogen can fill in origin and destination of travel, and possibly stop over, if needed. The emissions are calculated based on the number of km between the airports, data taken from Google Maps API using the GCD. Depending on the distance travelled (0 < 463 km; 464 - 1 108 km; 1 109 – 6 482 km; >6482 km), different emission factors (0.24; 0.15; 0.14; 0.14) and RFIs (1; 2; 2; 2) resulting in different CO$_2$e emission factors (0.24; 0.30; 0.28; 0.28) are used. The user can, as an alternative, use time length as an alternative input to calculate the emissions associated with the flight. Travel up to 3 hours in length is up to 2 000 km, 6 hours flight time is up to 4 500 km, 9 hours of flight, 7 000 km and above 9 hours of flight commonly include all flights with stop-overs. As detailed information about that type of trip is not known, flights within this interval are calculated based on the travel distance of 15 600 km, a trip corresponds to Stockholm - Sydney, Australia, without a stopover (Wickström, 2020).



DISTANS: 0 km

Flyg, tåg och buss

Ange de antal km du rest med tåg och buss, samt de antal flygresor (tur och retur) du gjort. Komplettera med antal hotellnätter.

TÅG/TUNNELBANA/SPÅRVAGN: 0 km

BUSS: 0 km

FLYGRUTT

PERSONER: 1 antal

AVRESA: Stockholm Arlanda Airport

SLUTDESTINATION: Gran Canaria Airport

CO$_2$e 243 TON

Pris 758.61 KR*

* inkl. 25% moms

Figure AII.16. Picture of Vi-Skogen emissions calculator (klimatkalkylatorn.viskogen.se, 2021) https://klimatkalkylatorn.viskogen.se/

9.2 Additional information on comparison of calculators on route and verification with Flight Record Data

Table AII.1. Overview of the results of the calculators assessing emission for the 4 analysed routes. The last two rows show the results of CO_2 emission calculated from FDR data.

Route/Climate calculator	RFI	ARN - LPA		ARN - CHQ		ARN - FNC		ARN - HRG	
		kg CO_2	kg CO_2e	kg CO_2	kg CO_2e	kg CO_2	kg CO_2e	kg CO_2	kg CO_2e
ICAO (pass)	2	296	592	203	407	298	597	252	504
Carbon footprint calculator	1.89	320	605	200	380	290	551	280	530
Finnair A321-231		271		164		291		233	
Lufthansa		259		170		236		229	
SAS 737-800W		295		194		270			
SAS 737-700W		340		224		311			
SAS A320-200NEO		244		160		223			
SAS A350-900		260		168		237			
SAS A330-300		314				286			
Utsläppsrätt.se	2.7	779	2 103	490	1 322	707	1 900	686	
Greenseat		350		260		380		370	
Climatecare	1.9	342	650	221	420	311	590	300	
Myclimate	2	350	700	240	480	328	655	319	637
Zeromission	2	350	700	240	480	328	655	319	
South Pole	1.9	368	700	243	462	337	640	326	620
Atmosfair	2.7	306	826	204	552	286	771	277	748
Klimatkompensera.se	1.9	484	920	263	500	421	800	411	780
Vi-Skogen	2	605	1 210	410	820	550	1 100	535	1 070
Flightemissionmap	1.7	344	584	216	367	311	529	270	460
FDR Novair A321Neo		200		133	252	201	382	179	340
FDR SAS A320Neo		223							

Figure AII.17. CO_2 emissions per passenger per kilometre for the 4 analysed routes for 3 different aircraft types calculated with simplified emission tool (SET) (orange columns), for A320N and A321N calculated from FDR data and calculated with 3 different emission calculators (turquoise columns), one is SAS calculator for A320N.

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