Faculty of Aerospace Engineering

Technische Universiteit Delft

Is Aviation Technology going in the right direction regarding Climate Impact?

Guillaume GRANGIER
5581605

Course:
AE5211 Master Thesis

Supervisors:
Dr. Feijia YIN
Dr. Arvind GANGOLI RAO

Delft, October 31st 2023

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List of Abbreviations

Abbreviation	Description
ADS-B	Automatic Dependent Surveillance–Broadcast
AEDT	Aviation Environmental Design Tool
AEIC	Aviation Emissions Inventory Code
AIC	Aircraft Induced Clouds
APMI	Aircraft Performance Model Implementation
ATC	Air Traffic Control
BADA	Base of Aircraft DAta
BC	Black Carbon
BFFM2	Boeing fuel flow method
CFD	Computational Fluid Dynamics
CiC	Contrail induces Cloudiness
COALA	Compromised Aircraft performance model with Limited Accuracy
DLR	Deutsches Zentrum für Luft und Raumfahrt (German Center for Air and Space-flight)
EI	Emission Index
ERF	Effective Radiative Forcing
ETFMS	Enhanced tactical flow management system
ETMS	Enhanced Traffic Management System
FAA	Federal Aviation Administration
FATE	Four-dimensional Calculation of Aircraft Trajectories and Emissions
FDR	Flight Data Recorder
FOA	First-Order Approximation
FOI	Swedish Defence Research Agency
GAEC	Global Atmospheric Emissions Code
GAME	General Aircraft Modelling Environment
GDP	Gross Domestic Product
GNSS	Global Navigation Satellite System
HC	Hydro Carbons
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IHLG	Industry High-Level Group
IPCC	Intergovernmental Panel on Climate Change
IRF	Instantaneous Radiative Forcing
LTO	Landing and Take-Off
NMHC	Non Methane Hydro Carbons
nvPM	non-volatile Particle Matter
OAG	Official Airline Guide
openAP	Open source Aircraft Performance model
PEP	Performance Engineering Programs
PM	Particle Matter
PMO	Primary Mode Ozone
PSC	Polar Stratospheric Clouds
RF	Radiative Forcing
ROC	Rate Of Climb
ROD	Rate Of Descent
RPK	Revenue Passenger Kilometer
SA	Single Aisle
SAF	Sustainable Aviation Fuel
SAGE	System for Assessing Aviation's Global Emissions
SN	Smoke Number
TA	Twin Aisle TAS
True Air Speed	
TIM	Time-In-Mode
vPM	volatile Particle Matter

List of Symbols

Symbol	Description	Unit
ATR_{100}	Average Temperature Response	$[K]$
C_{fi}	Thrust specific fuel consumption coefficients	$[/]$
D	Aerodynamic drag	$[N]$
f_{nom}	Nominal fuel flow	$[kg/min]$
F_{corr}	Aging engine fuel consumption	$[kg/min]$
F_{new}	New engine fuel consumption	$[kg/min]$
g_0	Gravitational acceleration	$[m/s^2]$
h	Geodetic altitude	$[m]$
m	Aircraft mass	$[kg]$
$P3$	Total pressure at the combustor inlet	$[Pa]$
Thr	Thrust	$[N]$
$T3$	Total temperature at the combustor inlet	$[K]$
V_{TAS}	True airspeed	$[m/s]$
δ	Logarithmic engine degradation	$[/]$
Δpn	Soot particle number change	$[/]$
ΔRF	Radiative Forcing change	$[/]$
ΔTs	Global mean surface temperature change	$[K]$
η	Thrust specific fuel consumption	$[kg/min.kN]$
λ	Climate sensitivity parameter	$[K/Wm^{-2}]$

1 Abstract

The aviation industry is shouting out its aim to reach "net-zero carbon" by 2050. Nevertheless, air traffic is expected to grow up until then, and if fuel consumption is reduced by new technologies and aircraft, other sources of global warming such as NO_x emissions and contrails are less considered. Therefore, the climate impact improvement of new technologies compared to older ones is not straightforward and requires a deep analysis. This work performs such an analysis via three steps: The selection of a new fleet to be compared with the actual fleet (2019), a comparison between the two fleets emissions via an Aviation Emission Inventory code, and a climate impact assessment with the tool AirClim. The new fleet analysed consists of the replacement of 14 old (entry in service before 2002) Airbus and Boeing aircraft with their new versions (entry in service between 2011 & 2018). The results show a reduction of 8.7% of fuel consumed by total aviation just by replacing the 14 old aircraft with the new ones. On the other hand, it leads to an 8.0% NO_x emissions increase. Nevertheless, the climate impact assessment concludes that this NO_x emissions increase lowers the surface temperature change due to aviation. This is explained by the strong influence of NO_x emissions location on its climate impact. Overall, this new fleet leads to a decrease in temperature change due to aviation in 2050 of 5.3 mK (-5.2%). This work gives important conclusions on the priorities that need to be set for the development of 'greener' aviation technologies.

2 Acknowledgements

First, I would like to thank my two supervisors, Dr. Feijia Yin and Dr. Arvind Gangoli Rao, for their precious guidance and feedback. Thanks to them, I have worked on a topic both fascinating and crucial. I feel like I have made a contribution and I am very grateful to have had this opportunity.

I would like to thank Rik for his kindness and selfless support.

I would also like to thank my parents for their constant support and for always giving their best to understand what I do.

I would like to thank my friends, Étienne, Grégoire, Robin and Julien, who erased the loneliness part of this work thanks to many discussions and library days.

Finally, to Marion, thank you for your unlimited support, and for your constant help to find motivation. Thanks to you, this master's thesis is the best work I could do.

3 Introduction

Aircraft manufacturers focus on reducing CO_2 emissions and sometimes mention NO_x emissions [1, 2, 3]. In the meantime, research has been focusing on non-CO_2 emissions to better understand aviation's global impact on climate [4]. Results show that the climate impact of non-CO_2 emissions is very likely to be comparable to CO_2 warming effect, and might be even greater [5]. This makes the 2 to 2.5% figure [6] as aviation's contribution to global CO_2 emissions non-representative of the actual urgency of mitigating aviation's climate impact.
In addition, air traffic is widely expected to continue its growth in the next decades and to double before 2050 [7]. The COVID-19 pandemic has slowed down the traffic increase and probably delayed it by five to ten years, but as all passed crises (the 1973 oil crises, the 9/11 terrorist attack, or the 2007-2008 financial crises for example), it will not reverse the growing trend on a long-term basis [8]. This expected growth intensifies the need to reduce aviation emissions that contribute to global warming.
To mitigate aviation's climate impact, it is necessary to analyse it and, as a first step, quantify its emissions. The most accurate process to make this calculation is the development of a bottom-up inventory. This requires air traffic, aircraft, and engine data as well as performances and emissions tools to estimate the precise emissions of each flight. Such inventories have been developed in the last decades and help to analyse accurately quantities and locations of the species emitted by aircraft [9]. As a second step, aviation emissions' impact on global warming needs to be assessed. To do so, a tool such as AirClim can be used. Developed by V. Grewe and A. Stenke [10], it calculates the surface temperature changes due to aviation emissions.
In this work, the new generation aircraft are compared to their predecessors. This is done through the two steps previously mentioned. First, an Aviation Emissions Inventory code, taken from Kroon et al. (2022) [11] is used to compare their emissions. Then, the results are used as inputs for AirClim to assess their global warming potential.

4 Literature review

4.1 Aviation Climate Impact

4.1.1 Earth's atmosphere

The atmosphere composition is impacted by aviation's emissions and more precisely troposphere and stratosphere are altered. Indeed, subsonic commercial aircraft mostly fly in the Upper Troposphere and the Lower Stratosphere, between 9km and 13km of altitude (See Figure 1) while supersonic aircraft fly at higher altitudes, up to 20km [12]. Species emitted impact the atmosphere in two main ways: direct warming through the greenhouse effect and altering troposphere and stratosphere chemistry. The latter includes enhancing or diminishing already present species such as Ozone or Methane, and influencing the formation of clouds such as contrails, cirrus or PSC (Polar Stratospheric Clouds). Finally, air quality is impacted, especially close to airports where species are emitted at low altitudes.

Studies show that aviation emissions mostly affect the troposphere and their effect on the stratosphere is negligible. Indeed, upper transport is rare and since species are emitted at the lower part of the stratosphere, its global chemistry is only slightly affected. [13]

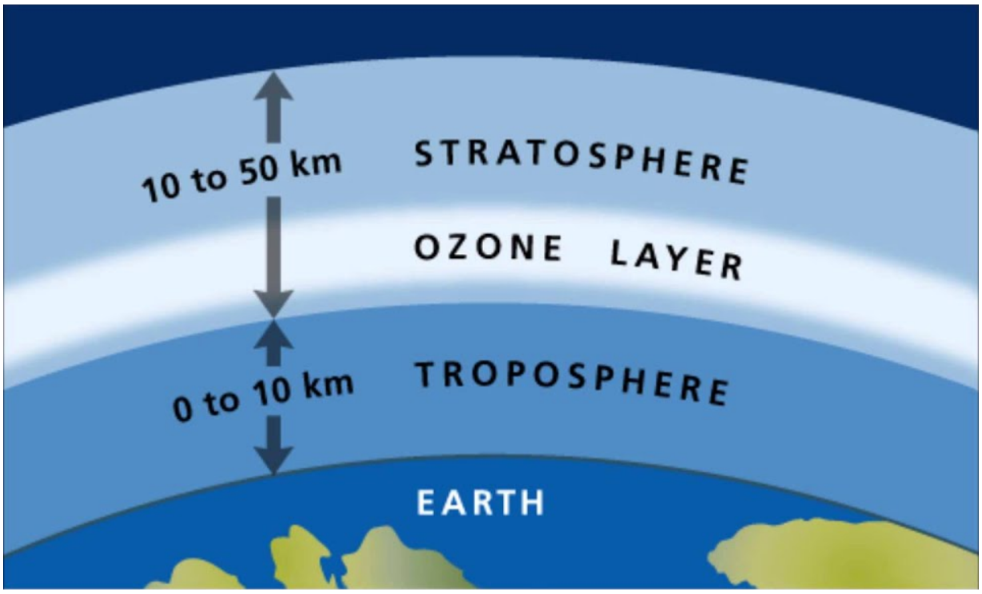

Figure 1: Earth's atmosphere first layers. [14]

4.1.2 Species emitted by aircraft

Most aircraft flying nowadays use kerosene as a fuel which can be chemically described as $C_nH_m + S + aromatics$. The combustion occurring in the engine gives complete combustion products such as CO_2, H_2O, N_2, O_2 and SO_2 (See equations 1 & 2). Because of incomplete combustion and impurities in the fuel, many other products are emitted, mainly: NO_x, CO, HC, $soot$, and SO_x [12].

The most used fuel is kerosene Jet A1 with a mean composition of $C_{12}H_{23}$ which gives the following reaction equation: [13]

$$C_{12}H_{23} + 17.75O_2 \rightarrow 12CO_2 + 11.5H_2O \tag{1}$$

This simplified chemical form is convenient to explain the basics of the combustion of kerosene with air, although it is far from being representative of the detailed chemical kinetics happening [15]. A more precise equation of the complete combustion, without specifying the coefficients: [16]

$$a_1C_nH_x + a_2O_2 + a_3N_2 + a_4S \rightarrow a_5CO_2 + a_6H_2O + a_7O_2 + a_8N_2 + a_9SO_2 \tag{2}$$

Carbon Dioxide CO_2

Carbon Dioxide (CO_2) is the most emitted species by aviation. Most recent studies estimate its Emission Index (EI) to be around $3.16kg/kg^{-1}$ [17] [18]. CO_2 effects are also very well understood, and, as a reference for climate warming due to human activities assessment, it is often cited alone when talking about aviation's impact on climate. Indeed, the figure of 2 to 3% is largely used to account for aviation's contribution to climate change and more precisely to CO_2 emissions [6]. This does not take into account all the other species which are today known to have a larger effect than CO_2 alone [5]. These species are presented further below in this section.

Water vapour H_2O

Water vapour (H_2O) is the other main product of complete combustion. It is the second most emitted species with an Emission index around $1.23 - 1.24kg/kg^{-1}$ [5] [17] [18]. H_2O emissions result in a minor direct impact on climate but are at the origin of contrails formation (See 4.1.3) which have a major contribution to aviation climate impact. H_2O also plays a role in PSC formation and ozone depletion in the stratosphere which tends to have a warming effect. H_2O emissions in the troposphere have a negligible effect since they are small compared to their natural presence and have a short residence time (about 9 days). Nevertheless, stratospheric water vapour emissions have a bigger impact, since their residence time is much longer there (months to years). This results in a direct radiative forcing [12].

Nitrogen oxides NO_x

Nitrogen oxides (NO_x, which represents both NO and NO_2) is formed from the Nitrogen and Oxygen present in the air. The higher the temperature, the more NO_x will be produced. Thus, NO_x emissions are directly proportional to thrust power as shown in Figure 2. NO_x is not a greenhouse gas but is at the origin of ozone (O_3) formation and methane (CH_4) depletion in the troposphere. As a consequence, it has an essential impact on radiative forcing [12]. More precisely, NO_x emissions result in four major changes in atmosphere chemistry: [19]

- Short-term ozone increase.
- Long-term ozone decrease (Primary Mode Ozone, PMO).
- Methane decrease.
- Stratospheric water vapour decrease.

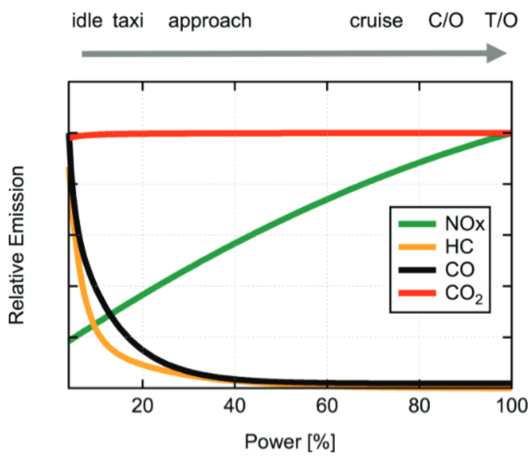

Figure 2: The trends in emissions in function of engine power setting for gas turbine engines (Where C/O stands for Climb Out and T/O for Take Off). [20].

Oxidised sulphur SO_x

Oxidised sulphur (SO_x) is produced because of the sulphur contained in the fuel. Several species containing sulphur are produced due to aircraft emissions: SO_2, SO_3, SO_4 and H_2SO_4. Only a small fraction of the sulphur (3-5% [5] [21]) is at the origin of H_2SO_4, but as an important precursor of aerosols, it plays an important role [13]. Sulphur-related emissions are also known to impact contrail and aviation-induced cirrus cloud formation as well as ozone chemistry. These two phenomena remain not well understood [22].

Carbon Monoxide CO

Carbon monoxide (CO) is emitted due to incomplete combustion with an emission index around $3g/kg^{-1}$. It can lead to a slight increase in ozone but is mainly relevant when air quality and health impact are studied. In high concentrations, CO represents a hazard and as a consequence, there often are alarms in cockpits when its concentration is too high [20]. As an incomplete combustion product, CO is mostly emitted at low power settings (See Figure 2).

Hydrocarbons HC

HydroCarbons (HC) are emitted, with a very low emission index of about $0.4g/kg^{-1}$. They include many species, and mainly "light HCs ($C_2 - C_6$)" [13]. Like CO, HC are mainly emitted at low engine power settings, mainly corresponding to taxi and idle (See figure 2. This is because HC comes from unburnt fuel which is more present at low power conditions [20].

Particle Matter

ICAO define non-volatile Particle Matter (nvPM) as "Emitted particles that exist at a gas turbine engine exhaust nozzle exit plane that do not volatilize when heated to a temperature of 350 °C" [23]. nvPM are mainly composed of Black Carbon and soot [24] [25]. Volatile particle are also emitted, such that PM (Particle Matter) include both vPM and nvPM. vPM include sulphate particles as well, in addition to organics coming from unburnt fuel and lubricants. Some experiments identified nitrate PM but in a negligible quantity [26].

It is known that nvPMs play a role in climate and cloudiness, but they more importantly highly alter air quality and are associated with health hazards [27]. nvPM emissions are studied through two key data: $nvPM_n$ and $nvPM_m$, respectively the number and the mass of the total nvPM emitted. Both mass and number of nvPM are highly engine power sensitive, and the greatest EIs are at idle and take-off, because of a less efficient combustion [20].

4.1.3 Global climate impact

Direct radiative forcing

Radiative forcing (RF) is a concept used to measure the warming or cooling impact of a species on Earth. More precisely, it is a measure of the energy received compared to the energy radiated to space. A positive RF means more energy absorbed and direct global warming, while a negative RF is associated with a cooling effect. Figure 3 (from Kärcher [28]) shows the radiation perturbations from different species.

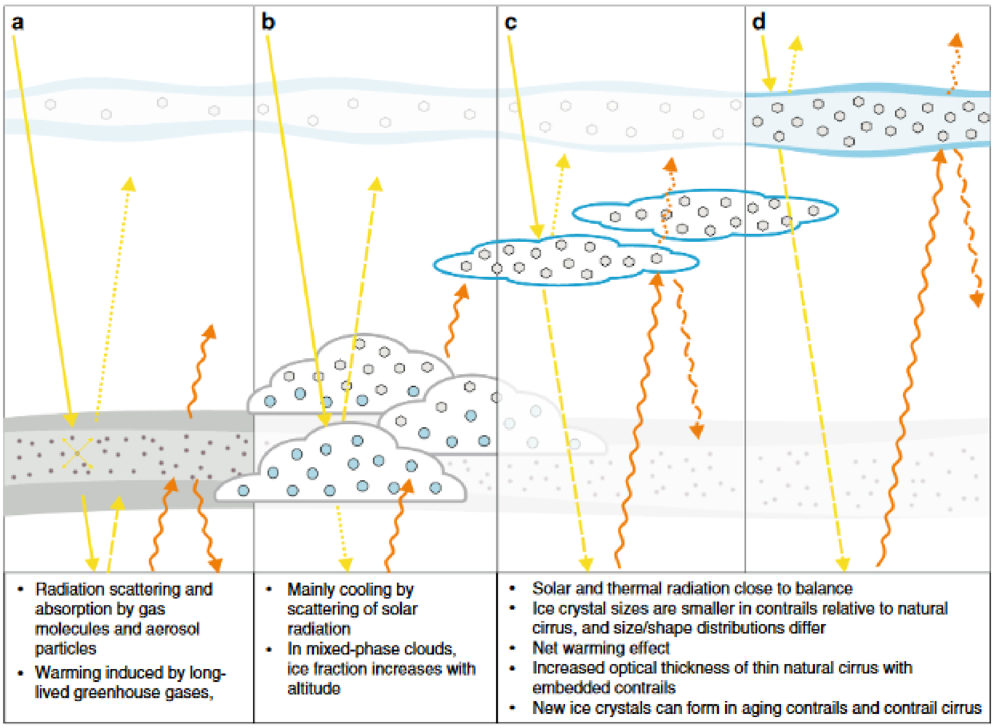

Figure 3: Representation of incoming shortwaves and outgoing longwaves perturbed by gases, aerosols and clouds [28].

Radiative forcing allows us to measure and compare the impact on the climate of different species emitted by aviation. It also gives a more concrete dimension through the global mean surface temperature change ΔT_s, calculated using the following equation:

$$\Delta T_s = \lambda * RF \tag{3}$$

With λ (K/Wm^{-2}) the climate sensitivity parameter. It does not vary with the forcing but with the species studied.
Emissions of species which absorb or emit radiations lead to a direct positive or negative RF. It is mainly the case for CO_2 and H_2O. When species alter the atmosphere chemistry, it leads to indirect RF. In particular, aviation emissions alter Ozone (O_3), Methane (CH_4), and clouds, all of which represent the greatest source of RF [5]. These indirect effects are further discussed in the following sections.

RF, IRF & ERF

Different types of radiative forcing exist, taking into account different 'adjustments' (defined by Smith et al. [29] as "changes in state that occur purely as a result of the action of a forcing agent or slow feedbacks that occur as a result of a change in global mean surface temperature"). The instantaneous radiative forcing (IRF) does not include adjustments and is thus the initial perturbation to Earth's radiation budget. The Radiative Forcing (RF) is stratospherically adjusted, meaning it includes a stratospheric temperature adjustment. The Effective Radiative Forcing (ERF), now preferred, is slightly more developed with all tropospheric and land surface adjustments in addition to RF.
The ERF requires the climate model to be calculated. Several models exist, and improvements are constantly being made even though some uncertainties remain, especially when estimating cloud responses. Other 'types' of RF exist, with different adjustments, associated with different calculation methods [29].

Ozone

Ozone plays a major role in the atmosphere and in the Earth's surface temperature. Most of the ozone is located in the stratosphere, around 80%, which explains the term 'ozone layer'. Nevertheless, aviation emissions mainly impact tropospheric ozone by increasing its formation via a cycle of reactions. This is mainly due to the NO_x emitted which is significant compared to natural sources. Although H_2O, CO, and NMHCs (Non-Methane Hydro Carbons) are part of its formation process, their perturbation due to aviation is too low to have a real impact on O_3 formation rates [12]. The chemistry related to ozone formation is described in Figure 4. It implies the following equations [13]:

$$OH + CO \rightarrow H + CO_2 \tag{4}$$

$$H + O_2 + M \rightarrow HO_2 + M \tag{5}$$

$$HO_2 + NO \rightarrow NO_2 + OH \tag{6}$$

$$NO_2 \xrightarrow{\text{hv}} NO + O(^3P) \tag{7}$$

$$O(^3P) + O_2 + M \rightarrow O_3 + M \tag{8}$$

Where M represents a gaseous third body such as O_2 or N_2 and $O(^3P)$ is atomic oxygen.
Ozone formation relies on the cycle of equations $OH - HO_2$ and $NO_2 - NO$ as can be seen in Figure 4 and equations 6 & 7. This explains the role of aviation and more precisely NO_x emissions in ozone formation. HO_2 on the other hand requires CH_4, CO or an NMHC to react with OH and O_2 as equations 4 & 5. Finally, ozone is formed through equation 8.

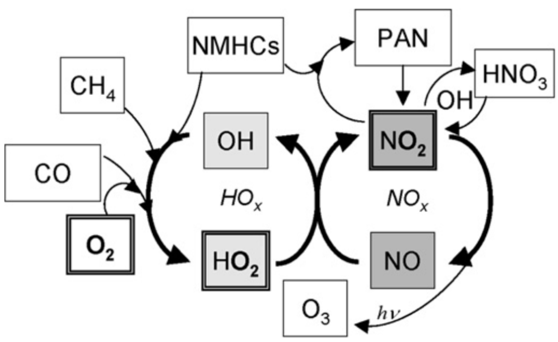

Figure 4: Sketch of the main tropospheric O3-related chemistry [13].

Methane

Methane (CH_4) is a greenhouse gas like CO_2 and O_3. It is mainly impacted by aviation NO_x emissions. More precisely, OH consumption is increased (See section 4.1.3 & Figure 4) and is a sink for CH_4 [12]:

$$CH_4 + OH \rightarrow CH_3 + H_2O \tag{9}$$

This leads to a decrease in both ozone and stratospheric water vapour. Less CH_4 leads to a decrease in ozone production through equation 4. As a consequence, NO_x emissions lead to a negative RF term due to long-term ozone depletion (called Primary Mode Ozone, PMO). A fourth RF term, negative as well, comes from a stratospheric water vapour decrease. Indeed, oxidation of methane is a main source of stratospheric water vapour [30].

Aerosols

Aerosols are very fine particles in suspension which can be divided into two categories: primary and secondary aerosols. Primary aerosols are mainly composed of Black Carbon (BC), which usually comes from fossil fuel combustion such as aircraft engine combustion. Secondary aerosols come from precursor gases such as sulphate [31]. Aerosols scatter solar radiations and BC aerosols absorb them leading to direct RF. Their global impact is still under discussion and not well understood. Their capacity to alter clouds and ice nucleation adds to the difficulty of fully understanding their effect on climate [32]. Nevertheless, studies tend to agree on a cooling effect from sulphate aerosols, mainly induced by cloud forcing. A negative direct RF is also found but very low compared to the indirect effect. On the other hand, BC aerosols contribute to a small positive indirect RF [5].

Contrails

Contrails are clouds produced by aircraft which can be seen at the end of their engines, thus following their path. They are formed due to the freezing of water droplets. Contrail formation isn't systematic and depends upon the atmospheric conditions, in particular temperature and humidity, and the engine performances. More precisely, contrails are formed if the Schmidt-Appleman criterion is satisfied [33]. Aerosol emissions play a role in contrail formation since ice particles form around aerosols. Nevertheless, simulations demonstrated contrails would form even without any soot or sulphur emitted from the aircraft. In other words, there are enough particles already present in the atmosphere to form contrails.

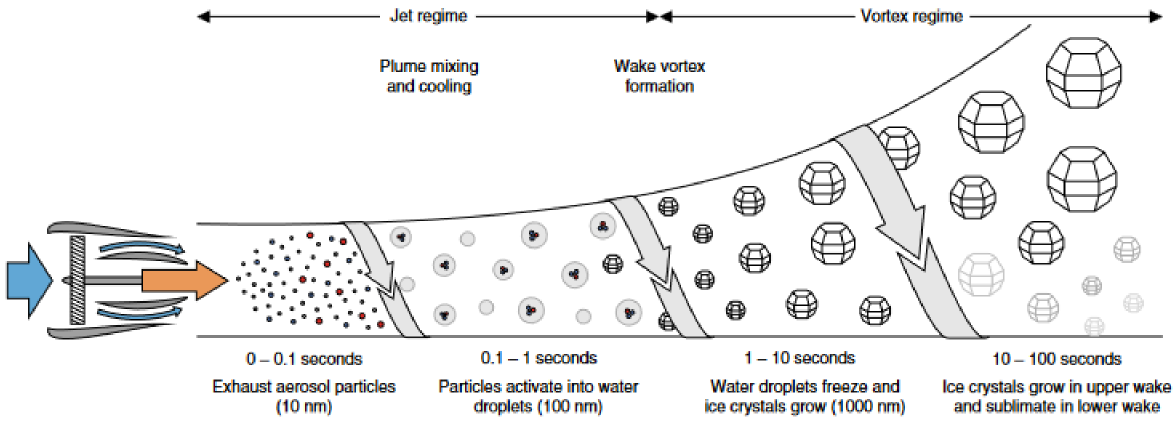

Figure 5: Formation of contrails at the exit of the engine [28].

Their lifetime varies with the atmospheric conditions, and if the relative humidity concerning ice is low enough, the contrail may persist and last for hours [4]. They usually then deform and merge with other clouds to form 'contrail cirrus' [33]. The different aviation-induced clouds can be seen in the three images of Figure 6.

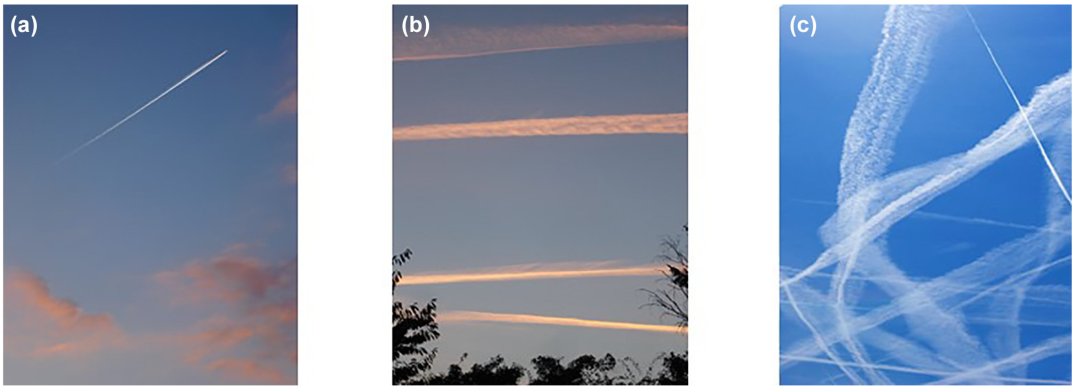

Figure 6: Aircraft-induced clouds (AIC): (a) short-lived contrail, (b) long-lived persistent contrails, and (c) long-lived contrail cirrus [34].

Climate impact of contrails raised attention decades ago [35], and the IPCC (1999, [12]) identified it as a source of radiative forcing comparable to CO_2. Nevertheless, it is only more recently that contrails impact was calculated as the biggest contribution to aviation radiative forcing [5]. Progress has also been made on the understanding of contrail formation, development and climate impact. Ulrich SCHUMANN and Andrew J. HEYMSFIELD summed up the key parameters in [33]:

Number of ice particles in young contrails N_{ice}	**Contrails lifetime, age**	**Climate impact**
Emissions, wake dynamics	Initial number of ice particles	Total extinction and lifetime
Number of soot particles	Ambient RHi, T, p, D_{IS}	Temp
Ambient RHi, p, temp	Mixing and sedimentation	Solar and terrestrial top of the atmosphere radiances
Particle losses in sinking wake vortex	Ambient vertical motion	Efficacy

Table 1: Key parameters controlling contrail properties and effects [33].

Estimations of contrails impact have also progressed in calculating the contrail-cirrus contribution. Indeed older studies ([12], [16]) only include line-shaped contrails, thus not taking into account the whole life cycle of contrails. Works on the interactions between aerosols and clouds are still to be done [5].

Supersonic aviation

Supersonic aviation has a different climate impact since species are mostly emitted at different altitudes. Supersonic aircraft fly higher, in the stratosphere, up to 20km of altitude. The emissions remain close to those of subsonic aircraft and the global effects are similar. The main changes are [13]:

- A much higher direct positive RF due to H_2O emissions since it has a bigger climate impact in the stratosphere than in the troposphere, as discussed in Section 4.1.2.
- NO_x emissions result in a global negative RF, due to a decrease of ozone (depending on the models) and a very slight decrease in methane.

CO_2, soot particles, linear contrail and contrail-cirrus all result in a positive RF, and sulphur particles in a negative RF, as for subsonic aviation. On the other hand, their magnitude may differ and highly depend on the altitude species are emitted.

Global impact

Taking into account all the positive and negative RF due to aviation emissions leads to an estimation of its global impact on climate. The result, done by D.S. Lee et al. for 1940 to 2018 [5], can be seen in Figure 7.

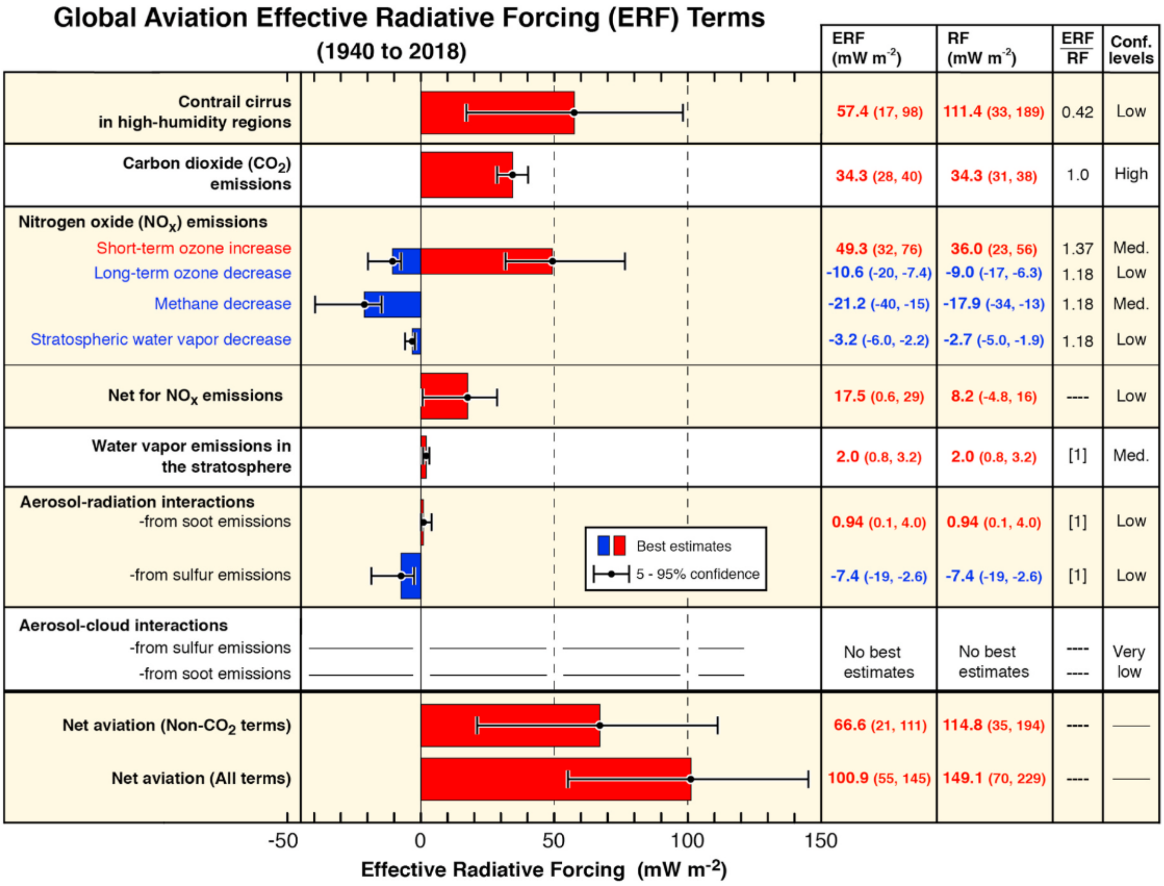

Figure 7: Global aviation ERF terms calculated by D.S. Lee et al. in [5].

As can be seen in Figure 7, uncertainties remain high, in particular for contrails and NO_x emissions. There is a factor 3 between the lowest net aviation total RF and the highest when including all the uncertainties. Nevertheless, even the least estimation leads to a significant contribution to the total anthropogenic RF, estimated to be around 2300-2400 $mW.m^{-2}$ [5].

4.2 Emission inventories

4.2.1 Air traffic

Past growth and actual state of air traffic

Since 1950, aviation has been growing almost continuously. From 1988 to 2007, there was an average rapid growth of around 4% per year, leading to an overall twice as many flights per year increase after 20 years. As can be seen in Figure 8, numerous important events have caused traffic growth to slow down significantly over short periods [36]. In the meantime, ticket prices dropped, mainly due to increasing competition between airlines and the expansion of the aviation market: More airports, more aircraft, more efficiency [37]. For example, A trip from Milan to Paris, according to the European Commission [38], cost 16 times less in 2017 than in 1992.

In 2018, before the COVID-19 pandemic, there were approximately 4.3 billion passengers carried, corresponding to 12 million passengers on more than 100,000 flights per day. According to the Industry High-Level Group (IHLG) aviation benefits report of 2019, the sector contributed to 10.2 million jobs and $704 billion to gross domestic product (GDP), which is close to the United Kingdom's economic size and population [39].

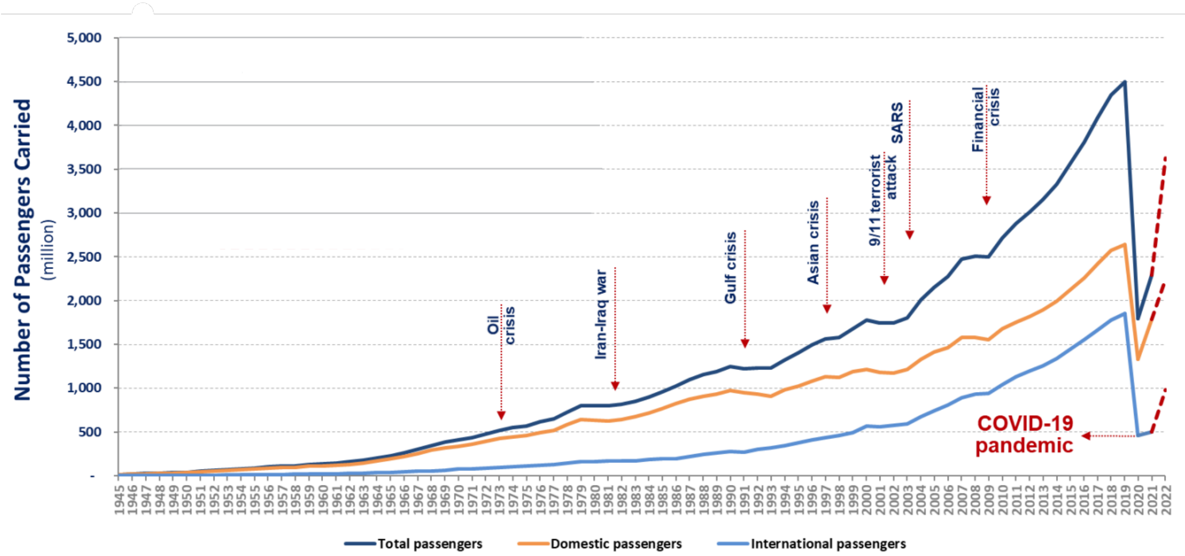

Figure 8: World passenger traffic evolution 1945 – 2022 [36].

The COVID-19 pandemic then had a much higher impact than the previous crisis (Figures 8 & 9). According to the International Air Transport Association (IATA), global passenger traffic declined by 66% in 2020 compared to 2019. Financially, this resulted in a loss of around $370 billion in 2020, according to IATA [40]. Nevertheless, air traffic is now close to its state before the pandemic. The traffic in 2022 reached 68.5% of the pre-pandemic levels. Although the recovery is not uniform, it is expected that air passenger numbers will have recovered around 2024 [8]. The war in Ukraine also impacted air traffic, especially close to the country, but the overall impact is relatively small [7].

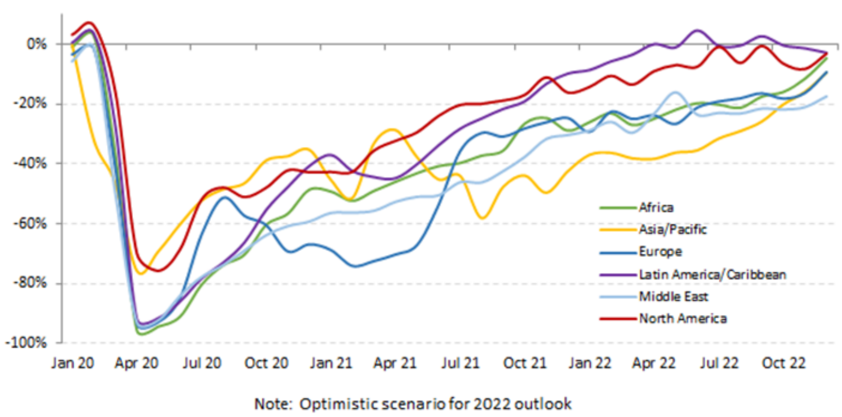

Figure 9: Regional difference in the pace of recovery (Passenger number compared to 2019) [41].

It is also important to note the geographical distribution of air traffic. Indeed, There is an important unbalance when looking at the number of flights per region. Figure 10 clearly shows the high concentration in the Northern Hemisphere and the very low number of flights in the Southern Hemisphere in comparison. More precisely, the RPK contributions of Africa and Latin America are respectively 2% and 5%, although their population represent more than 20% of the world population [42].

Figure 10: Regional development of global air transport [37].

Scenarios for the future

Although it is not possible to predict what the air traffic state will be in a few decades without uncertainties, several studies still propose estimates of what it will most probably look like. These predictions take into account multiple key factors such as economic and demographic trends. Demographic factors lead for example to an increase in certain countries (Mexico, Canada, India, Indonesia, United States and Brazil) but a decrease in others (China, Germany, Italy, Russia and Japan). Significant growth is also expected in less developed regions such as Africa in the next decades [43]. As seen in the past and Section 4.2.1, an international crisis can cause a temporary decline in growth, but the overall trend is not severely impacted. This is why forecasting air traffic remains realistic and useful. Most of the studies predict a global increase in the next decades. The annual growth rate varies from 3.1% for Waypoint [43] to 3.8% and 3.9% for Boeing [44] and Airbus [45] respectively. This leads to a minimum of 2.5 times the 2019 levels in 2050. A similar result was obtained from the Eurocontrol Aviation Outlook scenario, as can be seen in Figure 11. Even if all these results have relatively large uncertainties, the lowest scenarios still predict an overall significant growth [7].

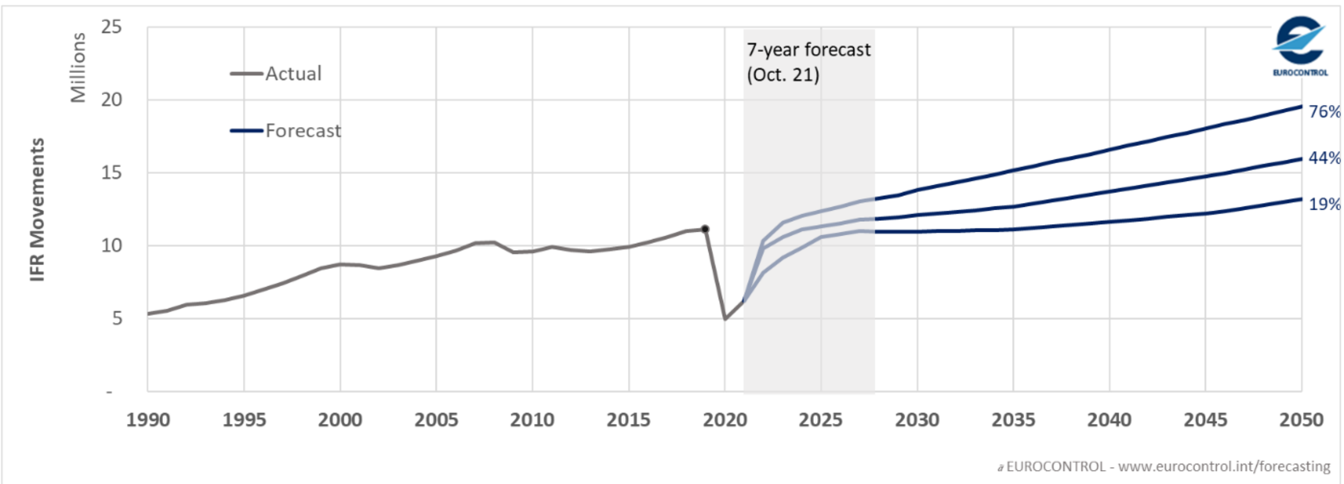

Figure 11: Flight Forecast for Europe, with total growth between 2019 and 2050 [7].

Types of flights

The majority of air traffic is composed of scheduled commercial flights. Nevertheless, there are many other flights, for which data is not necessarily collected. ICAO classifies the flights as shown in Figure 12:

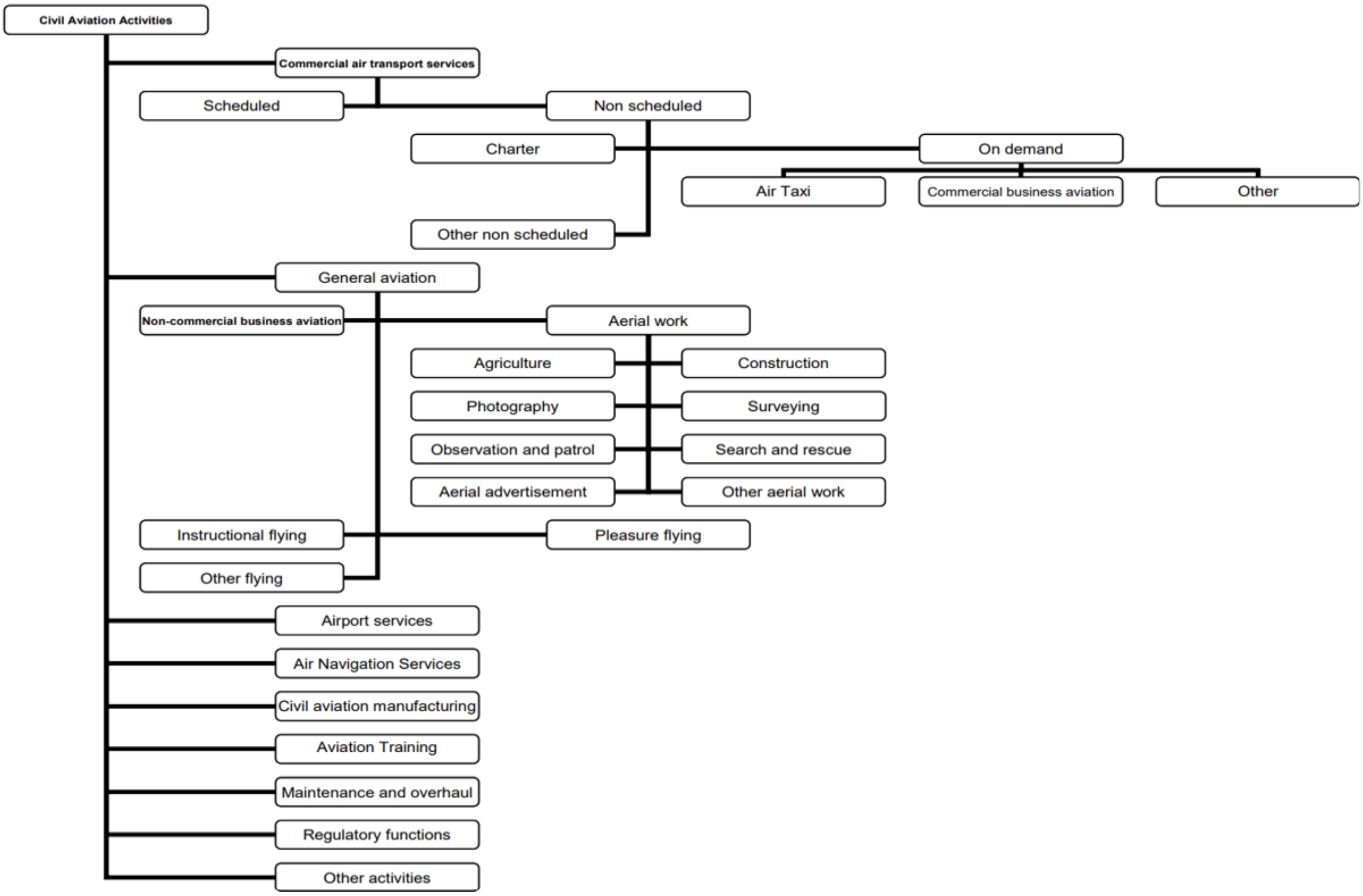

Figure 12: Proposed ICAO classification of civil aviation activities [46].

As can be seen at the top of Figure 12, this classification is only composed of civil flights. This is to be opposed to military activities, for which data is not accessible. Among civil flights, all "commercial air transport services" data are collected by the airliners and can be accessed through different organisations (See Section 4.2.1). It is important to specify that, here, non-scheduled flights do not correspond to flights for which data is not collected. Scheduled flights are commercial air transport flights either planned and included in an available timetable or served regularly. As an example, all charter data are collected, and ICAO does offer non-scheduled traffic statistics [47]. Unlisted flights mostly consist of military activities and private activities such as instructional and pleasure flying.

Tracking system ADS-B

Aircraft used to be equipped with simple radar systems, calculating their position from a ground-based antenna. Nevertheless, since 2020, a new tracking system called Automatic Dependent Surveillance–Broadcast (ADS-B) has been mandatory for all aircraft [48] [49]. This system uses a Global Navigation Satellite System (GNSS) to accurately calculate its position. It also enables aircraft to transmit all the relevant data such as position, velocity or direction to air traffic control or other aircraft. ADS-B is also a great breakthrough for research since the data is more accurate and can be easily collected and analysed. Several studies have proven that it can be used to extract flight trajectories, phases (ground, climb, cruise, descent), and performance data (velocity, altitude,...) [50] [51]. This can then lead to emissions calculation and inventories, although recent works pointed out ADS-B coverage is far from being exhaustive yet. Its use still leads to more accurate results, especially when combined with flight schedule data [18].

Databases

There are many different organisations collecting flight data. Considering historic schedule data:

- Official Airline Guide (OAG) [52].
- Capstats provided by RDC Aviation via Flightglobal [53].
- Enhanced Traffic Management System (ETMS) provided by Federal Aviation Administration (FAA) and Volpe National Transportation Center [54].
- Enhanced tactical flow management system (ETFMS) provided by Eurocontrol [55].
- Top-Sky ATC (Air Traffic Control) provided by Thales [56].

ADS-B data can be collected through Flightradar24 [57] and the open-source sensor network for research openSKY [50].

4.2.2 Aircraft performances

Existing programs

Whether it is used for air traffic management or emission inventories, aircraft performance calculation is a necessary and important step in many studies. It enables obtaining much more accurate results than approximations based on means and 'representative aircraft'. Several software that models aircraft performance have been developed, among which:

- Base of Aircraft DAta (BADA) developed by Eurocontrol [58].
- PIANO developed by Lissys Ltd [59].
- openAP (Open source Aircraft Performance model) [60].

Other software exists, such as COALA (Compromised Aircraft performance model with Limited Accuracy), using partly BADA data [61]. General Aircraft Modelling Environment (GAME) by EUROCONTROL and Performance Engineering Programs (PEP) by Airbus can also be cited as performance tools, although the first one is only a kinematic model, and the second one is for Airbus aircraft [60].
These models require data on aircraft and engines. These data are not easy to access and databases are rarely exhaustive. Nevertheless, data from the main manufacturers are public and having a significant part of the aircraft flying is possible. The aircraft performance software usually has a database with the aircraft and engine data required. This is the case for the ones discussed previously [58] [59] [60].

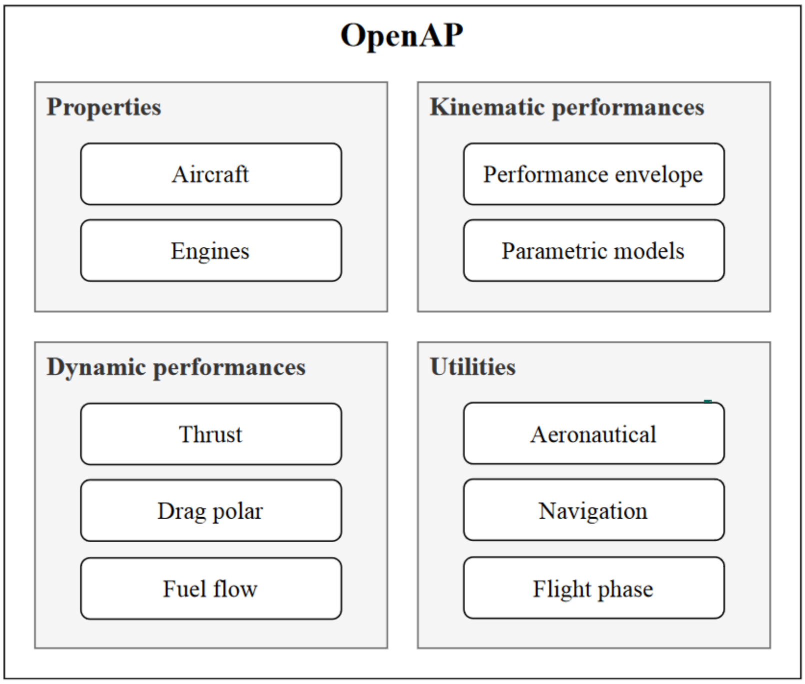

Figure 13: Structure of the openAP software [60].

The structure of openAP as shown in Figure 13 is representative of other software, including BADA. The properties come from tables and represent inputs. They include aircraft and engine data required to simulate a flight trajectory and performance. These properties are then used, along with the aircraft, the flight plan and the weather parameters chosen to simulate the flight. The models used usually include aerodynamics (Kinematic performances) and engine thrust and fuel flow (Dynamic performances). The full flight plan is thus simulated, from the take-off to the landing with the global aircraft performances.

Flight phases and Time-in-Mode

A flight is composed of several phases, such as take-off, cruise or landing. The Time-in-mode (TIM) represent the duration for one of these phases. Flight phases and their TIM are key data in the analysis of aircraft flight and performances. There are different levels of detail in the division of a flight into phases, a highly detailed one is shown in Figure 14:

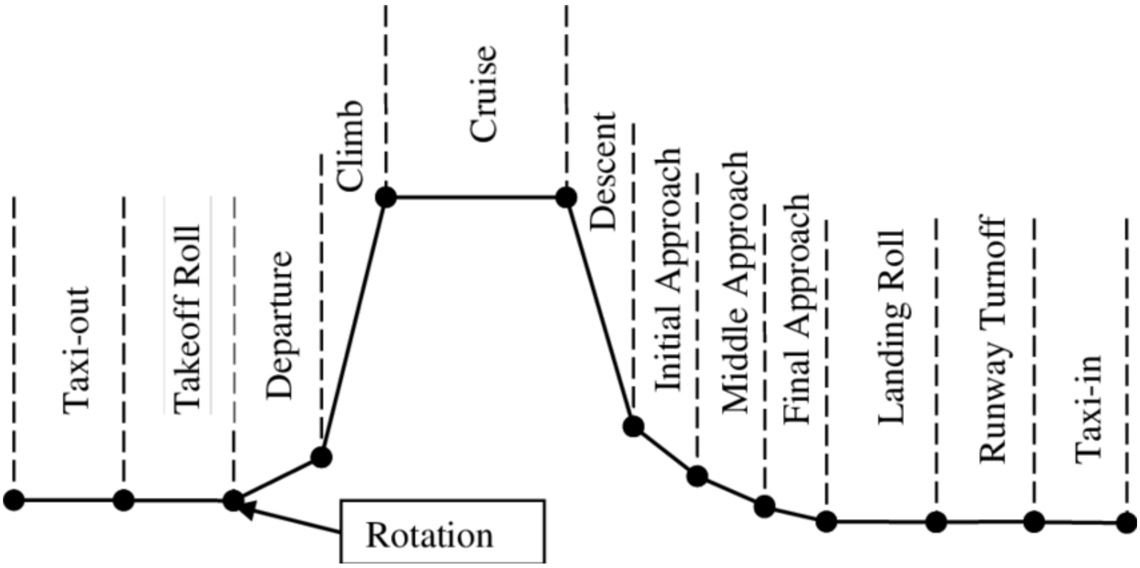

Figure 14: Flight phases [62].

For example, BADA divides the flight into the following phases: [58]

- TO - Take-Off configuration
- IC - Initial Climb configuration
- CL - Climb configuration
- CR - CRuise (clean) configuration
- DES - DEScent configuration
- HOLD - HOLD configuration
- AP - APproach configuration
- LD - LanDing configuration
- GD - GrounD

For analysis purposes, it can be chosen to make a different division, as was done in [18] when using BADA with a division into six phases: "taxi out (TOUT), take-off (TO), climb (CL), cruise (CR), descent (DES) (including approach and landing) and taxi in (TIN)."

4.2.3 Emissions calculation

Fuel burnt

The amount of fuel burnt is usually derived from the fuel flow. The latter has to be calculated and highly depends on many parameters, mainly: the engine, the aircraft, the flight phase, and the weather conditions. The fuel flow can be derived from the thrust, from: [58]

$$f_{nom} = \eta * Thr \tag{10}$$

Where f_{nom} is the nominal fuel flow and Thr is the Thrust. η is the thrust-specific fuel consumption, and can be calculated as follows (depending on the type of engine, Jet engine or Turboprop engine): [58]

$$Jet: \qquad \eta = C_{f1} * \left(1 + \frac{V_{TAS}}{C_{f2}}\right) \tag{11}$$

$$Turboprop: \quad \eta = C_{f1} * \left(1 - \frac{V_{TAS}}{C_{f2}}\right) * \left(\frac{V_{TAS}}{1000}\right) \tag{12}$$

Where C_{f1} and C_{f2} are thrust-specific fuel consumption coefficients and V_{TAS} is the true airspeed.
Considering the thrust, BADA follows the Total Energy Model (TEM), which corresponds to the following equation: [58]

$$(Thr - D) * V_{TAS} = mg_0\frac{dh}{dt} + mV_{TAS}\frac{dV_{TAS}}{dt} \tag{13}$$

Where D is the aerodynamic drag, m the aircraft mass, h the geodetic altitude, and g_0 the gravitational acceleration.

Emission indices

As described in Section 4.1.2, CO_2 and H_2O emissions are direct products of the combustion, and as such, are proportional to the fuel burnt. Similarly, SO_x depends on the sulphur content of the fuel and its emissions are proportional to fuel burnt [63]. This means that their emission indices are constant with weather conditions and mainly depend on the fuel used.
Moreover, the great majority of aviation fuel still is kerosene-based. The most used fuels are Jet-A (76% of the global aviation consumption) and JP-8 and RP-3 for military aviation [64]. All these fuels are kerosene-based and have similar compositions, and thus similar emissions [65] [66]. In the meantime, flying with Sustainable Aviation Fuel (SAF) is still under development, and the fuel does not represent a significant amount of worldwide fuel use. It is estimated that less than 0.1% global aviation fuel consumption comes from SAF [67].
Thus, most studies take EI of the three species CO_2, H_2O and SO_x as constant and only calculate their emissions in function of the fuel burnt. The usual values of their emission indices can be found in Section 4.1.2.

Fuel flow method

Other species, and more precisely NO_x, CO and HC, depend on many parameters such as engine parameters and atmospheric conditions. Unlike CO_2, H_2O and SO_x, they require a complex calculation method to take into account these parameters. Several methods exist with different strengths and weaknesses. There are three main types of calculation methods: [68]

- Correlation-based methods (Specific to a combustor)
- P_3T_3 and Fuel flow methods ("generalizable")
- Combustor models (CFD simulations)

Correlation-based methods and Combustor models are not suitable for inventories since they are too specific for one and too computationally expensive for the other. Among the others, the scientifically preferred method is the 'P3T3' method, since it is the most accurate for a limited complexity. It uses internal engine parameters and more precisely P3 and T3 (Which give their name), respectively the total pressure and total temperature at the combustor inlet [69]. Similarly, the Omega correlation method (used for CO and HC emissions calculation) uses, among others, the engine parameter Ω, the reciprocal combustor loading parameter [70]. These methods require precise knowledge of the engine and combustor chamber, as well as parameters that are rarely publicly available. Consequently, fuel flow methods, less accurate, but more accessible have been developed and are widely used. More precisely, Boeing and DLR both have calculation methods. They require less specific data and publicly available data on engines, for example in the ICAO engine emissions databank for jet engines [23] and the FOI (Swedish Defence Research Agency) emissions databank for turboprop engines [71]. More precisely, both methods calculate the fuel flow by deriving it from a reference fuel flow known for certain atmospheric conditions. The precision of the Boeing fuel flow method (BFFM2) for NO_x emissions is around 10 % [69] [70], and even less for CO and HC. Nevertheless, its convenience makes it particularly popular among emissions inventories (Cf Section 4.2.4).

nvPM

The principal source of nvPM is soot, as discussed in Section 4.1.2. There is much less knowledge on how to properly estimate soot emissions compared to other species, and it is often neglected or not taken into account. Nevertheless, methods exist and can be applied although much uncertainty about the results remains. The most common method relies on smoke number (SN) measurements by collecting soot on filters [12].A First-Order Approximation (FOA) is then derived from the correlation between soot and SN. Several FOAs have been developed due to regular updates on the initial technique. FOA2 added PM estimation, and FOA3 precised the PM calculation by estimating nvPM, sulfur-related volatile compounds, and fuel organics as three independent PM components [26]. Finally, FOA4 improved the SN and $nvPM_m$ correlation and added an estimation of $nvPM_n$ [17]. These results can be found in the ICAO Aircraft Engine Emissions Databank, for the four trust settings representative of the different flight phases, as defined by ICAO: 100% for take-off, 85% for climb, 30% for approach and 7% for taxi/ground idle [23].

Figure 15 below shows the recapitulation of the main calculation methods for aircraft emissions, as described in the previous sections.

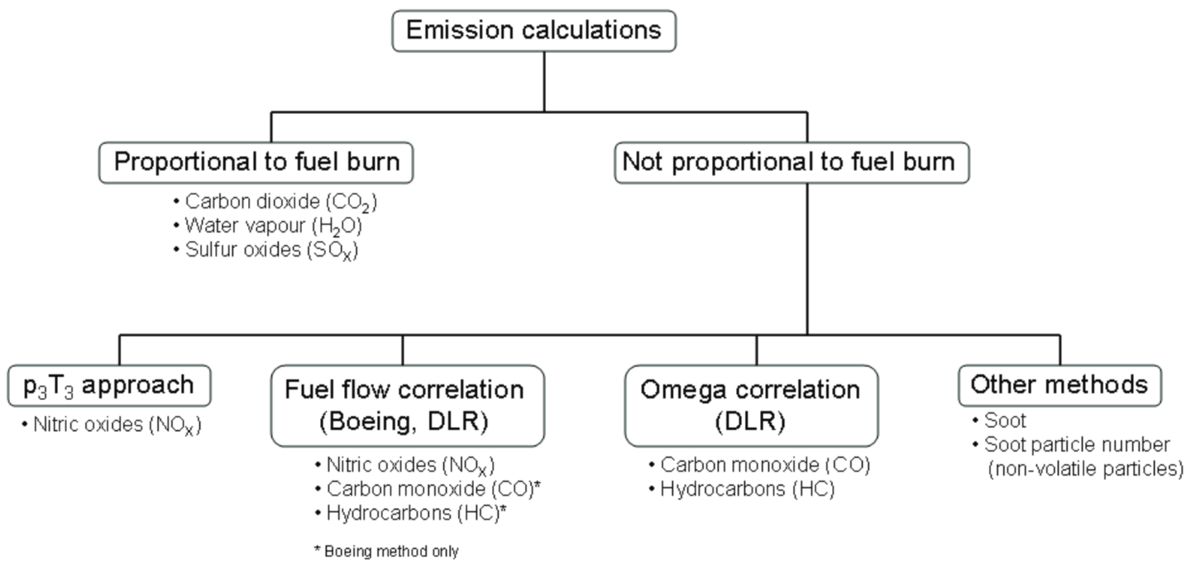

Figure 15: Overview on methods for in-flight emission calculation [70].

4.2.4 Existing inventories

Global bottom-up inventories

Interest in Emissions inventories started a few decades ago at the beginning of the 1990s in particular with the NASA inventory for the years 1990 and 1992 [72]. The IPCC report [12] in 1999 was already identifying non-CO_2 emissions climate impact as comparable CO_2 emissions. This led to a growing interest in the 2000s for bottom-up emissions inventories, seen as the most accurate manner to estimate aviation contribution to climate change [9]. Indeed, they take into account many key parameters such as aircraft and engine data, atmospheric conditions and emissions location to output three-dimensional chemistry-climate models. As discussed in the previous sections, emissions are highly dependent on all these data and producing such an inventory requires many steps and the use of several databases and tools.
Many inventories have been made through the years (See Table 2 below), all with their particularities. Nevertheless, they all present the same main steps and procedures:

- Flights data are collected from a global air traffic data provider.
- Aircraft and engine parameters are obtained from a databank.
- A model is used to simulate the flights and calculate the aircraft performances and consumption.
- An emission calculation tool estimates the global results using previously obtained data.

Main author	Kroon	Quadros	Wasiuk	Simone	Schäfer	Wilkerson	Owen	Kim	Eyers	Baughcum
Year published	2022	2022	2016	2013	2012	2010	2009	2007	2004	1996
Source	[11]	[18]	[73]	[74]	[75]	[76]	[77]	[78]	[59]	[72]
Years studied	2019	2017-2020	2005-2011	2005	2000-2010 2011-2030	2006	2000 2050	2000-2005	2002 2025	1992
Species	CO_2, H_2O, SO_x NO_x, HC, CO Soot	CO_2, H_2O, SO_x NO_x, HC, CO $nvPM_n$, $nvPM_m$	CO_2, H_2O, SO_x NO_x, HC, CO	CO_2, SO_x NO_x, HC, CO	NO_x, HC, CO soot	CO_2, H_2O, SO_x NO_x, HC, CO PM	CO_2 NO_x	CO_2, H_2O, SO_x NO_x, HC, CO	CO_2, H_2O NO_x, HC, CO Soot, PM_n	NO_x, HC, CO
Air traffic	F24	OAG, F24, Sky	Capstats	OAG	OAG	OAG	OAG	OAG	FAA, BACK	OAG
Performance tool	BADA	BADA	BADA	BADA	BADA	BADA	PIANO	BADA	PIANO	BMAP
Emission tool	PEM	openAVEM	APMI	AEIC	FATE	AEDT	FAST	SAGE	AERO2k	GAEC

Table 2: Global Bottom-up Emissions inventories summary.

There are several takeaways from this table 2:
- The great majority of the inventories use OAG data as an air traffic data source. Wasiuk et al. [73] used Capstats because it is more affordable than OAG data. Nevertheless, Wasiuk et al. also compared both sources and found that there was 94% of similarity. Quadros et al. [18] added to OAG data Flightradar24 and OpenSky data to study ADS-B data (See Section 4.2.1).
- Almost all the inventories use BADA (Eurocontrol) for the aircraft performance calculation. The PIANO software, although still available [79] and still updated regularly [80], was mostly chosen in the 2000s. As discussed in Section 4.2.2, an Open-Source software has been recently developed to face the lack of diversity in available performance tools [60].
- On the other hand, every inventory created its own Emission tool to gather the different data and results (See Section 4.2.3). It is also interesting to note that all the papers in Table 2 used the BFFM2, except Eyers et al. who preferred the DLR method [59].

Other inventories

Several emissions inventories have been developed that focus on specific locations. In particular, inventories focusing on a country such as China [81] [82] [83] or Australia [84] or on airports emissions [85] [86]. Although they don't enable the estimation of global aviation's impact on climate change, they present other benefits.

Firstly, reducing the scope facilitates the gathering of data and can lead to more exhaustive and precise results [84]. The analysis of emissions from China's civil aviation made by Liu et al. [81] studies a much longer period than global inventories usually do (1980–2015, See Table 2 in comparison) and focuses on both atmospheric and air quality impacts.
Many inventories focusing on LTO (Landing and Take-Off) emissions have estimated the impact of aviation on air quality around airports [87].
These inventories can also be seen as proofs of concept. Pham et al. were the first to propose an inventory using real-time air traffic trajectory data [84].

Forecast inventories

As discussed in Section 4.2.1, Air traffic is expected to grow in the coming decades. Even if there is much improvement in aircraft technologies and fuels, it is difficult to predict whether emissions will be reduced as they are required by the Paris Agreement [88]. The making of global bottom-up inventories is then necessary to study the exact contribution to climate change of aviation and the remaining progress that needs to be achieved. More precisely, forecast inventories need to be developed to estimate the impact of today's intended actions and confirm their adequacy.

A few such inventories have been made and in particular, Eyers et al. for 2025 [59], Schäfer et al. for 2030 [75] and Owen et al. for 2050 [77] (See Table 2). All of them followed a similar methodology:

- Air traffic forecast scenario
- A representative fleet assuming technology improvements through the years
- Emissions calculation with the same process as a basic inventory.

Future air traffic scenarios have been discussed in Section 4.2.1. The inventories use both recent aircraft and assumed technology progress through a mean annual reduction of fuel consumption for future fleets. The latter follows the previous trends of around 1-2% and is taken closer to 1% to account for an expected decrease of improvements in the coming decades [77]. The results of these three studies are comparable with recent statistics in terms of fuel consumption. More precisely, Eyers et al. (2004) [59] obtained 327 Tg of fuel consumed, and Schäfer et al. (2012) [75] 344 Tg both for 2025. Owen et al. (2009) [77] calculated 336 Tg for 2020. In comparison, according to IATA [89], 297 Tg of fuel would have been consumed in 2020 without the Covid-19 impact. Nevertheless, the NO_x predictions of the studies are more optimistic than recent estimations [18], meaning the technological progress has been less important than expected in the reduction of NO_x emissions.

Several papers have analysed the incoming aircraft technologies progress to evaluate their potential contribution to reducing aviation's climate impact. On a short-term basis, it is possible to predict accurately the future aircraft fleet by replacing older aircraft with new ones [90]. For example, Airbus and Boeing dominate the aircraft global market and the A320ceo and B737-800 alone contributed to respectively 20.5% and 17.9% of 2022 flights according to Cirium data [91]. Nevertheless, these aircraft are from an old generation, as their first flight were in 1987 for the Airbus and 1997 for the Boeing. In comparison, the new generation aircraft A320neo and 737 MAX 8 were responsible for only 2.7% and 2.3% respectively of 2022 flights. Studies analysing the emissions improvements from future fleets all conclude on a reduction of CO_2 emissions, up to 15% [92] [93]. They also conclude that aircraft technology improvements are not sufficient to stabilize aviation's emissions considering the expected growth in traffic [94] [95]. Nevertheless, these studies don't focus on the short-term, and more importantly, rarely take into account non-CO_2 emissions and focus on fuel consumption. For example, [96] focused on both fuel consumption and NO_x emissions outlook to 2050 and predicts that the mean NO_x EI will continue to grow until at least 2035. More generally, Grewe et al. (2016) [97] in "Climate impact evaluation of future green aircraft technologies" highlights the possibility of compensating fuel efficiency improvements with non-CO_2 negative effects. In particular, contrails are known to be more likely to form with higher overall propulsion efficiency [98].

More recently, Grewe et al. (2021) [99] evaluated the overall aviation contribution to climate warming in the following years and up to 2050. The methodology is similar to the one previously explained. The paper concludes that aviation RF will very unlikely decrease. Terrenoire et al. (2019) [100] estimated future CO_2 emissions and obtained similar results.

4.2.5 Uncertainties

Although bottom-up inventories are the most accurate and exhaustive aviation emissions calculation, many uncertainties remain. The confidence intervals of the emissions results are often very large [5] [74] because they depend on several uncertainties which are discussed in the sections below.

Aviation emissions calculation

As discussed in Section 4.2.3, emissions calculations are based on emission indices. These are taken as averages and can slightly vary depending on the flight conditions. Nevertheless, the greatest uncertainty for CO_2, H_2O and SO_x (Which emissions are proportional to the amount of fuel burnt) comes from the uncertainties on the fuel consumption which depends on many factors. Among them, aircraft and engine data, aircraft performance and flight path are discussed below. Overall, this leads to a significant uncertainty (See Table 3).

Regarding NO_x, CO, and HC, there is a high uncertainty coming from the fuel flow method (Usually BFFM2). As discussed in Section 4.2.3, the largest errors are in CO and HC emissions calculation, mostly because of their sensitivity to the engine power setting [74]. This is confirmed by the large differences between the inventories results [9].

The standard ICAO LTO cycle proposes a 7% engine power setting for idling and taxiing power. This assumption is not exact and the actual power can be below this value. The corresponding emission indices are then usually extrapolated, and the lack of knowledge on HC and CO EIs at these power settings create large errors [63].

Outside of the 7% engine power setting issue, the LTO cycle used holds for large uncertainties as well. The error due to TIMs is estimated to be around 10% [85]. Indeed, Quadros et al. (2022) [18] calculated a change in the fraction of fuel burning during LTO from 10.8 to 13.5% when using different LTO cycles.

Simone et al. (2013) [74] estimated the global uncertainties using a "Monte Carlo simulation consisting of 1000 model executions". The results are shown in the table below:

Emission	Nominal (Tg)	Coefficient of variation (%)
Fuel Burn	180.6	16.7
CO_2 as C	155.6	16.8
SO_x as S	0.108	17.9
NO_x as NO_2	2.689	23.7
CO	0.749	28.8
HC as CH_4	0.201	42.6

Table 3: Summary of global scheduled civil aviation fuel burn and emissions estimated by AEIC [74]

As expected, Fuel burn, CO_2 and SO_x have similar coefficients of variation. The other emissions have larger errors, and especially HC which has high uncertainty at low trust.

Aircraft performances calculation

Another source of uncertainty is the aircraft performance calculation. Simone et al. (2013) [74] identified three main uncertainties in BADA, the most used software for inventories:

- Error in the dependency of aircraft engine performances on altitude and speed resulting in an uncertainty of 11%.
- Error in the dependency of aircraft lift and drag performances on altitude and speed resulting in an uncertainty of 14%.
- Errors for aircraft not supported by BADA and for which estimations based on similar aircraft are made resulting in an uncertainty of 1%.

Aircraft and engines data

The data used for emission calculations is another source of uncertainty. Apart from errors directly in the data, the performances of the engine are estimated for new engines and engine degradation is often not considered although it accounts for significant errors [18]. Seymour et al. (2020) [101] conducted an expert interview with Pratt & Whitney and used the following approximation to take into account engine ageing:

$$F_{corr} = \frac{F_{new}}{100 - \delta(t)} \tag{14}$$

Where F_{corr} and F_{new} are respectively the ageing and new engine fuel consumption. And δ is the logarithmic engine degradation calculated as follows:

$$\delta(t) = -1.28log(t+1) \quad \text{for medium-haul aircraft} \tag{15}$$

$$\delta(t) = -1.34log(t+1) \quad \text{for long-haul aircraft} \tag{16}$$

Jakovljevic et al. (2018) [102] estimated that engine degradation emissions account for 3.6 to 6.4% of the total CO_2 emissions. The study also developed a calculation method for determining CO_2 emissions during the life cycle of aircraft.

Air traffic data

Air traffic data as well is not perfectly representative of the actual traffic. Firstly, a parameter to correct the actual trajectory is necessary. indeed, the shortest path between departure and arrival is rarely representative of the actual route followed [18]. Indeed, it has been estimated that the routes of OAG data underestimate actual aviation operations by 10–15% [9].

The data retrieved also presents errors, such as variations in the takeoff weight or the cruise altitude [74]. More precisely, whether the takeoff weight is taken from FDR (flight data recorder) or ADS-B, or estimated from known averages, it results in high uncertainties [74].

Finally, nonscheduled flights are the main cause of the non-exhaustivity of air traffic data. Both non-commercial aviation and military aviation data are not publicly available although they largely contribute to global aviation emissions. Military aviation is estimated to contribute to 10-15% of the total fuel burn [76] [9]. This is in line with the AERO2k inventory which included military flights and obtained a contribution of 11% to the global fuel consumption [59]. Unscheduled flights also account for a significant part of aviation fuel consumption which is estimated to be around 9% [101].

4.3 Conclusion and research questions

Aircraft emit many species other than CO_2 which alter the atmospheric composition and chemistry. As a consequence, aviation's climate impact is very complex and, to this day, far from being fully understood. Nevertheless, tremendous progress has been made since the 1990s and estimations agree to attribute 4 to 5% of the anthropogenic global warming to aviation. This figure includes a significant contribution of non-CO_2 effects, and in particular NO_x and contrails impact. To better evaluate these effects, which are highly sensitive to flight data (Aircraft, engine, location, atmospheric conditions, etc.), bottom-up inventories that accurately calculate global aviation emissions are required. Several such inventories have been produced since the 1990s, on different periods and all with their particularities. The method remains the same: retrieving air traffic, aircraft and engine data, simulating aircraft performance and calculating aircraft emissions. This results in estimations of global aviation emissions of each species which can then be used to evaluate climate impacts.

A few forecast bottom-up inventories can be cited, such as Eyers et al. (2004) for 2025 [59], Schäfer et al. (2012) for 2030 [75] and Owen et al. (2009) for 2050 [77]. Nevertheless, work on future aviation emissions remains to be done. Due to technological progress, fuel efficiency is constantly increasing, leading to significantly less CO_2 emitted. Nevertheless, non-CO_2 effects seem to be less taken into account - with NO_x emissions increasing for instance. Overall, the future aviation contribution to global warming remains unclear.

This literature study raises the following research questions:

- What are the expected emissions from the next generation aircraft compared to actual ones?
- What will be the climate impact resulting from these emissions?

These questions can be answered by first producing a bottom-up forecast inventory. Future air traffic and future aircraft fleets (the most recent aircraft to replace the oldest ones) have to be estimated. Then, by evaluating the climate effects of the calculated emissions.

5 Emissions assessment tools

5.1 Emission inventory code

5.1.1 Structure

In order to calculate aviation emissions, the code from Kroon (2022) is used [11]. The paper consists of an inventory of aviation emissions for 2019. For this purpose, a code was written in Python by the author. It follows the same logic as described in subsection 4.2, and represented in Figure 16.

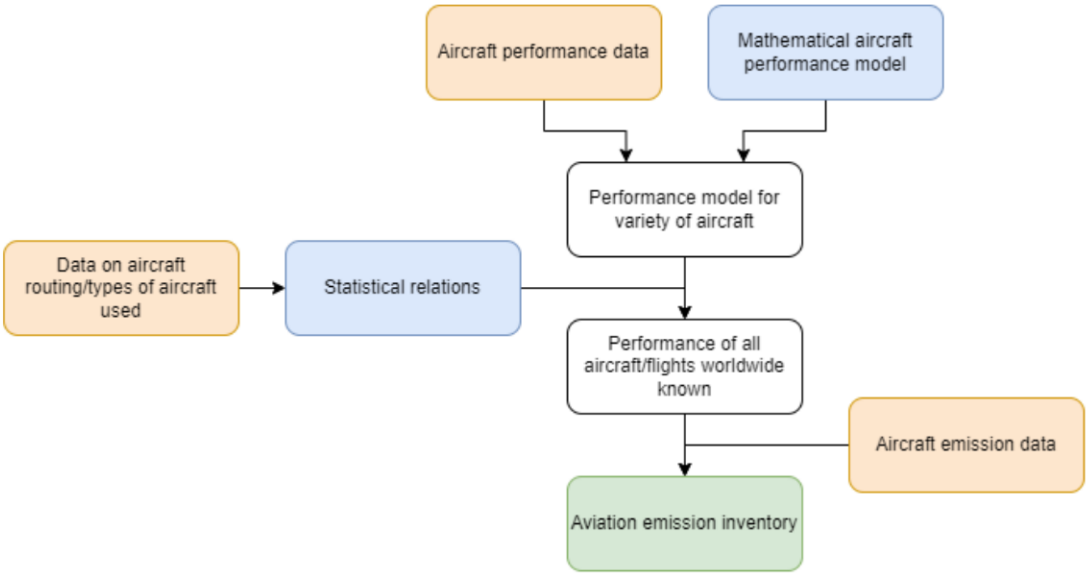

Figure 16: Basic flow chart of an emission inventory code, from Kroon (2022) [11].

The code uses three databases and performs calculations to calculate aviation emissions:

- Air traffic data - Flightradar24 [57].
- Aircraft performance data - BADA tables [58].
- Engine emissions data - ICAO [23].

These three steps are further described in the following sections.

5.1.2 Air traffic

The database used for air traffic is taken from FlightRadar24 [57]. The year studied in this Master Thesis is the same as in Kroon (2022) [11]: 2019. This was chosen to avoid the short-medium-term impact of Covid-19. For 2019, the FlightRadar24 database contains approximately 52 million flights. Consequently, the concept of representative week was chosen since it was impossible to analyse that many flights. To choose the week, flight frequency over the year was analysed and can be seen in Figure 17 below.

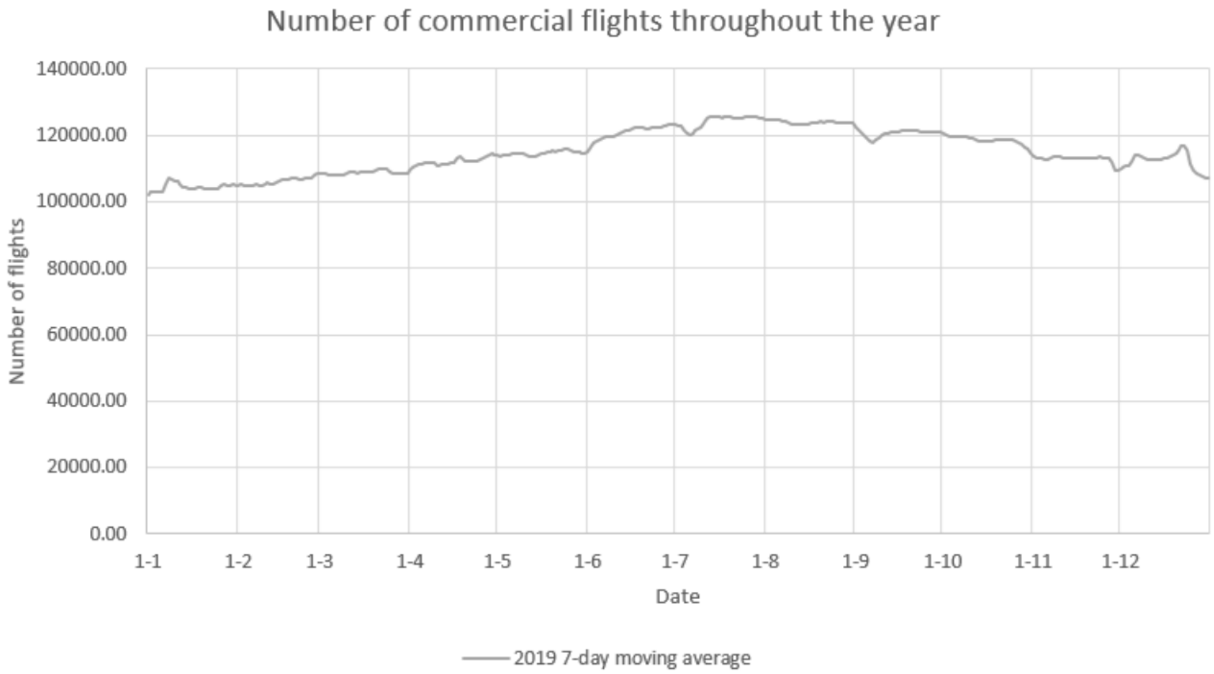

Figure 17: Number of flights in the FlightRadar24 database, 7-day average over 2019 (Kroon et al. 2022 [11].

After analysis, the week 21 of 2019 was chosen (Monday May 20 - Sunday May 26) [11]. FlightRadar24 data contains information on the flights, but only the aircraft model and the airports of departure and arrival are required and used for the code. When either of these three information is not available, the flight cannot be analysed. If these three key data are well retrieved, the flight can be simulated; the process is described in the next section.

5.1.3 Aircraft performances and emissions

The aircraft performances database is taken from the Base of Aircraft DAta (BADA) of Eurocontrol [58]. It was compared by Kroon (2022) [11] with openAP and pianox, and found as more precise and easier to use. This is in line with other inventories (See subsection 4.2). The BADA files contain key data on aircraft such as engine type, payload mass, airspeed (TAS), rate of climb (ROC) or rate of descent (ROD).
For the emissions, the ICAO engine emissions databank [23] is used. It contains for each engine data on the fuel consumption and emission indices for several stages of the flight (such as taxi, idle,...).
Combining performance and emission data, the whole flight is simulated, and emissions can be calculated. The flowchart can be seen below in Figure 18.

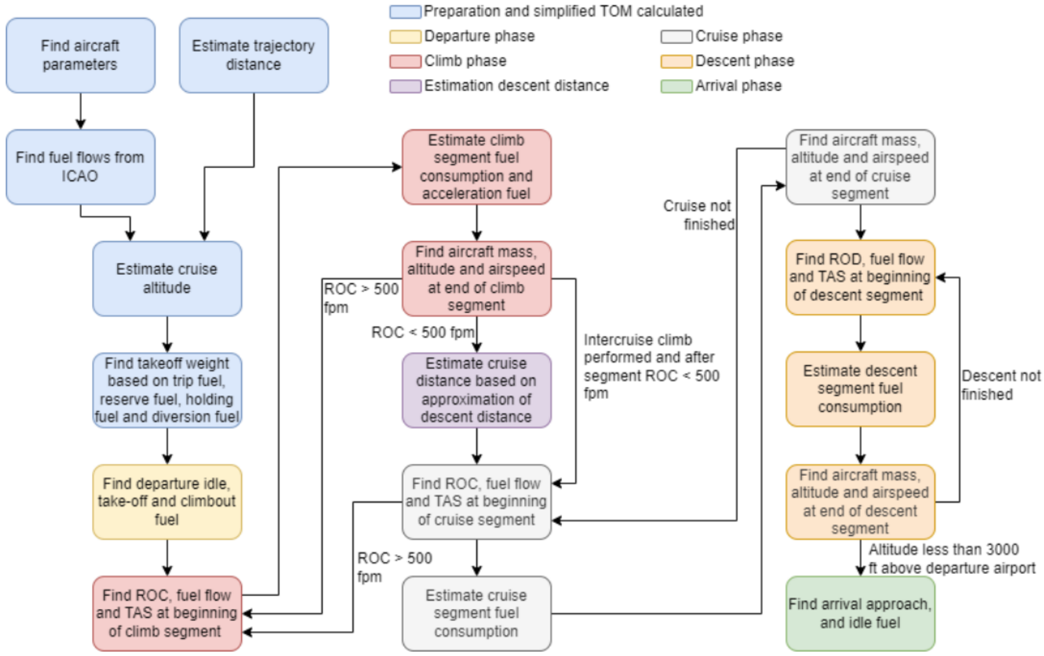

Figure 18: Flowchart of the performance model part of the code [11].

5.1.4 Results for 2019

The code used for the aviation emissions inventory has many outputs. First, the following species emissions are calculated for each flight:

- CO_2
- CO
- HC
- NO_x
- $Soot$ (Also referred as BC, see section 4.1.2)
- H_2O
- SO_x

For each flight, all these emissions are stored in 3D grids with a resolution of 1°x 1°x 1,000 ft. An analysis is therefore possible on every category wanted: short-haul, long-haul, Airbus, Boeing, etc.
To obtain emissions, other key data were calculated such as distance flown or fuel consumption, and can also be retrieved.
To obtain the total emissions for 2019 from the representative week, a factor is used to take into account the number of days (7 to 365) and the average number of flights per week (806,631 to 808,637):

$$f = \frac{365}{7} \frac{808,637}{806,631} \tag{17}$$

The results can be seen in Table 4.

Species	Fuel [Tg]	CO_2[Tg]	CO[Gg]	HC[Gg]	NO_x[Tg]	SO_x[Gg]	H_2O[Tg]	Soot[Gg]
Emissions	272.0	857.1	634.2	45.6	5.3	217.6	336.3	6.8

Table 4: Total aviation emissions for 2019.

5.2 AirClim

5.2.1 Structure

AirClim is a tool developed by V. Grewe and A. Stenke and first presented in 2008 in "AirClim: an efficient tool for climate evaluation of aircraft technology" [10]. It is based on the model of Sausen and Schumann [103]. AirClim aims to measure aviation's global impact on climate, taking into account CO_2 emissions but also NO_x, H_2O and the location of these emissions. To do so, aviation emissions data as well as atmospheric data are used as inputs. AirClim then estimates aviation's atmospheric impacts in terms of radiative forcing and near-surface temperature changes.

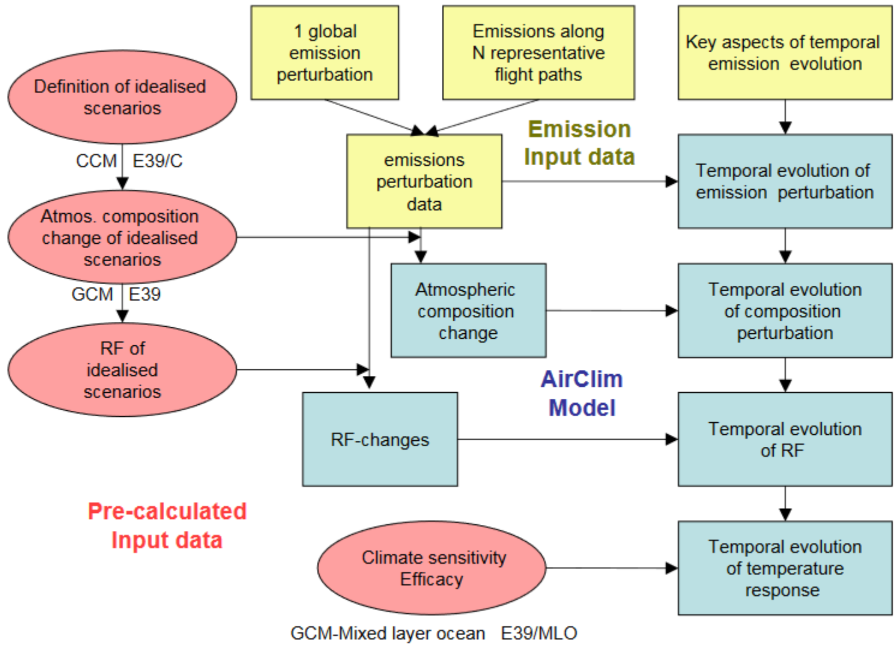

Figure 19: AirClim flowchart: "Overview of the multi-step approach to derive near-surface temperature changes and ozone depletion from emission scenarios" [10].

AirClim uses a coupled climate-chemistry model called ECHAM4.L39(DLR)/CHEM, or E39/C, described in Hein et al. (2001) [104]. First, idealised scenarios (See Figure 19) are simulated on 24 emission regions. For each region, uniform emission strengths are set. Then, the model is applied to obtain a radiative forcing corresponding to the idealised emissions. Finally, the aviation emissions input by the user are combined linearly to obtain the radiative forcing and temperature change due to these perturbations.

More precisely, AirClim takes as an input fuel consumption (to get CO_2 and H_2O emissions through constant emission indices) and NO_x emissions. The location of these emissions is also taken into account and has a major influence on their impact. After running a simulation, AirClim outputs both radiative forcing and temperature changes for each year (in between the start and end years chosen by the user) linked to the following species:

- CO_2 (Direct RF)
- H_2O (Direct RF)
- Contrails (Due to H_2O)
- O_3 (Due to NO_x, short-term)
- CH_4 (Due to NO_x, long-term, CH_4 reduction)
- PMO (Due to NO_x, long-term, O_3 reduction)

They correspond to the main sources of aviation's climate impact, as described in subsubsection 4.1.3. The model includes the three main impacts of NO_x emissions (Thus excluding the minor fourth one, Stratospheric water vapour decrease). The corresponding calculation is performed through the climate chemistry model E39/CA. This model is also used for contrails estimations, as well as the ECHAM4-CCMod model (See Burkhardt and Kärcher, 2009 [105], 2011 [106]) for Contrail induces Cloudiness (CiC).

AirClim also requires a background fuel consumption scenario. Between 1940 and nowadays, aviation fuel consumption per year is known and estimated. AirClim needs to add to these data the forecasting fuel consumption up to 2100. The main file chosen for the background fuel consumption data is taken from Grewe et al. (2021) [99], and can be found in the Appendix (subsection C).

5.2.2 Limits and uncertainties

Dahlmann et al. (2016) [97] ran a Monte Carlo simulation with AirClim to analyse the uncertainties and limits of AirClim. The uncertainties on each of the species mentioned above are indeed quite significant. The following table is given in the paper:

	CO_2	H_2O	O_3	O_3^{pm}	CH_4	**CiC**
Sigma	0.015	0.15	0.09	0.03	0.03	0.15
Minimum	0.95	0.5	0.7	0.9	0.9	0.5
Median	1.0	1.0	1.0	1.0	1.0	1.0
Maximum	1.05	1.5	1.3	1.1	1.1	1.5

Table 5: "Median and upper and lower limit of the uncertainty range for radiative forcing (RF) for each climate agent (CO_2, H_2O, O_3, O_3^{pm}, CH_4, CiC), and error probability distribution" [97]

Nevertheless, AirClim is meant to study mitigation options and significant differences were found when changing the scenarios for similar emission inventories. The paper then concludes that the large uncertainties do not prevent from comparing scenarios.
Apart from the uncertainties on the chemical reactions and the exact influence of the different species on the atmosphere, AirClim also presents theoretical limits due to its structure. The atmosphere is divided into 24 regions, which necessarily implies approximations. More importantly, AirClim is a tool estimating futuristic impacts, and as such requires forecasting. As a result, the further the estimations, the more uncertainties there are. Looking at 2100, for instance, is therefore an indication of the potential consequences of actual emissions compared to other scenarios and not an attempt to predict with precision temperature changes [10].

5.3 Code modifications

5.3.1 Aircraft fleet analysis

The next section (section 6) presents the analysis of the 2019 aircraft fleet and its emissions. The goal is first to review the actual fleet and the emission contributions per aircraft, and then to look into future fleet emissions (Composed of modern already existing aircraft).
To do so, the code was modified to retrieve the emissions data per aircraft. New outputs were added to obtain all the emissions values, as well as the number of flights, the total distance flown and the fuel consumption for each aircraft.
After a first analysis of the results, it was decided to focus on Airbus and Boeing aircraft for several reasons:

- They covered more than 85% of the total distance and more than 90% of the total fuel consumed by aviation in 2019 (See Figure 27).
- All of their data is available, including in the BADA files (See Figure 26 & Figure 25).
- It is possible to forecast their fleet more accurately (See next paragraph).

Indeed, since the two companies represent a very large part of the global market, their planes are produced in much larger quantities, and it takes decades to replace the most used aircraft. For example, the A320 CEO (First year in service in 1988) still represented 18.3% of the flights and 14.2% of the total distance flown. In comparison, the A320 NEO (First year in service in 2016) flew 3.02% of the flights for 2.32% of the total distance. Similarly, the B737-500 (First year in service in 1990) still flew 0.30% of all the flights in 2019, compared to the 2.13% of its newer version, the B737-900, which came out in 2001. It can thus be expected that the most recent aircraft such as the A320 NEO family, or the B737 MAX family will not have fully replaced their older versions before several years, if not decades.

5.3.2 Contrails and soot

The influence of soot on contrails is not directly implemented in AirClim. To include it in the results, the following relation from Grewe et al. (2021) [99] is used. It follows the linearisation obtained from Figure 1f of Burkhardt et al. (2018) [107]:

$$\Delta RF^{contrails} = \frac{arctan(1.9\Delta pn^{0.74})}{arctan(1.9)} \quad (18)$$

Where $\Delta RF^{contrails}$ corresponds to the change in contrails radiative forcing due to the change in soot emissions Δpn. The change in soot is only considered for altitudes between 7 to 13 km of altitude, where contrails are mostly formed [108]. To convert the soot emissions from kg to number of particles, the graph (figure 18) from Eyers et al. (2002) is used [59].

5.3.3 Input for AirClim

As explained previously, AirClim requires as an input a 3D data file containing aircraft emissions. The corresponding files were created with the emission inventory code. More precisely, the file is composed of 7 variables:

- Longitude
- Latitude
- Altitude
- Fuel consumed
- NO_x emitted
- Flight distance
- Conversion in year

As the emission inventory code stores emissions in 3D grids, the fuel consumed, NO_x emissions and distance flown in function of the location were easy to regroup. The altitude is required to be in hPa for AirClim, therefore a conversion was made since the values calculated by the code are in feet. A table of the conversion used can be found in the Appendix (subsection B). Concerning the conversion in a year, since the files contain values for one week, a multiplication factor was calculated. More precisely, the average number of flights per week was taken from FlightRadar24 (808,637 in 2019) [57]. Then, a ratio was calculated, based on the actual number of flights analysed by the code (652,915 for the week in May for instance). To this ratio was added the number of days: 365/7.

5.4 Verification and validation

5.4.1 Fleet validation with another week

As discussed in subsubsection 5.1.2, the data used for air traffic for this work come from a week in May, called representative week. To verify the validity of the 'representative' character of this data, the code was run for another week. The week chosen is the second week of January (and the first full week of the year). As can be seen, in Figure 17, it corresponds to the lowest traffic of the year and as such, to an extreme case.

Species / Data source	Distance per flight (km)	Fuel (kg/km)	CO_2 (kg/kg)	CO (g/kg)	HC (g/kg)	NO_x (g/kg)	SO_x (g/kg)	H_2O (kg/kg)	Soot (mg/kg)
Representative week (May)	787.9	9.330	3.151	2.466	0.169	18.247	0.800	1.237	24.259
Comparison week (Jan)	810.0	9.414	3.151	2.399	0.165	18.398	0.800	1.237	23.848

Table 6: Total aviation emissions for 2019.

Table 6 presents the average emission indices for each week. The distance per flight slightly varies (by less than 3%). This can be explained by the holidays around New Year's Eve, usually leading to longer trips. On the other hand, all the emission indices are very close from one week to another. The fuel consumption has less than 1% of difference. This is an important result since big differences in emissions can be observed for the same aircraft for a different flight, as will be discussed in subsection 7.2.

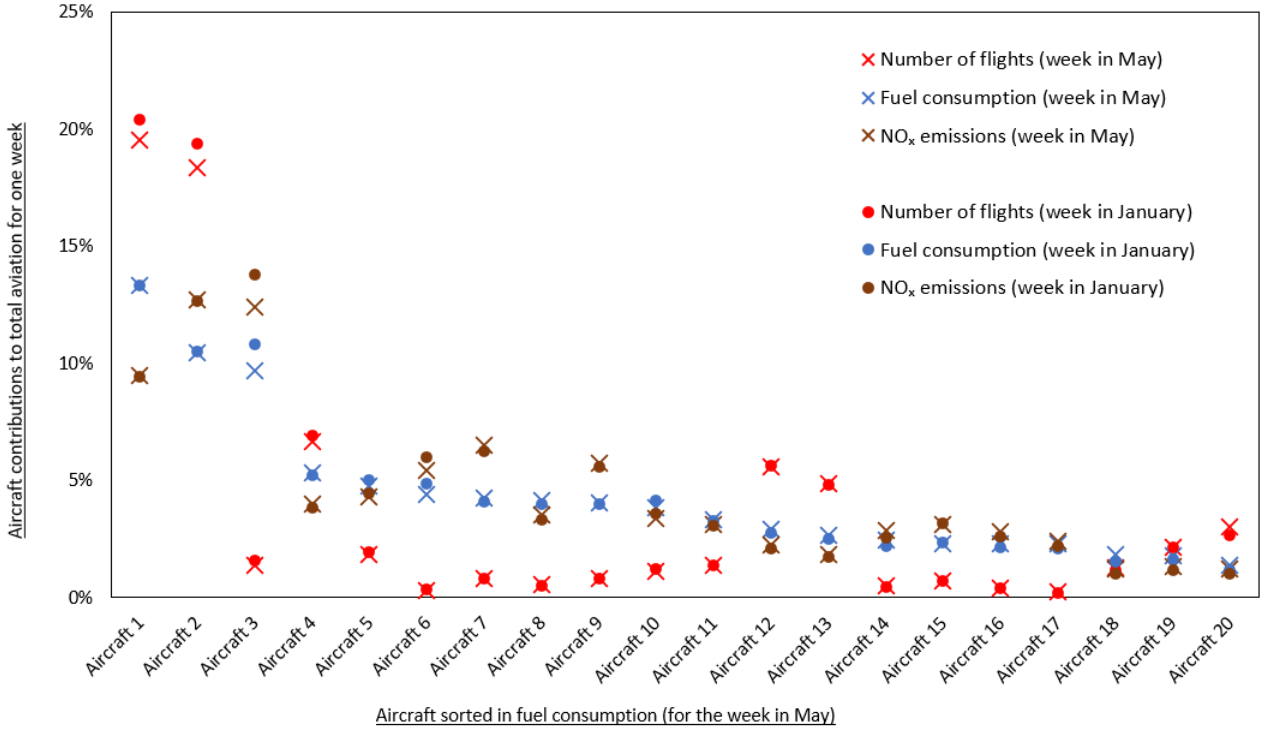

Figure 20: Aircraft contributions to total aviation for two different weeks (Representative week X, 20th to 26th May and comparison week O, 7th to 13th January).

Finally, Figure 20 shows the number of flights, the fuel consumed and the NO_x emissions aircraft contributions to total aviation. The results are shown for both weeks, the representative week in May (crosses) and the comparison week in January (circles). The crosses and the circles are mixed for almost every aircraft and category, confirming a good result. A few aircraft, and in particular the ones flying the most, show small variations. Nevertheless, the biggest differences never exceed 1.5% between the two weeks' contributions.

5.4.2 AirClim validation

Similarly, to validate the input files and settings chosen for AirClim, the base results of both weeks were compared with a paper from the literature, Grewe et al. (2021) [99]. The settings chosen are:

- Start Year - 1940
- Normalization Year - 2000
- Emissions Year - 2019
- End Year - 2100

The normalization year corresponds to the calculation of the Average Temperature Response:

$$ATR_{100} = \frac{1}{100} \int_0^{100} \Delta T(t) dt \tag{19}$$

Grewe et al. (2008) [10] suggest using three emission datasets: A base scenario and two other scenarios with changes that the user wishes to compare. Nevertheless, this requires keeping the background constant after the date of added technology [10]. For this work, it would have meant keeping emissions constant starting from 2030 or 2040 at the latest, when predictions expect a large growth up to 2050 minimum (See section 4.2.1). It was therefore decided to keep the settings of the actual fleet emission dataset (as written above) for all of the new cases to compare them. This legitimately increases the emissions and enables an easier comparison.

The results for both weeks in comparison with the literature are shown below.

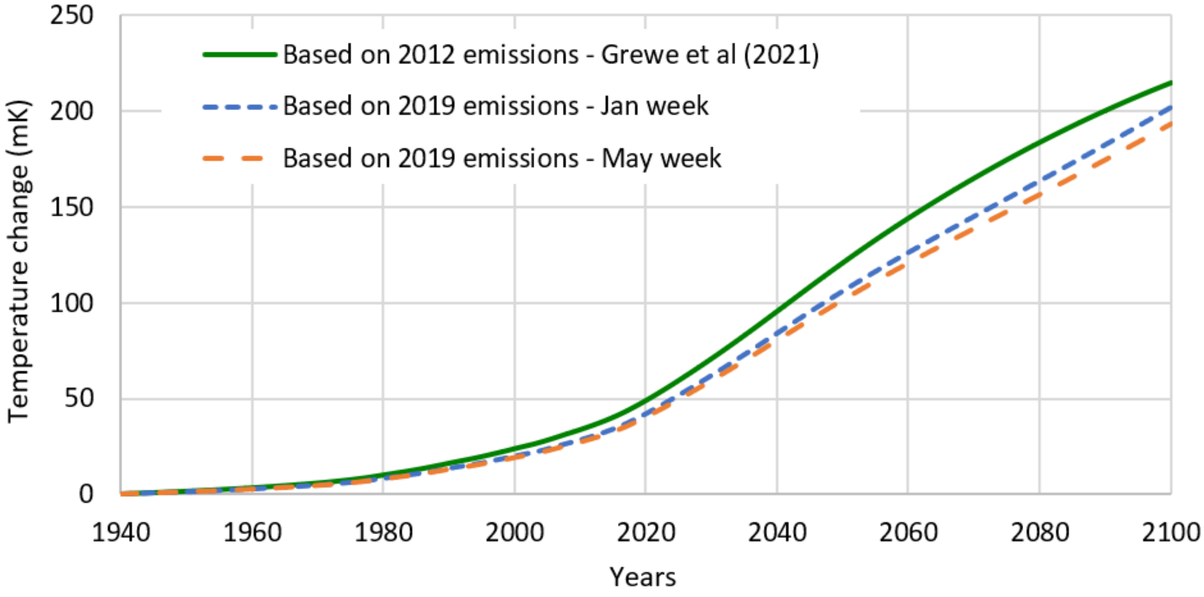

Figure 21: Temperature change through the years due to aviation emissions [99]

Figure 21 shows the temporal evolution of the total temperature change (taking into account all the emissions and radiative forcing responses) due to aviation. The Literature results are slightly higher with a peak in difference around 2070. Overall, the difference remains quite small. The two weeks studied present even closer results with a very similar shape, and a slightly higher final value for the week in January.

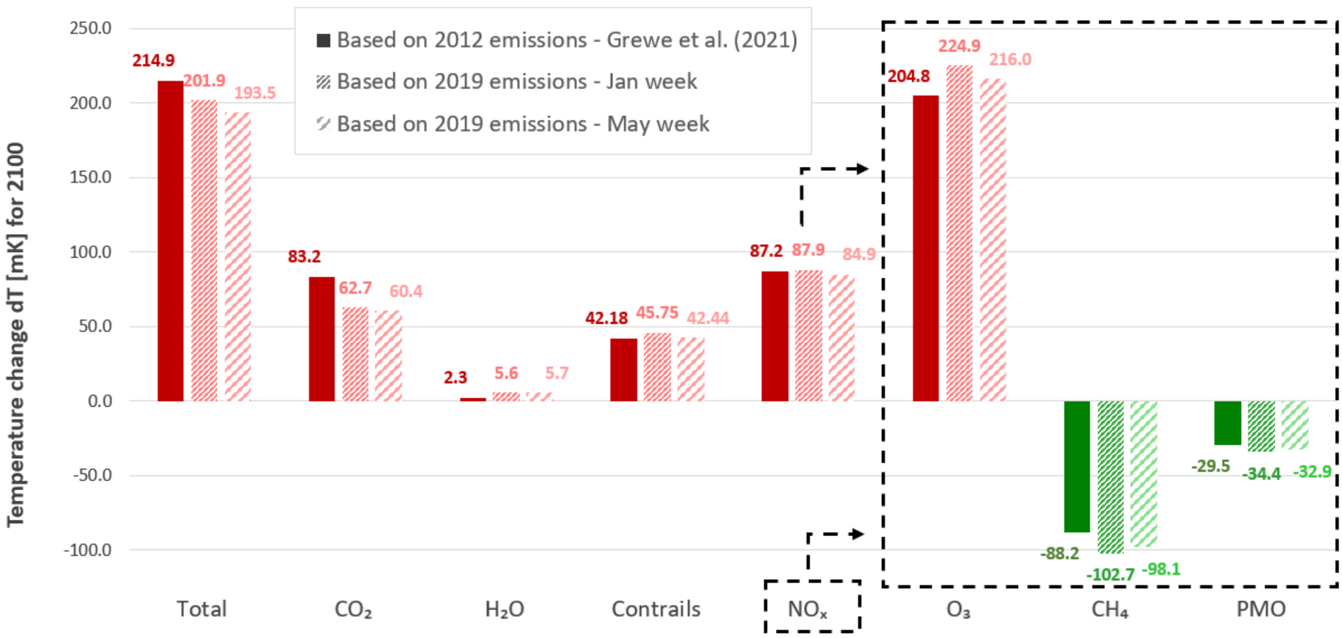

Figure 22: Temperature change for 2100 due to aviation emissions [99]

Figure 22 shows the detailed temperature changes due to aviation in 2100. Again, the results are highly similar. The most important difference can be observed for the CO_2 emissions, which have a significantly higher impact according to Grewe et al. (2021). This could be explained by the estimations before the year 2019. The results for this work are based on actual technology, which has significantly lower fuel consumption than between 1940 and 2000. When looking at the year 2005, a big difference can already be noted with Grewe et al. (2021): +7.17 mK for the latter compared to +4.48 mK for the May week due to CO_2.
The high values for the NO_x contributions (O_3, CH_4 and PMO) compared to previous studies such as Lee et al. (2009) [16] are explained by the inclusion of recent progress on the influence of aviation NO_x emissions [99]. Indeed, Grewe et al. (2019) described important considerations to be taken when estimating ozone changes due to aviation NO_x [109].

6 Aircraft emissions analysis

6.1 Airbus and Boeing

6.1.1 History

Airbus and Boeing have been dominating the commercial aircraft market, which makes this industry a "duopoly". Nevertheless, several other manufacturers have tried to compete with them in the past. Back in the 1960s, Boeing, as well as McDonnell-Douglas and Lockheed (Three American firms) were ruling the industry [110]. Boeing produced its first aircraft around the end of the 1950s, as can be seen in Figure 26, with the B707. It is only two decades after, in the 1970s, that the three companies Hawker Siddeley of the United Kingdom, Aérospatiale of France, and Deutche Aerospace of Germany formed Airbus with the "A300 project" [111] (See Figure 25. Then, with the A320 and the B737, the two companies became very successful. In the meantime, during the 1980s and the 1990s, McDonnell Douglas and Lockheed faced severe drawbacks. As a result, McDonnell Douglas was bought from Boeing in 1997 and Lockheed disappeared in 1995 with the merger with Martin Marietta [112]. By the 2000s, Airbus and Boeing were the only firms remaining and dominated the whole market (See Figure 23) [111].

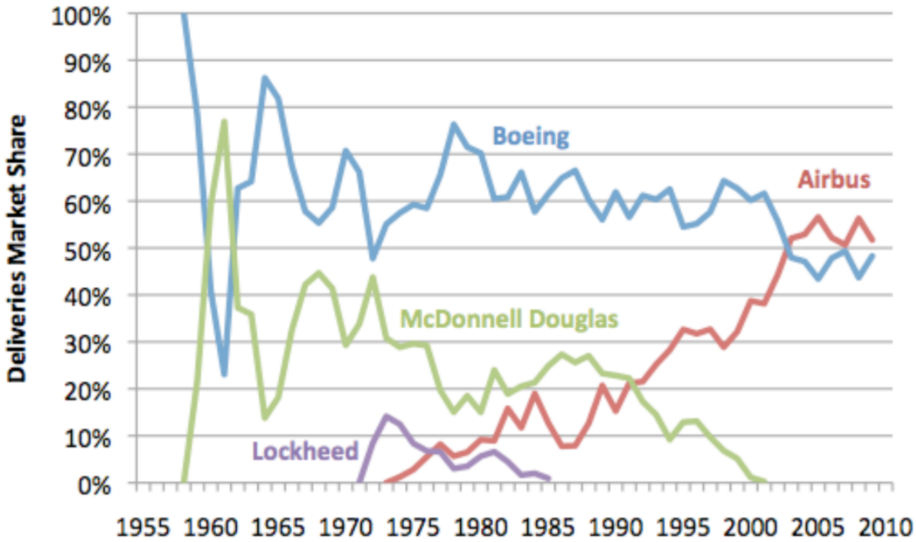

Figure 23: Large commercial aircraft manufacturer market shares (100+ seat jetliner deliveries) 1960-2009. [113]

Commercial aircraft can be divided into two categories [110]:

- Narrow-body aircraft - Single aisle - Short range (< 6,000 km) - ≈ 100 to 200 passengers.
- Wide-body aircraft - Double aisle - Medium / Long range (< 14,000 km) - ≈ 200 to 450 passengers.

For example, A320 and B737 are typical narrow-body aircraft, while B747 and A340 are wide-body aircraft. On the other hand, smaller aircraft, with less than 100 seats, are often classified as Regional jets [110]. If Airbus and Boeing still are the only manufacturers of large commercial aircraft, other firms have manufactured regional jets. In particular, Embraer and Bombardier were seen as the main competitors during the past couple of decades. This duality was even described as two duopolies [114] [115]. Nevertheless, with time, the two jet manufacturers started to extend their market and built bigger aircraft: Embraer 190 (2004, 100 seats), Embraer 195 (2006, 110 seats) and CRJ-1000 (2008, 100 seats), CS-100 (2013, 110 seats) and CS-300 (2015, 130 seats) for Bombardier. A new competition started as these aircraft could compete with Airbus and Boeing single-aisle aircraft such as the A320 or B737 [115]. The competition stopped a few years later, in 2018, when Boeing bought the Embraer commercial branch and Airbus bought the CS-series aircraft to Bombardier [114]. The distribution of aircraft in service and aircraft orders for November 2018 can be seen in Figure 24.

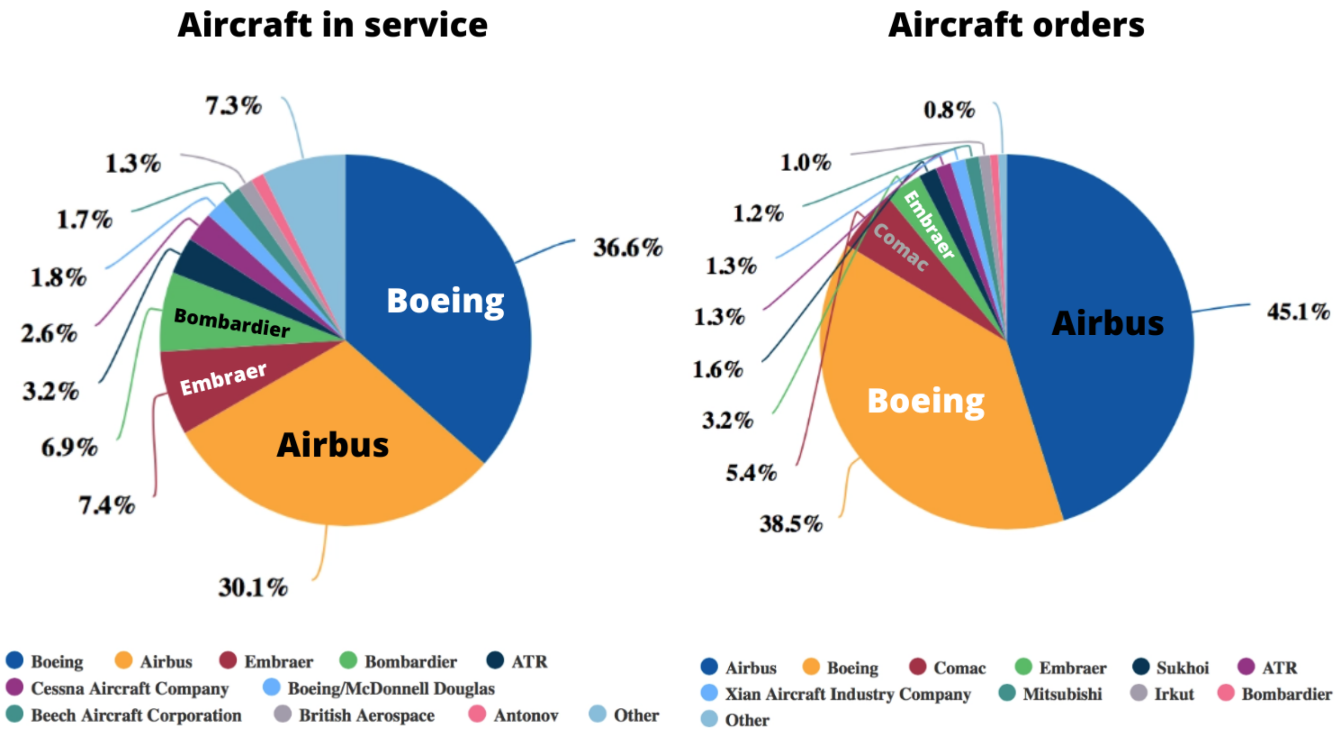

Figure 24: Percentages of Aircraft in service (left) and Aircraft orders (right) per manufacturers as of mid-November 2018. [116]

More recently, a Chinese company, Comac (established in 2008), started manufacturing commercial aircraft with the assumed goal of competing with Airbus and Boeing. The C919, comparable to the A320 and the B737, is a 130-seat aircraft. Its first flight was in 2017, and its first delivery in 2022 [117]. It can be seen in Figure 24 above that the company represented more than 5% of the aircraft orders in 2018. Nevertheless, the C919 alone does not seem to represent a big threat to Airbus and Boeing's clear domination as for now [118].

AIRBUS								
Family	A220	A300	A310	A320	A330	A340	A350	A380
1970		A30B 1974						
1980			A310 1983					
				A320 1988				
1990						A342 1993		
						A343 1993		
		A306 1994		A321 1994	A333 1994			
				A319 1996				
					A332 1998			
2000						A345 2002		
						A346 2002		
				A318 2003				
								A388 2007
2010							A359 2015	
	BCS1 2016							
	BCS3 2016			A20N 2016				
				A21N 2017				
					A339 2018		A35K 2018	
				A19N 2019				
2020					A338 2020			

Figure 25: List of Airbus aircraft and the year of their service entry. [119] [120]

In Figure 25 and Figure 26 can be seen all the Airbus and Boeing aircraft with their year of service entry. The table is divided into aircraft families and ordered chronologically. The four character codes are the ICAO code of aircraft. They are short versions of the actual name, for example, A320 NEO is A20N, and B737 MAX is B37M. The whole list can be found in the Appendix (subsection A).

BOEING									
Family	B707	B717	B727	B737	B747	B757	B767	B777	B787
1950	B701 1958								
1960	B703 1960								
			B722 1968	B731 1968					
				B732 1969					
1970					B741 1970				
					B742 1971				
					B74S 1976				
1980							B762 1982		
					B743 1983	B752 1983			
				B733 1984					
							B763 1986		
				B734 1988					
					B744 1989				
1990				B735 1990					
								B772 1995	
				B737 1997					
				B736 1998				B773 1998	
				B738 1998					
		B712 1999				B753 1999	B764 1999		
2000				B739 2001					
								B77W 2004	
								B77L 2006	
2010					B748 2011				B788 2011
									B789 2014
				B38M 2017					
				B37M 2017					
				B39M 2018					B78X 2018
2020								B778 2025	
								B779 2025	

Figure 26: List of Boeing aircraft and the year of their service entry (In red BADA files not available). [121] [120]

6.1.2 Actual fleet

Airbus and Boeing dominate the commercial aircraft industry. It can be seen when looking at the contributions of their aircraft to total aviation number of flights, distance flown, and emissions, as shown in Figure 27. Due to the regional jets, more than 23% of the flights in 2019 were flown by other aircraft than Boeing and Airbus ones, but when looking at the distance, the number reduces to 12.8%. It is even more striking for the fuel consumption as Airbus and Boeing aircraft consumed more than 90% of the fuel consumed by total aviation. This difference is also due to the bigger sizes of Airbus and Boeing aircraft, which can carry more passengers. When counting the other three firms Bombardier, Embraer, and McDonnell Douglas, the five companies' aircraft represented more than 99% of the fuel consumed by total aviation.

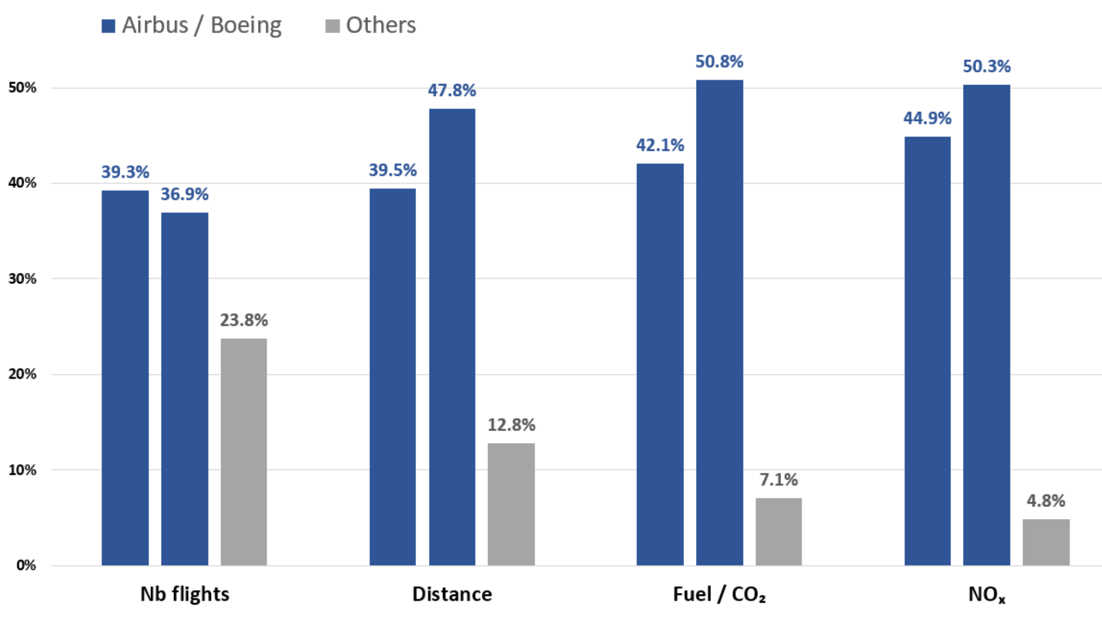

Figure 27: Airbus and Boeing aircraft contributions to aviation emissions for the representative week in 2019.

6.2 Selection of the new fleet

The great majority of all these flights are flown by old-generation aircraft. The table in Figure 28 shows Airbus and Boeing families of new generations of aircraft and their older versions. Aircraft that do not have newer versions, such as the A380, are not listed here. It can be seen at the bottom of the figure that old aircraft represent around 60% of the distance and fuel consumed despite having modern versions already on the market. This is due, as discussed in 5.3, to the strong inertia of the aeronautical industry and market.
It is to be noted the difference in seat capacity between old and new aircraft. All of the modern ones can carry more passengers, with an increase in seat capacity varying between 0 to +20%. This explains the higher value of the fuel consumed compared to the distance flown between the new generations (14% of the total fuel for 11% of the total distance) and the old generations (55% for 61%). Another important reason for these figures is the contributions of medium-haul and long-haul aircraft. For the older ones, medium-haul aircraft which have a much lower fuel consumption than long-haul aircraft contribute a lot more in the total.
Finally, it is important to note that "old generations of aircraft" do not correspond to the oldest generation, and all the aircraft listed as 'old' in Figure 28 are improved versions of even older aircraft (Such as the first version of the B737 which flew in 1968). The actual old generation corresponds to entries in service between 1986 and 2002, meaning two to three decades before the year studied (2019). In comparison, their newer versions entered the market between 2011 and 2019.
The 'new versions' of aircraft here all correspond to aircraft that were made to fly the same flights as their predecessors. For example, the B777-200 LR & B777-300 ER are extended range versions (as suggested by their names), and not exactly improved versions of the B777-200 and -300.
Indeed, when replacing the initial versions with the extended range ones, the results showed higher emissions for almost all the species. Nevertheless, when looking at the emission indices the longer-range aircraft did not show higher values than their previous versions. This is because they were calculated based on the flights they operated. But the extended range B777-300 flew in 2019 on average more than 2700km per flight, compared to less than 1100km for the initial B777-300. Therefore they could not be included here.

SA - Single-aisle (Narrow body) Aircraft				
Family	Decade entry in service	Seats (avg)	Distance (km) per flight (avg)	Nb Aircraft
SA 1 old	1990	160	647	3
SA 1 new	2010	170	652	
SA 2 old	1990	160	726	3
SA 2 new	2010	170	753	
SA 3 old	1990	250	1721	2
SA 3 new	2010	260	/	

TA - Twin-aisle (Wide body) Aircraft				
Family	Decade entry in service	Seats (avg)	Distance (km) per flight (avg)	Nb Aircraft
TA 1 old	1980	270	1489	3
TA 1 new	2010	290	2755	
TA 2 old	1990	310	3354	2
TA 2 new	2010	350	2660	
TA 3 old	1980	420	2377	1
TA 3 new	2010	470	2938	

6 **old**-generation families : **61%** of the total distance and **55%** of the total fuel consumed by aviation in 2019
6 **new**-generation families : **11%** of the total distance and **14%** of the total fuel consumed by aviation in 2019

Figure 28: Airbus and Boeing old and new versions for several aircraft families [121] [119].

7 Technology comparison

7.1 Fleet changes

To analyse the 'future' fleet and more precisely the modern aircraft in comparison with older ones, 14 aircraft were replaced. The replacements correspond to Figure 28. This means that for the analysis of the 'New fleet', all the flights flown by an 'old aircraft' (from Figure 28) during the representative week of 2019 are virtually flown by its new version. Moreover, the emissions resulting are multiplied by the seat capacity factor. For example, if a new aircraft has 10% seats more than its predecessor, all its emissions, at all locations, are multiplied by $\frac{100}{110}$. Therefore, the 14 'old aircraft' are not part of the 'New fleet'. The 'Actual fleet' on the opposite represents the unchanged data and includes both old and modern aircraft that were flying in May 2019.

7.2 Emissions evolution with modern aircraft

Figure 29 below shows emissions' evolution between each old-generation family of aircraft and their modern versions. Each couple of aircraft (an old and a new one) is compared based on the same flights, those flown by the 14 old-generation aircraft in the representative week in 2019. The distance slightly changes: this is due to the calculation method of the code. The data gathered from the air traffic source include the departure and arrival airports. The flight path is then calculated using the aircraft data (such as typical cruise altitude). This leads to small distance differences between two aircraft for the same flights. Here, the capacity is taken into account, and the differences in emissions shown correspond to a difference per seat.

The great majority of green boxes highlight the overall reduction of emissions. When looking at the fuel column, two families consume 20% less than their predecessors. This is in line with the official announcement. For example, SA 1 new was announced to save 15, 20 and 20% of fuel for the three aircraft, compared to 15.9%, 22.9% and 19.6% (without the seat adjustment) calculated with the code. Similarly, the SA 2 new were expected to show a 20% fuel reduction. Again, the results here are very close with -17.0%, -19.2% and -20.8% (without the seat adjustment) of fuel consumed for the three models of the family. On the other hand, SA 3 new are supposed to emit 12% less CO_2 against 7.0% and 6.1% calculated. Likewise, the TA 3 new officially saves 16% of fuel compared to the old one, but only a 7.4% reduction was found. [119] [121]

A striking result is the high increase in NO_x for hf of the families. It is important to note that it comes from both higher NO_x emission indices for modern aircraft and low NO_x emissions from older aircraft. Indeed, when looking at aircraft emission indices for the families showing an increase, it is found a NO_x emission index of around 25g/kg, compared to 21 to 24g/kg for the other families. The same conclusion holds for the higher CO emissions for SA 1 and SA 3.

	Familly	Distance	Fuel	CO_2	CO	HC	NO_x	Soot	H_2O	SO_x	Seats
Single Aisle	SA 1	+0.09%	-20.8%	-20.9%	+32.7%	-43.2%	-8.4%	-56.6%	-20.8%	-20.8%	+6.6%
	SA 2	+0.42%	-19.1%	-19.0%	-65.4%	-41.6%	+59.0%	-84.6%	-19.1%	-19.1%	+10.0%
	SA 3	-0.01%	-6.5%	-6.6%	+71.8%	-5.3%	-12.7%	-56.1%	-6.5%	-6.5%	+1.9%
Twin Aisle	TA 1	+0.46%	-4.0%	-3.9%	-67.3%	-99.1%	+72.0%	+43.4%	-4.0%	-4.0%	+10.4%
	TA 2	+0.01%	-31.0%	-31.0%	-10.3%	-84.7%	-11.4%	+117.8%	-31.0%	-31.0%	+15.3%
	TA 3	+0.25%	-7.4%	-7.4%	-1.7%	-67.9%	+19.6%	+91.5%	-7.4%	-7.4%	+12.3%

Figure 29: Emissions evolution when replacing an old aircraft with its newer version for the same flights. Seats taken into account.

It is also necessary to look at the exact contributions of the old-generation aircraft. Figure 30 shows the 14 old-generation aircraft emissions compared to all aviation. For example, if the TA 2 have largely decreased emissions, they only have a small impact when replacing the original versions because of their low number of flights. On the opposite, SA 1 & 2 are expected to highly contribute to global emission changes due to their important number of flights.

	Familly	Nb flights	Distance	Fuel	CO_2	CO	HC	NO_x	Soot	H_2O	SO_x
Single Aisle	SA 1	30.6%	25.1%	18.7%	18.7%	17.7%	20.6%	18.9%	24.4%	18.7%	18.7%
	SA 2	26.5%	24.4%	17.8%	17.8%	32.1%	17.5%	12.7%	27.9%	17.8%	17.8%
	SA 3	2.9%	6.4%	8.6%	8.6%	4.3%	6.0%	7.7%	4.4%	8.6%	8.6%
Twin Aisle	TA 1	1.6%	3.0%	3.8%	3.8%	5.0%	13.5%	3.6%	2.7%	3.8%	3.8%
	TA 2	0.17%	0.73%	1.3%	1.3%	0.52%	0.42%	1.3%	0.66%	1.3%	1.3%
	TA 3	0.55%	1.7%	4.2%	4.2%	0.80%	3.5%	3.5%	3.9%	4.2%	4.2%

Figure 30: Contributions of the older aircraft to total aviation emissions.

Finally, Figure 31 takes into account both emissions evolution and contributions. The table shows the contribution to total aviation emissions evolution (as presented in Figure 33) of the 14 new aircraft. As a result, the SA 1 & 2 families are the source of major changes because of the high number of flights they operate. NO_x emissions increase is mainly due to the SA 2, responsible for +7.5%. Similarly, CO emissions changes are mostly induced by the SA 1 and 3 with respectively +5.8% and +3.1% but are highly compensated by the reduction from the SA 2 (-21%). Globally, the expected results on modern aircraft can still be seen: Fuel consumption has decreased, and NO_x emissions tend to increase.

	Familly	Fuel	CO_2	CO	HC	NO_x	Soot	H_2O	SO_x
Single Aisle	SA 1	-3.9%	-3.9%	+5.8%	-8.9%	-1.6%	-13.8%	-3.9%	-3.9%
	SA 2	-3.4%	-3.4%	-21.0%	-7.3%	+7.5%	-23.6%	-3.4%	-3.4%
	SA 3	-0.6%	-0.6%	+3.1%	-0.3%	-1.0%	-2.5%	-0.6%	-0.6%
Twin Aisle	TA 1	-0.2%	-0.1%	-3.4%	-13.3%	+2.6%	+1.2%	-0.2%	-0.2%
	TA 2	-0.4%	-0.4%	-0.1%	-0.4%	-0.2%	+0.8%	-0.4%	-0.4%
	TA 3	-0.3%	-0.3%	-0.0%	-2.4%	+0.7%	+3.5%	-0.3%	-0.3%

Figure 31: Evolution of total aviation emissions for each aircraft replacement.

The evolution of the 14 aircraft emissions between the old and new versions are presented in Figure 32. The data shown corresponds to the flights flown by the old aircraft originally in the representative week in 2019. Therefore the results are dependent on the contributions of each aircraft to the number of flights and distance flown, and is not a mean of the 14 evolution as discussed above. Both results, taking or not taking into account seats, are presented here. Since every new version has an increased seat capacity, the differences in emissions are all lowered when including it.

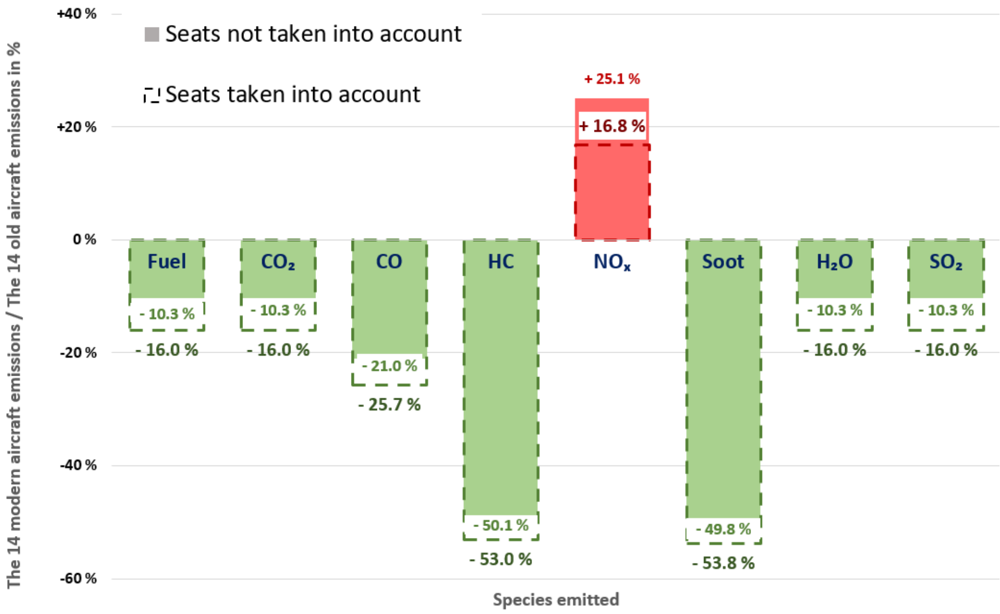

Figure 32: Emissions evolution when replacing the 14 old Airbus and Boeing aircraft with new versions.

Even without the seat capacity factor, all the emissions have been lowered significantly, except for NO_x emissions which have largely increased by 25.1%. Fuel use has been reduced by 10.3%, as CO_2, H_2O and SO_x. The other species emissions were even more reduced with -21.0% for CO and around 50% of *reduction* for HC and *Soot*. As a result, the global fleet emissions follow the same trends with slightly fewer changes as shown in Figure 33. The NO_x emissions still show a significant increase of 12.0%, while other emissions have decreased. This result also confirms the importance of the 14 aircraft chosen and their high contribution to total aviation emissions.

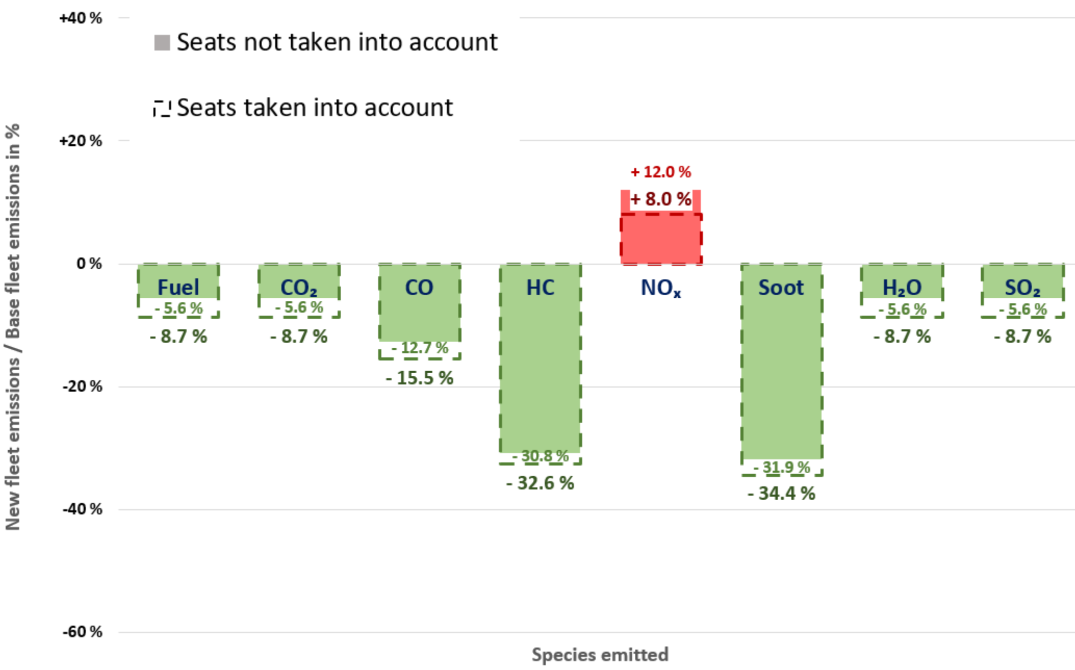

Figure 33: Emissions evolution for total aviation when replacing the 14 old Airbus and Boeing aircraft with new versions.

In Figure 34 can be seen the distinction between Airbus and Boeing's new aircraft contributions to total emission changes. One company shows a large NO_x increase, compared to a small decrease for the other. More surprisingly, one caused a major CO increase, hidden by a greater decrease for the other one. All other emissions are reduced for both companies.

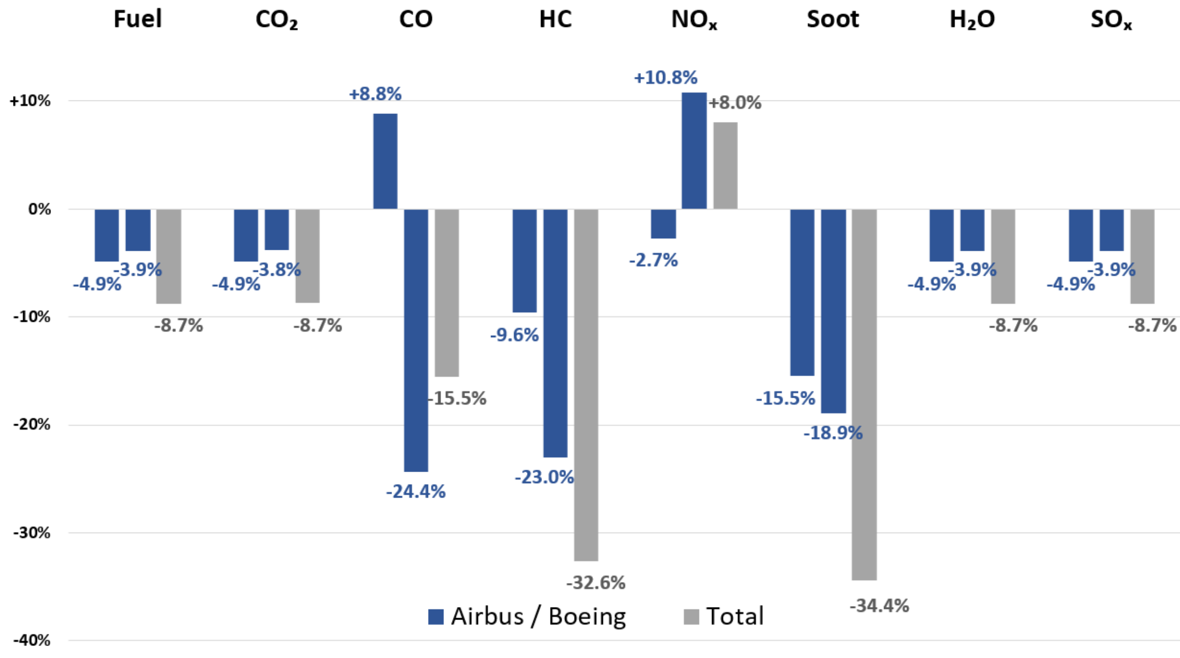

Figure 34: Evolution of Airbus and Boeing modern vs old aircraft emissions.

7.3 Atmosphere impact evolution with modern aircraft

The results obtained with AirClim are discussed in this section. The set-up was discussed in section 5. The years chosen in the settings are the same for all the simulations. First, in subsubsection 7.3.1, the background is kept to 'CurTec' taken from Grewe et al. (2021) [99] and given in the Appendix (subsection C). The proportion of biofuels is also kept at 0% for all years. Then, the influence of these two parameters is evaluated. In subsubsection 7.3.2, another background is input, 'FP2050' also available in the Appendix. Finally, in subsubsection 7.3.3, the biofuel contribution is set at 1% in 2021 and grows progressively to reach 50% in 2050 and is then constant up to 2100.

The 'actual fleet' corresponds to the unchanged results of the representative week analysis: the FlightRadar24 data from the fourth week of May 2019. The 'new fleet' corresponds to the same data, with 14 aircraft replaced by their new versions. This is shown in Figure 28. Again, the seat capacity is taken into account.

7.3.1 New vs actual fleet

Figure 35 presents the evolution of the difference in temperature change between the new and the actual fleet (Seat capacity difference taken into account). The main variation comes from NO_x emissions. The exponential evolution of the CH_4 and CO_2 can be noted in comparison with the more linear evolution of O_3. This is due to the short-term impact of NO_x on Ozone and its small lifetime compared to other species.

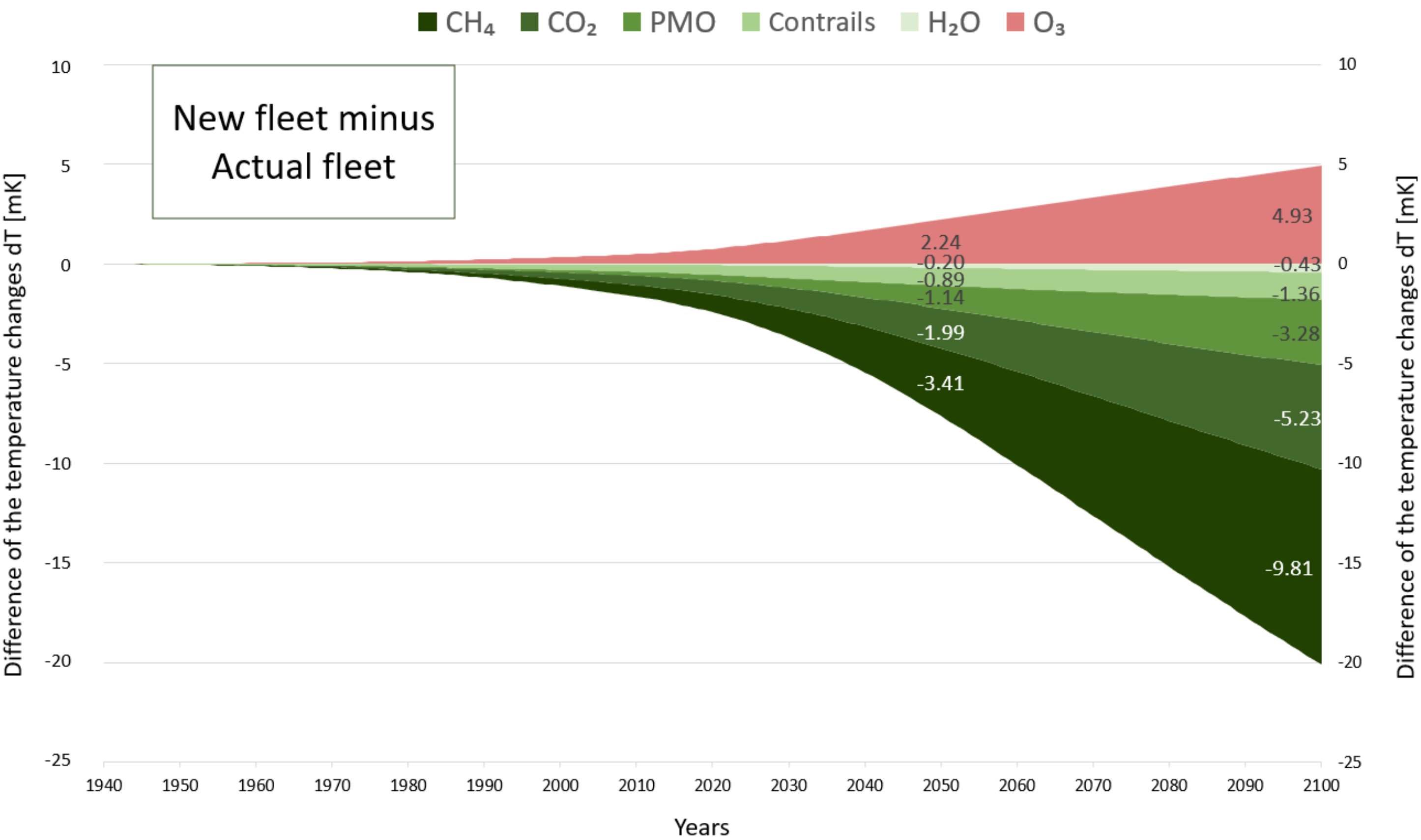

Figure 35: New fleet minus Actual fleet temperature changes due to aviation through the years.

The detailed results for both 2050 and 2100 can be seen in Figure 36. The NO_x contributions are regrouped in the bottom part of the Figure 36 to get a better idea of the overall difference. The CO_2 and H_2O impacts have decreased for the new fleet, as expected given the lower emissions calculated previously. The temperature changes due to contrails have also lowered, due to the reduction of soot (See 5.3). Without taking soot into account, the contrails' impact is slightly higher for the new fleet. This can be explained by different cruise altitudes, which also implies different distances flown for the same flights in Figure 29. Surprisingly, the global NO_x contribution has lowered as well: If the temperature change due to ozone perturbation is higher for the new fleet, the CH_4 and PMO have even more decreased leading to a global diminution.

It is important to note that the temperature change due to CO_2 has almost tripled between 2050 and 2100. In comparison, the temperature change related to O_3 has only slightly more than doubled. This is due to the much higher lifetime of CO_2 (decades) compared to the ozone (weeks). The cause is demonstrated by Grewe et al. (2008): For the CO_2 and O_3 to have the same radiative forcing increase rates, there has to be a 6 to 7% annual growth of fuel consumption [10]. This is the case around 2015-2020 (Without taking into account COVID-19), but the growth lowers to 1.23% in 2050 and 0.73% in 2100. The strong inertia of CO_2 is also demonstrated by the growing difference between the actual and the new fleet.

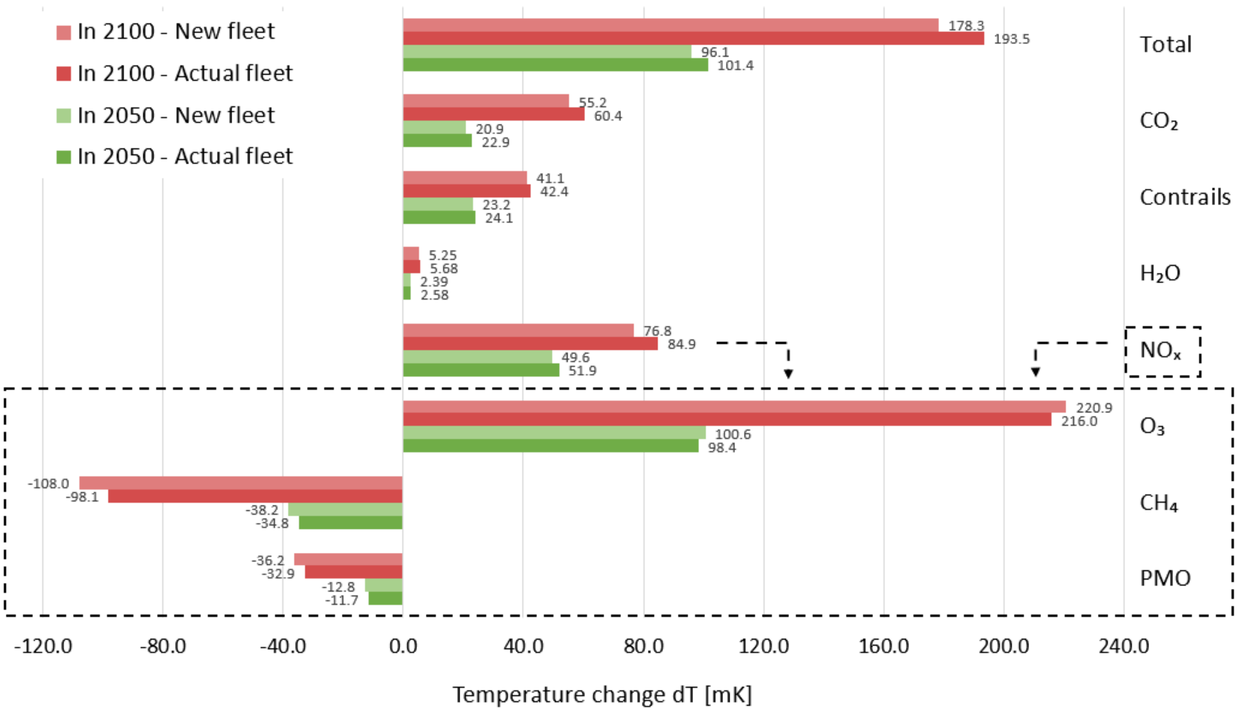

Figure 36: New fleet vs Actual fleet temperature changes due to aviation for 2050 and 2100.

To analyse more precisely these results, two other fleets were created:

- 'SA 1 updated' fleet: Only one SA 1 aircraft is changed and all its flights are virtually flown by the new version.
- 'SA 2 updated' fleet: Only one SA 2 aircraft is changed and all its flights are virtually flown by the new version.

These two aircraft were chosen because of their major contributions to the emissions changes when comparing the new to the actual fleet (See Figure 31). More precisely, the 'SA 1 updated' fleet corresponds to a reduction of 1.9% of fuel consumed and 5.1% of NO_x emitted. On the opposite, the 'SA 2 updated' fleet shows a decrease of 2.0% of fuel but an increase of 6.0% of NO_x. The results for the 'SA 1 updated' fleet are presented below.

The results are very different from the previous comparison (See Figure 37. For this case, a reduction in NO_x emissions did lead to a reduction in temperature change due to this climate agent. More precisely, the increase of temperature change due to CH_4 and PMO does not compensate for the decrease due to O_3 as can be seen in Figure 37. More importantly, the difference due to NO_x is almost the same between 2050 and 2100, respectively -1.53 mK and -1.59 mK. When taking a closer look, the trends show that this difference is on an increasing trend in 2100 as CH_4 cooling increases faster than O_3 warming.

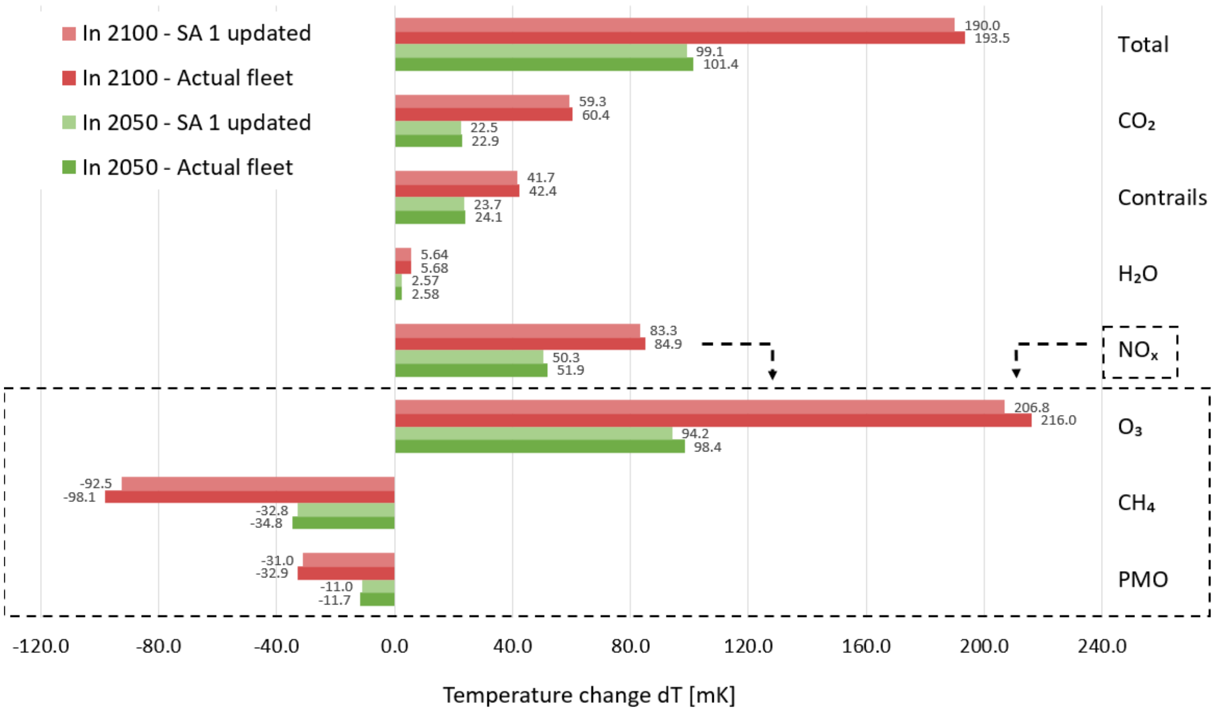

Figure 37: 'SA 1 updated' fleet vs Actual fleet temperature changes due to aviation for 2050 and 2100.

For the 'SA 2 updated' fleet, Figure 38 shows that the differences follow the same directions as for the global new fleet. The five same climate agents CH_4, PMO, CO_2, contrails and H_2O show a decrease. The magnitudes of those differences are also in the same order, CH_4 showing the biggest gap and H_2O the smallest. The same observation can be made for the NO_x impact: O_3 contribution is significantly bigger. Overall, the NO_x increased emissions lead to almost no change for the two fleets in 2050 (-0.1 mK), but a significant change in 2100 (-2.2 mK).

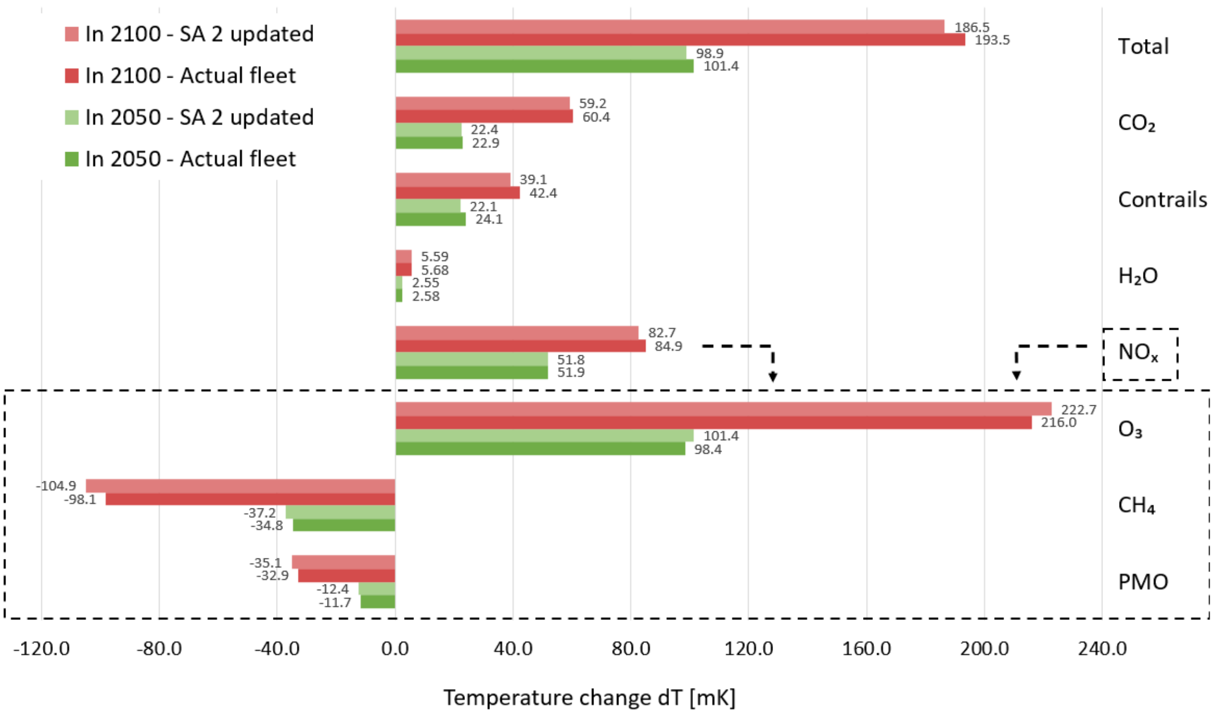

Figure 38: 'B737-800 replaced by MAX' fleet vs Actual fleet temperature changes due to aviation for 2050 and 2100.

To understand this result, the SA 2 new and old aircraft NO_x emissions are plotted in function of the altitude. The emissions still correspond to the same flights for both aircraft, the ones flown by the old aircraft during the representative week of 2019, in May.

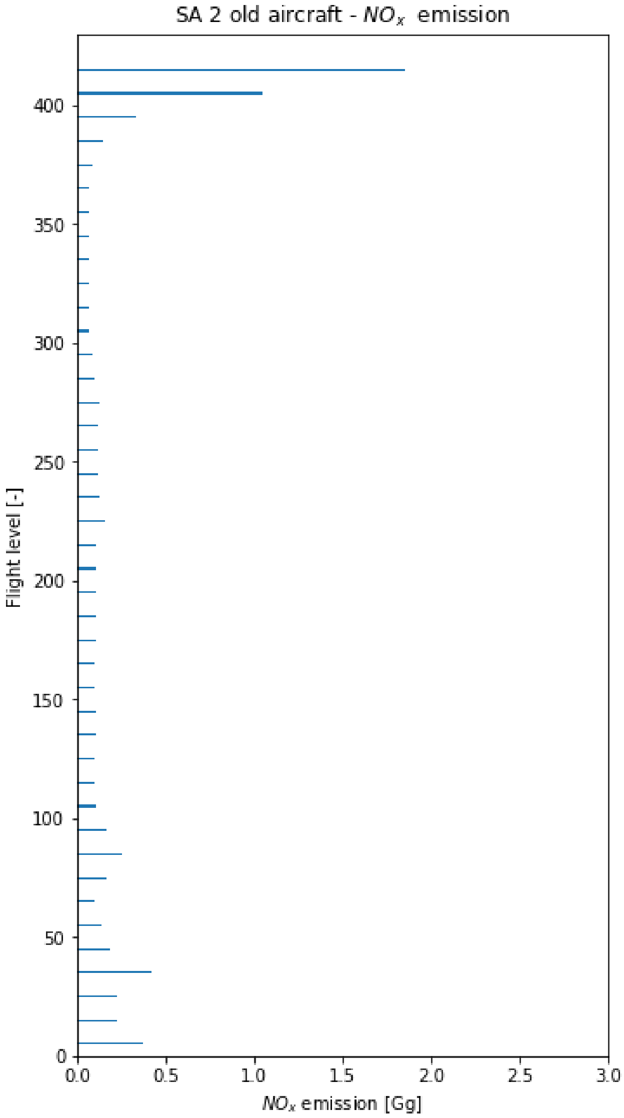

Figure 39: SA 2 old aircraft NO_x emissions in function of the flight level.

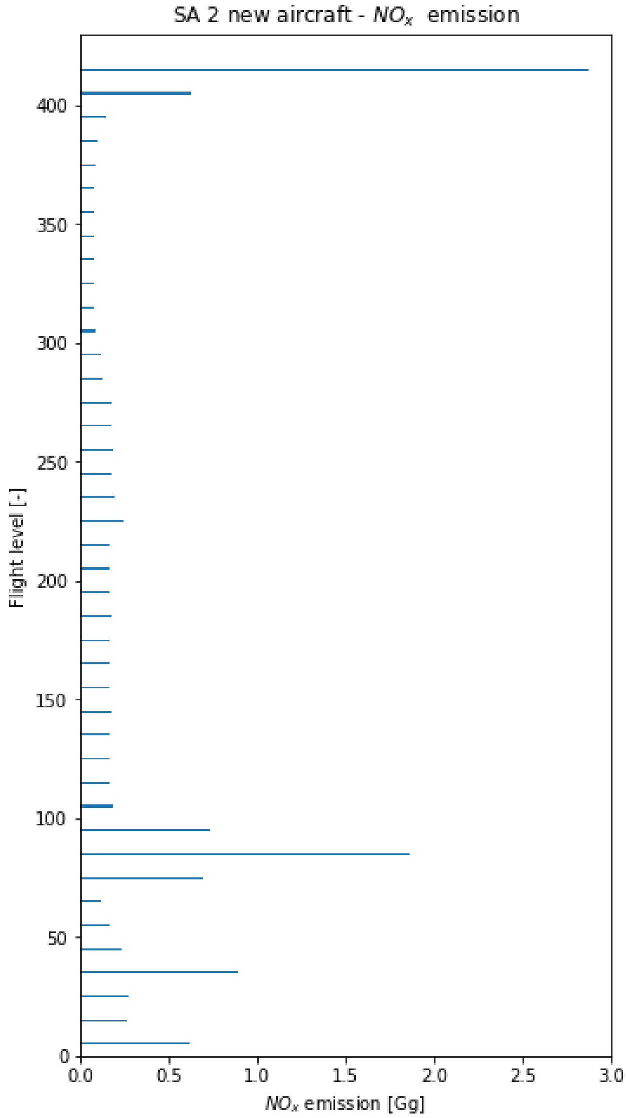

Figure 40: SA 2 new aircraft NO_x emissions in function of the flight level.

Around cruise altitude (Flight level of 400), the new version emits slightly more NO_x, with a very small difference in location. At low altitudes (Below a flight level of 100), on the other hand, the difference is striking. The emissions for the new version are much bigger. This is in line with the data from the ICAO engine emissions database [23]:

Aircraft	Engine model NO_x:	EI T/O [g/kg]	EI C/O [g/kg]	EI App [g/kg]	EI Idle [g/kg]
SA 2 old aircraft	CFM56	21.79	17.08	8.93	4.27
SA 2 new aircraft	LEAP	55.26	23.26	11.59	4.59

Table 7: NO_x emission indices for different flight phases of an SA 2 old and new aircraft from ICAO [23].

The different flight phases mentioned in Table 7 correspond to Take Off (T/O), Climb Out (C/O), Approach (App), and Idle. As expected after the results from Figure 39 & Figure 40, the emission index at take-off is much higher for the MAX version. On the opposite, the emission index at idle conditions is almost the same for both versions. These data lead to similar emissions at cruise altitude, and very different emissions at low altitudes from the two aircraft.

To verify the link between the altitude at which the NO_x is emitted and the impact on CH_4, another emissions file is created. The SA 2 new aircraft emissions only vs the SA 2 old aircraft emissions only are analysed. For the new version, the NO_x emissions below 12,500 feet (Flight level of 125) are multiplied by 4.

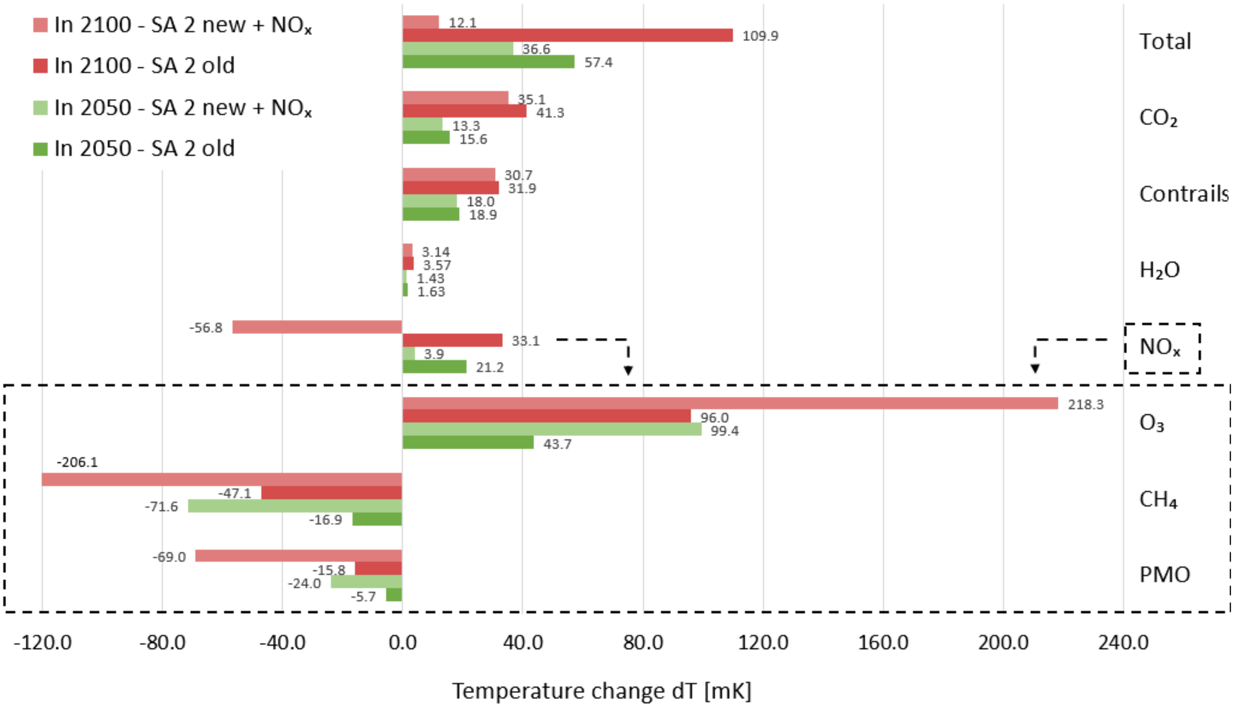

Figure 41: Temperature changes due to SA 2 old aircraft vs due to SA 2 new aircraft (with extra NO_x at low altitudes) for 2050 and 2100.

Figure 41 confirms the hypothesis: the altitude at which NO_x is emitted is the reason why the new fleet shows a lower temperature change even though more NO_x is emitted. This result was found and described by Grewe et al. (2008). The paper identifies the tropical troposphere as the region where NO_x emissions lower the most CH_4 lifetime (along with the stratosphere at supersonic altitudes). This is explained by fast chemistry. On the opposite, around the tropopause, close to cruise altitudes, chemistry is slow. In particular, OH formation (leading to methane depletion) is limited due to higher H_2O concentrations or UV irradiance [10] [122].

NO_x and chemistry

As discussed in subsubsection 4.1.3, NO_x emissions result in four major changes on atmosphere chemistry: [19]

- Short-term ozone increase.
- Long-term ozone decrease (Primary Mode Ozone, PMO).
- Methane decrease.
- Stratospheric water vapour decrease.

These effects are highly dependent on the location of emission and on the atmosphere's composition and state. NO_x emissions not only enhance ozone formation but also increase OH formation, which is a sink for methane. Therefore, NO_x atmosphere impact is dependent on the temperature and concentrations of both OH and CH_4 [123]. Similarly, the background NO_x plays a major role in NO_x emissions impact. For the same NO_x **surface** emissions, less background NO_x results in more ozone production, but also more methane depletion. The latter being more important, the overall effect is a decrease of the radiative forcing [124].

Nevertheless, the difference in lifetime between ozone and methane also means a different influence on the atmosphere. As the ozone has a short-term impact, it is quite in-homogeneous. On the opposite, the high lifetime of methane makes its response well-distributed. Overall, a cancellation of the two radiative forcing does not necessarily mean a cancellation on local scales [123].

NO_x and altitude

The altitude at which NO_x is emitted, as seen in the previous results, has a great influence on its radiative forcing. At cruise altitudes, around 8 to 12km, it was found that O_3 production is three to four times faster than at surface levels [124] [125]. Skowron et al. (2015) found that cruise altitude corresponds to the peak of ozone perturbations [123]. Indeed, above 12km of altitude, an "Ozone-neutral cruise" altitude can be found. Fritz et al. (2022) found an "ozone-neutral cruise around 14 km, with the exact altitude depending on the fuel sulfur content and/or the NOx emission index of the aircraft engines" [125].

NO_x and region

Due to the different background concentrations in the atmosphere for different regions, the location of emissions, apart from altitude, also plays a role in NO_x impact. In particular, the southern hemisphere has less background NO_x leading to a bigger impact per emission [125]. On the opposite, low latitude regions (Europe, North America) were found to have the lowest net radiative forcing due to NO_x emissions [123]. On the other hand, longitude change does not show a significant influence on NO_x radiative forcing [126].

NO_x conclusions

Overall, only looking at the magnitudes of NO_x emissions, or the emission indices of the engines gives very poor information on the atmosphere impact of aviation. The complex chemistry behind NO_x emissions leads to many parameters influencing the resulting net radiative forcing. It can go from significantly positive at cruise levels and high latitudes to negative close to the surface [124] [127].

7.3.2 Influence of background emission scenarios

Another background scenario was tested with the new and actual fleets to test its influence on the results. Taken from Grewe et al. (2021) (See Appendix - subsection C), the FP2050 background data assumes a large reduction in fuel consumption for aviation compared to the CurTec scenario. It goes on increasing up until 2050 (With a decreasing annual growth) but promptly reduces between 2050 and 2060. Afterwards, the fuel consumption very slightly grows up until 2100.

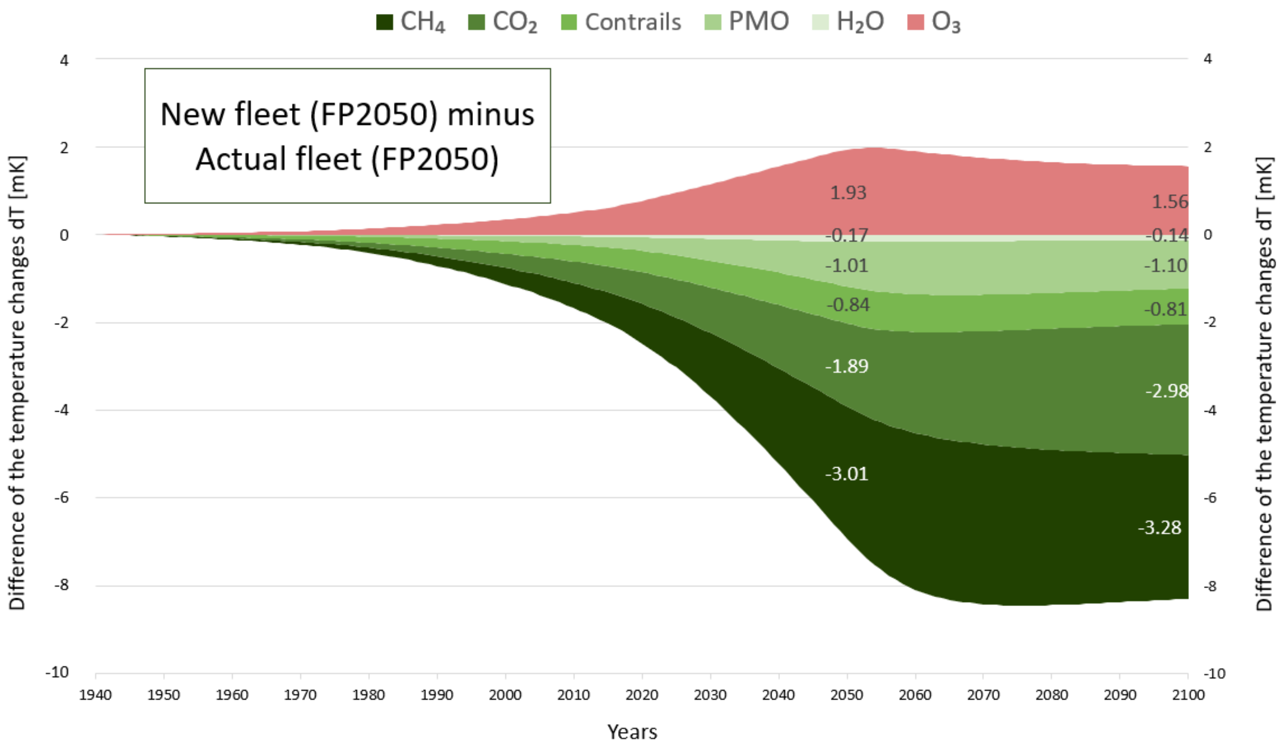

Figure 42: New fleet minus Actual fleet temperature changes due to aviation through the years (Background data FP2050).

It can be seen in Figure 42 the weird shape of the graphs. The fast reduction in fuel consumption around 2050 kills the trends and stops the sharp growth in temperature changes. The same holds for the differences between the two fleets. Figure 43 shows a decrease in the total NO_x related temperature change between 2050 and 2100. This is due to a much lower ozone radiative forcing a few decades after the peak in emissions. If the temperature change difference between the new and the actual fleet is almost the same as for the CurTec scenario in 2050 (-5.0 mK compared to -5.3 mK), it is much lower for 2100 (-6.7 mK compared to -15.2 mK). Nevertheless, in terms of percentages, the new fleet temperature change reduction is slightly bigger with this scenario. Indeed, with CurTec, the total temperature change was lowered in 2050 and 2100 by respectively -5.2% and -7.8%. With the FP2050 scenario, the reductions are -5.6% and -8.6%.

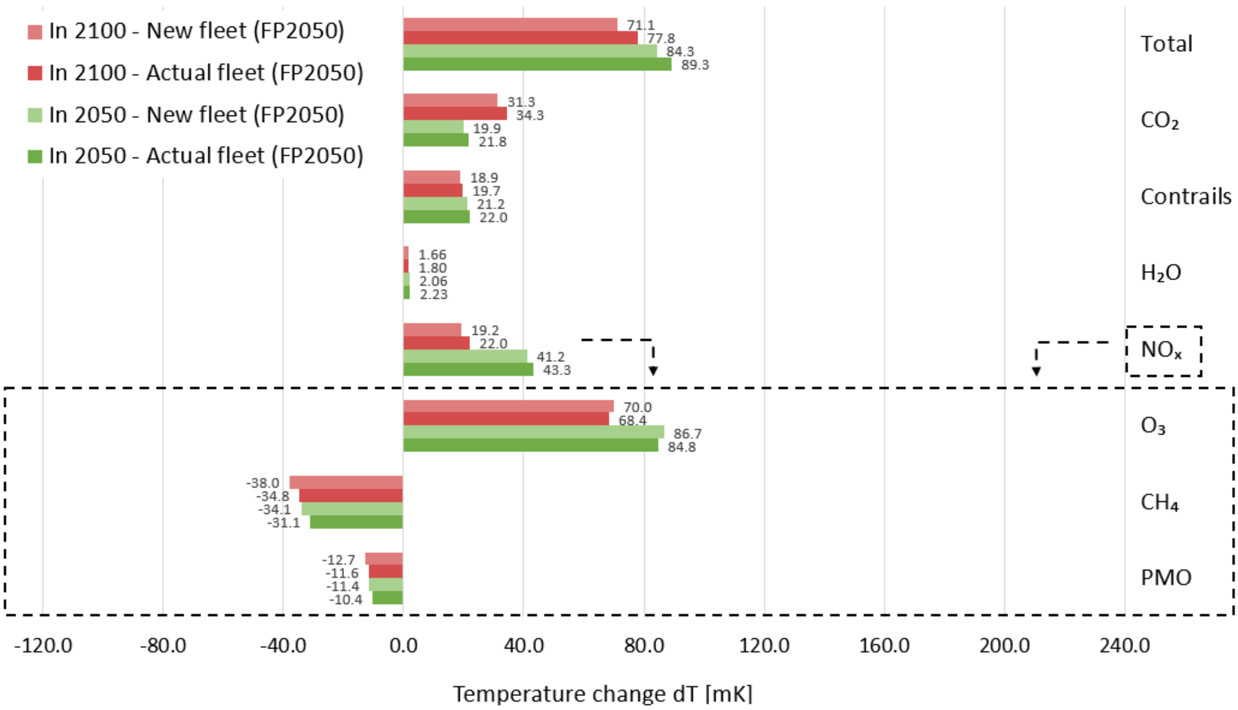

Figure 43: New fleet vs Actual fleet temperature changes due to aviation for 2050 and 2100 (Background data FP2050).

7.3.3 Influence of biofuels

The biofuels have the effect of decreasing the CO_2 emissions, as well as soot emissions. These effects are taken into account here, as shown in the results of Figure 44. All other climate agent impacts, except from CO_2 and Contrails remain unchanged. The reduction in CO_2 comes from the production of biofuels, which, per definition, use biomass. This can result in a reduction up to 80% [128]. The soot reduction from biofuels is taken into account through Equation 18. The proportion of biofuels used in this case grows progressively to 50% in 2050 and then is constant up to 2100. The results show a significant decrease when compared to the case without any biofuels. The overall reduction in temperature change corresponds to -6% for 2050 and 16% for 2100. It is interesting to see that by 2050, the effects of biofuels are much harder to see, and even lower than the technology change.
Other emissions could be impacted as well. Mazlan et al. (2016) estimated the JSPK (Jatropha bio-synthetic paraffinic kerosene) to reduce NO_x emissions up to 13% with a 100% of JSPK use [129]. Nevertheless, the use of biofuels is for the moment very limited and their effect cannot be predicted with much precision. Indeed, in 2019, less than 0.1% of the aviation fuel used came from biofuels [130].

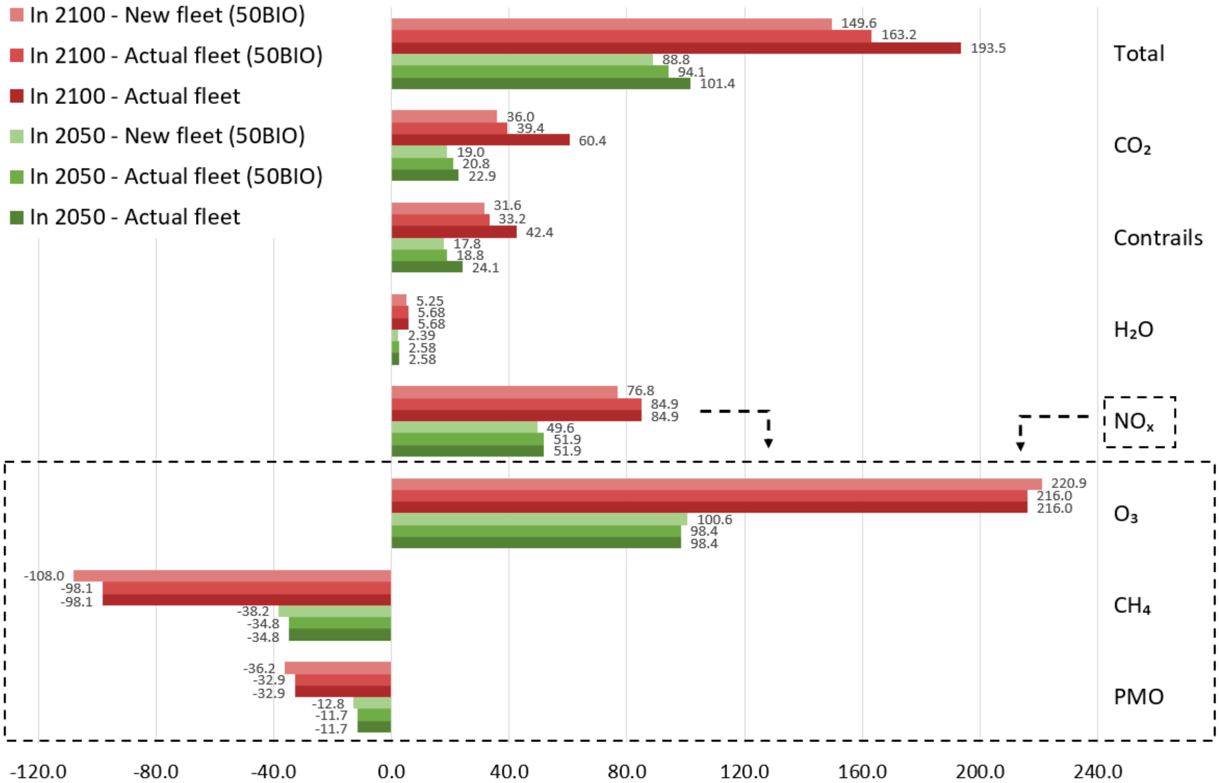

Figure 44: New fleet vs Actual fleet temperature changes due to aviation for 2050 and 2100 (with 30% of biofuels in 2100 and with no biofuels).

7.4 AirClim results for 2019

Uncertainties were added to the final result for 2019 Radiative Forcing due to aviation (See Figure 45). Those errors are based on the two codes: Uncertainties coming from the emissions inventory code and estimated by Kroon et al. (2022) [11], and uncertainties coming from AirClim and calculated by Grewe et al. (2016) [97].

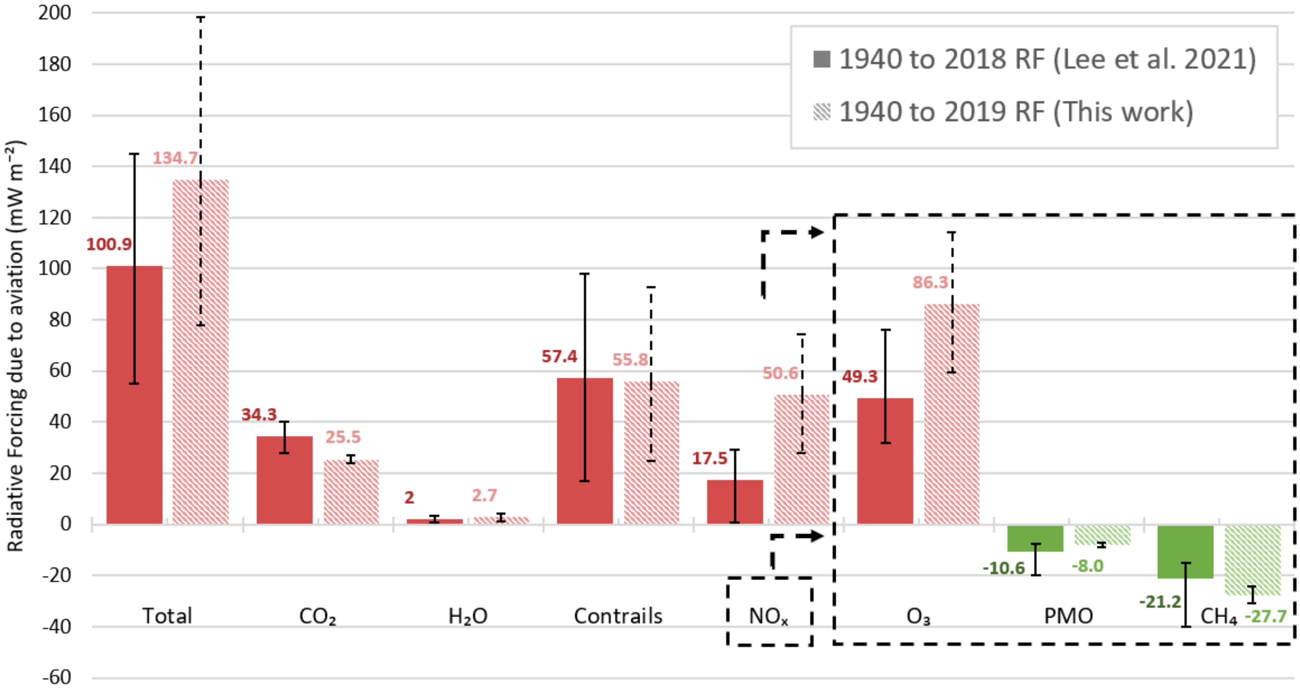

Figure 45: Radiative forcing due to aviation between 1940 and 2018 (From Lee et al. 2021 [5]) vs 2019 (This work).

Figure 45 shows the radiative forcing due to aviation in 2019. It is compared to the results of Lee et al. (2021). As discussed previously, the main difference corresponds to the NO_x emissions and is due to improved estimations of ozone changes due to aviation NO_x [109]. The CO_2 gap is mainly due to the total fuel consumed. Contrary to NO_x the location of emissions only has a small influence on its climate impact [10].

8 Conclusions

It was found that the new generation aircraft show significant reductions in emissions for all species, except for NO_x. In particular, replacing 14 aircraft with their updated versions in 2019 led to a decrease of 8.7% of fuel consumed by aviation. Species impacting air quality such as CO and HC are even more reduced, respectively by 15.5% and 32.6%.On the other hand, NO_x emissions are increased by 8.0% with the new aircraft. Nevertheless, this increase leads to better results for global warming: Due to an overcompensation of the methane and PMO cooling compared to the ozone warming, the overall temperature change due to NO_x emissions is lower with the modern aircraft. This result is explained by the different locations of emissions. It has a much lower impact when emitted at low altitudes than at cruise altitude.

Modern aircraft reduce the climate impact of aviation through all the climate agents: H_2O and CO_2 through less fuel consumption, NO_x, and also contrails. Indeed, the large soot emissions reduction (-10.6% around contrail formation altitudes) significantly reduces contrail formation and impact. The overall temperature change reduction for 2050 is reduced by 5.3 mK (-5.2%) when replacing the 14 aircraft - assuming the fleet then remains unchanged in both cases.

The conclusion of this work reflects Skowron et al. (2021) paper: NO_x emissions impact is difficult to predict and the focus should not be made on reducing aviation NO_x emissions. CO_2 emissions, much more predictable, should remain the first target for global warming mitigation. It is also to be noted that neither the actual technological improvements nor biofuels are sufficient to achieve the Paris Agreement goal of keeping global warming under +1.5°C. The results show that with an immediate replacement of the 14 old generation aircraft (which consumed 59% of the total fuel used by aviation in 2019) and a progressive increase of biofuels to reach 50% in 2050, the temperature change due to aviation would be of 88.8 mK in 2050. This represents 5.9% of +1.5°C. On the other hand, the reduction in the number of flights showed a much higher reduction potential in the analysis.

References

[1] International Air Transport Association (IATA). "Our Commitment to Fly Net Zero by 2050". In: (Oct. 2021). URL: https://www.iata.org/en/programs/environment/flynetzero/.

[2] International Civil Aviation Organization (ICAO). "States adopt net-zero 2050 global aspirational goal for international flight operations". In: (Oct. 2022). URL: https://www.icao.int/Newsroom/Pages/States-adopts-netzero-2050-aspirational-goal-for-international-flight-operations.aspx.

[3] Airbus. "Decarbonisation, Objective: net-zero carbon emissions by 2050". In: (2023). URL: https://www.airbus.com/en/sustainability/respecting-the-planet/decarbonisation#.

[4] R. Teoh et al. "Aviation contrail climate effects in the North Atlantic from 2016 to 2021". In: *Atmospheric Chemistry and Physics* 22.16 (2022), pp. 10919–10935. DOI: 10.5194/acp-22-10919-2022. URL: https://acp.copernicus.org/articles/22/10919/2022/.

[5] D.S. Lee et al. "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018". In: *Atmospheric Environment* 244 (Jan. 2021), p. 117834. ISSN: 13522310. DOI: 10.1016/j.atmosenv.2020.117834. URL: https://linkinghub.elsevier.com/retrieve/pii/S1352231020305689 (visited on 02/06/2023).

[6] North Carolina Climate Office. *'Unfair' to attack air passengers over climate change, says Airbus CEO*. URL: https://www.arabianbusiness.com/industries/transport/434434-it-is-unfair-that-it-has-become-trendy-to-attack-those-who-use-planes-says-airbus-ceo. (accessed: 09.03.2023).

[7] Eurocontrol. "Aviation Outlook 2050". In: (2022). URL: https://www.eurocontrol.int/forecasting.

[8] International Air Transport Association. "Air Passenger Numbers to Recover in 2024". In: (2022). URL: https://www.iata.org/en/pressroom/2022-releases/2022-03-01-01/.

[9] S. C. Olsen, D. J. Wuebbles, and B. Owen. *Comparison of global 3-D aviation emissions datasets*. preprint. Gases/Atmospheric Modelling/Troposphere/Chemistry (chemical composition and reactions), July 10, 2012. DOI: 10.5194/acpd-12-16885-2012. URL: https://acp.copernicus.org/preprints/12/16885/2012/acpd-12-16885-2012.pdf (visited on 02/08/2023).

[10] V. Grewe and A. Stenke. "AirClim: an efficient tool for climate evaluation of aircraft technology". In: *Atmospheric Chemistry and Physics* 8.16 (Aug. 11, 2008), pp. 4621–4639. ISSN: 1680-7324. DOI: 10.5194/acp-8-4621-2008. URL: https://acp.copernicus.org/articles/8/4621/2008/ (visited on 06/05/2023).

[11] Rik Kroon. "Aviation Emission Inventory". In: (2022). URL: http://resolver.tudelft.nl/uuid:83f7d044-b507-41b6-98de-90f3385c0214.

[12] Joyce E Penner. "IPCC Special Report on Aviation and the Global Atmosphere". In: (1999).

[13] D.S. Lee et al. "Transport impacts on atmosphere and climate: Aviation". In: *Atmospheric Environment* 44.37 (Dec. 2010), pp. 4678–4734. ISSN: 13522310. DOI: 10.1016/j.atmosenv.2009.06.005. URL: https://linkinghub.elsevier.com/retrieve/pii/S1352231009004956 (visited on 02/10/2023).

[14] North Carolina Climate Office. *Ozone Layer*. URL: https://legacy.climate.ncsu.edu/edu/OzoneLayer. (accessed: 01.03.2023).

[15] Yingwen Yan et al. "Simplified Chemical Reaction Mechanism for Surrogate Fuel of Aviation Kerosene and Its Verification". In: *Energy & Fuels* 30.12 (2016), pp. 10847–10857. DOI: 10.1021/acs.energyfuels.6b01852. eprint: https://doi.org/10.1021/acs.energyfuels.6b01852. URL: https://doi.org/10.1021/acs.energyfuels.6b01852.

[16] David S. Lee et al. "Aviation and global climate change in the 21st century". In: *Atmospheric Environment* 43.22 (July 2009), pp. 3520–3537. ISSN: 13522310. DOI: 10.1016/j.atmosenv.2009.04.024. URL: https://linkinghub.elsevier.com/retrieve/pii/S1352231009003574 (visited on 01/30/2023).

[17] *ICAO Airport Air Quality Manual - 2020*. 2020. URL: https://www.icao.int/publications/documents/9889_cons_en.pdf (visited on 02/14/2023).

[18] Flávio D. A. Quadros et al. "Global Civil Aviation Emissions Estimates for 2017–2020 Using ADS-B Data". In: *Journal of Aircraft* 59.6 (Nov. 2022). Number: 6, pp. 1394–1405. ISSN: 1533-3868. DOI: 10.2514/1.C036763. URL: https://arc.aiaa.org/doi/10.2514/1.C036763 (visited on 01/28/2023).

[19] A. Skowron, D. S. Lee, and R. R. De León. "The assessment of the impact of aviation NOx on ozone and other radiative forcing responses – The importance of representing cruise altitudes accurately". In: *Atmospheric Environment* 74 (Aug. 1, 2013), pp. 159–168. ISSN: 1352-2310. DOI: 10.1016/j.atmosenv.2013.03.034. URL: https://www.sciencedirect.com/science/article/pii/S1352231013002100 (visited on 02/14/2023).

[20] Tara I. Yacovitch et al. *Exhaust Emissions from In-Use General Aviation Aircraft.* Pages: 24612. Washington, D.C.: Transportation Research Board, Nov. 16, 2016. ISBN: 978-0-309-45233-5. DOI: 10.17226/24612. URL: https://www.nap.edu/catalog/24612 (visited on 01/28/2023).

[21] European Environment Agency. *EMEP/EEA air pollutant emission inventory guidebook 2019: technical guidance to prepare national emission inventories.* LU: Publications Office, 2019. URL: https://data.europa.eu/doi/10.2800/293657 (visited on 02/14/2023).

[22] EASA. "Reduction of sulphur limits in aviation fuel standards (SULPHUR)". In: (2010). URL: https://www.easa.europa.eu/en/document-library/research-reports/easa2008c11.

[23] ICAO. "Introduction to the ICAO Engine Emissions Databank". In: (2020).

[24] Fudong Ge et al. "Predicting aviation non-volatile particulate matter emissions at cruise via convolutional neural network". In: *Science of The Total Environment* 850 (Dec. 2022), p. 158089. ISSN: 00489697. DOI: 10.1016/j.scitotenv.2022.158089. URL: https://linkinghub.elsevier.com/retrieve/pii/S0048969722051889 (visited on 01/28/2023).

[25] Hulda R. Jonsdottir et al. "Non-Volatile Particle Emissions from Aircraft Turbine Engines at Ground-Idle Induce Oxidative Stress in Bronchial Cells". In: *Communications Biology 2* 1.90 (2019). DOI: 10.1038/s42003-019-0332-7. URL: https://doi.org/10.1038/s42003-019-0332-7.

[26] Roger L Wayson, Gregg G Fleming, and Ralph Iovinelli. "Methodology to Estimate Particulate Matter Emissions from Certified Commercial Aircraft Engines". In: *Journal of the Air & Waste Management Association* 59.1 (Jan. 2009), pp. 91–100. ISSN: 1096-2247, 2162-2906. DOI: 10.3155/1047-3289.59.1.91. URL: https://www.tandfonline.com/doi/full/10.3155/1047-3289.59.1.91 (visited on 01/28/2023).

[27] Bethan Owen et al. "Review: Particulate Matter Emissions from Aircraft". In: *Atmosphere* 13.8 (Aug. 3, 2022), p. 1230. ISSN: 2073-4433. DOI: 10.3390/atmos13081230. URL: https://www.mdpi.com/2073-4433/13/8/1230 (visited on 03/09/2023).

[28] Bernd Kärcher. "Formation and radiative forcing of contrail cirrus". In: *Nature Communications* 9.1 (May 8, 2018), p. 1824. ISSN: 2041-1723. DOI: 10.1038/s41467-018-04068-0. URL: https://www.nature.com/articles/s41467-018-04068-0 (visited on 03/12/2023).

[29] Christopher J. Smith et al. "Effective radiative forcing and adjustments in CMIP6 models". In: *Atmospheric Chemistry and Physics* 20.16 (Aug. 17, 2020). Publisher: Copernicus GmbH, pp. 9591–9618. ISSN: 1680-7316. DOI: 10.5194/acp-20-9591-2020. URL: https://acp.copernicus.org/articles/20/9591/2020/ (visited on 03/12/2023).

[30] D Ehhalt et al. "Atmospheric Chemistry and Greenhouse Gases". In: (2001).

[31] Gunnar Myhre et al. *Aerosols and their Relation to Global Climate and Climate Sensitivity — Learn Science at Scitable.* Cg_cat: Aerosols and their Relation to Global Climate and Climate Sensitivity Cg_level: MED Cg_topic: Aerosols and their Relation to Global Climate and Climate Sensitivity. 2013. URL: https://www.nature.com/scitable/knowledge/library/aerosols-and-their-relation-to-global-climate-102215345/ (visited on 03/09/2023).

[32] A. Gettelman and C. Chen. "The climate impact of aviation aerosols". In: *Geophysical Research Letters* 40.11 (June 16, 2013), pp. 2785–2789. ISSN: 0094-8276, 1944-8007. DOI: 10.1002/grl.50520. URL: https://onlinelibrary.wiley.com/doi/10.1002/grl.50520 (visited on 03/09/2023).

[33] Ulrich Schumann and Andrew J. Heymsfield. "On the Life Cycle of Individual Contrails and Contrail Cirrus". In: *Meteorological Monographs* 58 (Jan. 1, 2017), pp. 3.1–3.24. ISSN: 0065-9401. DOI: 10.1175/AMSMONOGRAPHS-D-16-0005.1. URL: http://journals.ametsoc.org/doi/10.1175/AMSMONOGRAPHS-D-16-0005.1 (visited on 03/12/2023).

[34] Lance Sherry and Terrence Thompson. "Primer on Aircraft Induced Clouds and Their Global Warming Mitigation Options". In: *Transportation Research Record* 2674.11 (2020), pp. 827–841. DOI: 10.1177/0361198120951188. eprint: https://doi.org/10.1177/0361198120951188. URL: https://doi.org/10.1177/0361198120951188.

[35] Ulrich Schumann. "On conditions for contrail formation from aircraft exhausts". In: *Meteorologische Zeitschrift* 5.1 (Mar. 1996), pp. 4–23. DOI: 10.1127/metz/5/1996/4. URL: http://dx.doi.org/10.1127/metz/5/1996/4.

[36] ICAO. "Effects of Novel Coronavirus (COVID-19) on Civil Aviation: Economic Impact Analysis". In: (2023). URL: https://www.icao.int/sustainability/Pages/Economic-Impacts-of-COVID-19.aspx.

[37] Johannes Reichmuth and Peter Berster. "Past and Future Developments of the Global Air Traffic". In: *Biokerosene.* Ed. by Martin Kaltschmitt and Ulf Neuling. Berlin, Heidelberg: Springer Berlin Heidelberg, 2018, pp. 13–31. ISBN: 978-3-662-53063-4 978-3-662-53065-8. DOI: 10.1007/978-3-662-53065-8_2. URL: http://link.springer.com/10.1007/978-3-662-53065-8_2 (visited on 02/13/2023).

[38] European comission. “EU Aviation: 25 years of reaching new heights”. In: (2017). URL: https://transport.ec.europa.eu/transport-modes/air/eu-aviation-25-years-reaching-new-heights-0_en.

[39] Industry High Level Group (IHLG). “Aviation Benefits report 2019”. In: (2019). URL: https://www.icao.int/sustainability/Pages/IHLG.aspx.

[40] International Air Transport Association. “Air Passenger Market Analysis”. In: (2020). URL: https://www.iata.org/en/iata-repository/publications/economic-reports/air-passenger-monthly-analysis---december-2020/.

[41] ICAO. “Economic Impacts of COVID-19 on Civil Aviation”. In: (2022). URL: https://unitingaviation.com/news/economic-development/the-impact-of-covid-19-on-global-air-passenger-traffic-in-2021/.

[42] Japan Aircraft Development Corporation. “Worldwide Market Forecast 2022-2041”. In: (2022). URL: http://www.jadc.jp/files/topics/174_ext_01_en_0.pdf.

[43] Aviation Benefits Beyond Borders. “Waypoint 2050 report”. In: (2021). URL: https://aviationbenefits.org/environmental-efficiency/climate-action/waypoint-2050/.

[44] Boeing. “Commercial Market Outlook 2022-2041”. In: (2022). URL: https://www.boeing.com/commercial/market/commercial-market-outlook/index.page?.

[45] Airbus. “Global Market Forecast 2022-2041”. In: (2022). URL: https://www.airbus.com/en/products-services/commercial-aircraft/market/global-market-forecast.

[46] ICAO. “REVIEW OF THE CLASSIFICATION AND DEFINITIONS USED FOR CIVIL AVIATION ACTIVITIES”. In: (2009). URL: https://www.icao.int/meetings/sta10/documents/sta10_wp007_en.pdf.

[47] ICAO. “NON-SCHEDULED TRAFFIC STATISTICS”. In: (). URL: https://data.icao.int/iCADS/Product/View/13.

[48] EASA. “Amendment to the Airspace Requirements on ADS-B and Mode S”. In: (2020). URL: https://www.easa.europa.eu/en/newsroom-and-events/news/amendment-airspace-requirements-ads-b-and-mode-s.

[49] FAA. “Automatic Dependent Surveillance-Broadcast (ADS-B) Out equipment and use.” In: (2020). URL: https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-91/subpart-C/section-91.225.

[50] Matthias Schafer et al. “Demonstration abstract: OpenSky — A large-scale ADS-B sensor network for research”. In: *IPSN-14 Proceedings of the 13th International Symposium on Information Processing in Sensor Networks*. 2014 13th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN). Berlin, Germany: IEEE, Apr. 2014, pp. 313–314. ISBN: 978-1-4799-3147-7 978-1-4799-3146-0. DOI: 10.1109/IPSN.2014.6846779. URL: http://ieeexplore.ieee.org/document/6846779/ (visited on 02/14/2023).

[51] Junzi Sun, Joost Ellerbroek, and Jacco Hoekstra. “Flight Extraction and Phase Identification for Large Automatic Dependent Surveillance–Broadcast Datasets”. In: *Journal of Aerospace Information Systems* 14.10 (Oct. 2017), pp. 566–572. ISSN: 1940-3151, 2327-3097. DOI: 10.2514/1.I010520. URL: https://arc.aiaa.org/doi/10.2514/1.I010520 (visited on 02/14/2023).

[52] Official Airline Guide OAG. “GLOBAL AIRLINE SCHEDULES DATA”. In: (2023). URL: https://www.oag.com/airline-schedules-data.

[53] RDC aviation and Flightglobal. “Capstats”. In: (2009). URL: https://www.flightglobal.com/capstats/88162.article.

[54] Federal Aviation Administration (FAA) and Volpe National Transportation Center. “Enhanced Traffic Management System (ETMS)”. In: (2023). URL: https://web.archive.org/web/20100124075647/http://hf.tc.faa.gov/projects/etms.htm.

[55] Eurocontrol. “Enhanced tactical flow management system (ETFMS)”. In: (2023). URL: https://www.eurocontrol.int/system/enhanced-tactical-flow-management-system.

[56] Thales. “TopSky ATC (Air Traffic Control)”. In: (2023). URL: https://www.thalesgroup.com/en/topsky-atc.

[57] Flightradar24. “Flightradar24 Data services”. In: (2023). URL: https://www.flightradar24.com/commercial-services/data-services.

[58] *European Organisation for the Safety of Air Navigation (EUROCONTROL)*. Type: dataset. Koninklijke Brill NV. DOI: 10.1163/1570-6664_iyb_SIM_org_39214. URL: https://referenceworks.brillonline.com/entries/international-year-book-and-statesmens-who-s-who/*-SIM_org_39214 (visited on 02/13/2023).

[59] C J Eyers et al. “AERO2k Global Aviation Emissions Inventories for 2002 and 2025”. In: ().

[60] Junzi Sun, Jacco M. Hoekstra, and Joost Ellerbroek. “OpenAP: An Open-Source Aircraft Performance Model for Air Transportation Studies and Simulations”. In: *Aerospace* 7.8 (July 23, 2020), p. 104. ISSN: 2226-4310. DOI: 10.3390/aerospace7080104. URL: https://www.mdpi.com/2226-4310/7/8/104 (visited on 02/13/2023).

[61] Judith Rosenow. “Flight Performance Modeling to optimize Trajectories”. In: Sept. 2016.

[62] Linda Kliment and Kamran Rokhsaz. “Flight Loads Analysis of Business Jets”. In: (Mar. 2017).

[63] D.K. Wasiuk, M.H. Lowenberg, and D.E. Shallcross. “An aircraft performance model implementation for the estimation of global and regional commercial aviation fuel burn and emissions”. In: *Transportation Research Part D: Transport and Environment* 35 (Mar. 2015), pp. 142–159. ISSN: 13619209. DOI: 10.1016/j.trd.2014.11.022. URL: https://linkinghub.elsevier.com/retrieve/pii/S1361920914001850 (visited on 01/30/2023).

[64] International Energy Agency (IEA). “Tracking Transport 2019”. In: (2019).

[65] Wei Jing, William L. Roberts, and Tiegang Fang. *Spray combustion of Jet-A and diesel fuels in a constant volume combustion chamber*. 2015. DOI: 10.1016/j.enconman.2014.10.010. URL: http://hdl.handle.net/10754/563975.

[66] Tongbin Zhao et al. “Combustion and emissions of RP-3 jet fuel and diesel fuel in a single-cylinder diesel engine”. In: *Frontiers in Energy* (Sept. 30, 2021). ISSN: 2095-1698. DOI: 10.1007/s11708-021-0787-3. URL: https://doi.org/10.1007/s11708-021-0787-3.

[67] International Energy Agency (IEA). “Aviation”. In: (2022). URL: https://www.iea.org/reports/aviation.

[68] Lukas Frederik Jakob Brink. “Modeling the Impact of Fuel Composition on Aircraft Engine NO, CO and Soot Emissions”. In: ().

[69] Doug DuBois and Gerald C. Paynter. ““Fuel Flow Method2” for Estimating Aircraft Emissions”. In: Non-Conference Specific Technical Papers - 2006. Aug. 30, 2006, pp. 2006–01–1987. DOI: 10.4271/2006-01-1987. URL: https://www.sae.org/content/2006-01-1987/ (visited on 02/01/2023).

[70] Martin Schaefer and Sebastian Bartosch. “Overview on fuel flow correlation methods for the calculation of NOx, CO and HC emissions and their implementation into aircraft performance software”. In: (July 2013).

[71] FOI (Swedish Defence Research Agency). “The Environmental Impact of Aircraft”. In: (2023). URL: https://www.foi.se/en/foi/research/aeronautics-and-space-issues/environmental-impact-of-aircraft.html.

[72] L Baughcum et al. “Scheduled Civil Aircraft Emission Inventories for 1992: Database Development and Analysis”. In: ().

[73] Donata Wasiuk et al. “A Commercial Aircraft Fuel Burn and Emissions Inventory for 2005–2011”. In: *Atmosphere* 7.6 (June 4, 2016), p. 78. ISSN: 2073-4433. DOI: 10.3390/atmos7060078. URL: http://www.mdpi.com/2073-4433/7/6/78 (visited on 01/28/2023).

[74] Nicholas W. Simone, Marc E.J. Stettler, and Steven R.H. Barrett. “Rapid estimation of global civil aviation emissions with uncertainty quantification”. In: *Transportation Research Part D: Transport and Environment* 25 (Dec. 2013), pp. 33–41. ISSN: 13619209. DOI: 10.1016/j.trd.2013.07.001. URL: https://linkinghub.elsevier.com/retrieve/pii/S1361920913001028 (visited on 01/27/2023).

[75] Martin Schaefer. “Development of a Forecast Model for Global Air Traffic Emissions”. In: ().

[76] J. T. Wilkerson et al. “Analysis of emission data from global commercial aviation: 2004 and 2006”. In: *Atmospheric Chemistry and Physics* 10.13 (July 14, 2010). Number: 13 Publisher: Copernicus GmbH, pp. 6391–6408. ISSN: 1680-7316. DOI: 10.5194/acp-10-6391-2010. URL: https://acp.copernicus.org/articles/10/6391/2010/acp-10-6391-2010.html (visited on 01/27/2023).

[77] Bethan Owen, David S. Lee, and Ling Lim. “Flying into the Future: Aviation Emissions Scenarios to 2050”. In: *Environmental Science & Technology* 44.7 (Apr. 1, 2010), pp. 2255–2260. ISSN: 0013-936X, 1520-5851. DOI: 10.1021/es902530z. URL: https://pubs.acs.org/doi/10.1021/es902530z (visited on 02/03/2023).

[78] Brian Kim et al. *System for assessing Aviation's Global Emissions (SAGE). Version 1.5 : global aviation emissions inventories for 2000 through 2004*. DOT-VNTSC-FAA-05-17. Issue: DOT-VNTSC-FAA-05-17. Jan. 1, 2006. URL: https://rosap.ntl.bts.gov/view/dot/6250 (visited on 01/28/2023).

[79] Lissys Ltd. “Pianox, Aircraft Emissions and Performance”. In: (2021). URL: https://www.lissys.uk/.

[80] Lissys Ltd. “A Brief Status Update (April 2020)”. In: (2020). URL: https://www.lissys.uk/updatecovid.html.

[81] Huanjia Liu et al. “Atmospheric emission inventory of multiple pollutants from civil aviation in China: Temporal trend, spatial distribution characteristics and emission features analysis”. In: *Science of The Total Environment* 648 (Jan. 2019), pp. 871–879. ISSN: 00489697. DOI: 10.1016/j.scitotenv.2018.07.407. URL: https://linkinghub.elsevier.com/retrieve/pii/S004896971832905X (visited on 01/28/2023).

[82] Jingran Zhang et al. “Developing a High-Resolution Emission Inventory of China’s Aviation Sector Using Real-World Flight Trajectory Data”. In: *Environmental Science & Technology* 56.9 (May 3, 2022). Number: 9, pp. 5743–5752. ISSN: 0013-936X, 1520-5851. DOI: 10.1021/acs.est.1c08741. URL: https://pubs.acs.org/doi/10.1021/acs.est.1c08741 (visited on 01/28/2023).

[83] Chen Lyu et al. “An emissions inventory using flight information reveals the long-term changes of aviation CO2 emissions in China”. In: *Energy* 262 (Jan. 2023), p. 125513. ISSN: 03605442. DOI: 10.1016/j.energy.2022.125513. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360544222023957 (visited on 01/28/2023).

[84] Viet Van Pham et al. “Aviation emission inventory development and analysis”. In: *Environmental Modelling & Software* 25.12 (Dec. 2010). Number: 12, pp. 1738–1753. ISSN: 13648152. DOI: 10.1016/j.envsoft.2010.04.004. URL: https://linkinghub.elsevier.com/retrieve/pii/S1364815210000964 (visited on 01/26/2023).

[85] M.E.J. Stettler, S. Eastham, and S.R.H. Barrett. “Air quality and public health impacts of UK airports. Part I: Emissions”. In: *Atmospheric Environment* 45.31 (Oct. 2011), pp. 5415–5424. ISSN: 13522310. DOI: 10.1016/j.atmosenv.2011.07.012. URL: https://linkinghub.elsevier.com/retrieve/pii/S135223101100728X (visited on 02/10/2023).

[86] M. Mazaheri, G.R. Johnson, and L. Morawska. “An inventory of particle and gaseous emissions from large aircraft thrust engine operations at an airport”. In: *Atmospheric Environment* 45.20 (June 2011). Number: 20, pp. 3500–3507. ISSN: 13522310. DOI: 10.1016/j.atmosenv.2010.12.012. URL: https://linkinghub.elsevier.com/retrieve/pii/S1352231010010381 (visited on 01/28/2023).

[87] Oleksandr Zaporozhets and Kateryna Synylo. “Improvements on aircraft engine emission and emission inventory asesessment inside the airport area”. In: *Energy* 140 (Dec. 2017), pp. 1350–1357. ISSN: 03605442. DOI: 10.1016/j.energy.2017.07.178. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360544217313713 (visited on 01/28/2023).

[88] Brandon Graver et al. “VISION 2050: ALIGNING AVIATION WITH THE PARIS AGREEMENT”. In: (2022). URL: https://theicct.org/publication/global-aviation-vision-2050-align-aviation-paris-jun22/.

[89] IATA. “Total fuel consumption of commercial airlines worldwide between 2005 and 2022”. In: (2020). URL: https://www.iata.org/en/programs/ops-infra/fuel/.

[90] Ivan Terekhov et al. “Assessing the impact of new technologies in aviation using a global aircraft fleet forecasting model”. In: (Oct. 2018).

[91] James PEARSON. “Most Used Commercial Aircraft Types In 2022”. In: (2022). URL: https://simpleflying.com/most-used-commercial-aircraft-types-2022/.

[92] Ivo Abrantes et al. “Sustainable aviation fuels and imminent technologies - CO2 emissions evolution towards 2050”. In: *Journal of Cleaner Production* 313 (Sept. 2021), p. 127937. ISSN: 09596526. DOI: 10.1016/j.jclepro.2021.127937. URL: https://linkinghub.elsevier.com/retrieve/pii/S0959652621021557 (visited on 03/28/2023).

[93] Kay O. Ploetner et al. “Technological and Operational Scenarios on Aircraft Fleet-Level towards ATAG and IATA 2050 Emission Targets”. In: *17th AIAA Aviation Technology, Integration, and Operations Conference.* 17th AIAA Aviation Technology, Integration, and Operations Conference. Denver, Colorado: American Institute of Aeronautics and Astronautics, June 5, 2017. ISBN: 978-1-62410-508-1. DOI: 10.2514/6.2017-3771. URL: https://arc.aiaa.org/doi/10.2514/6.2017-3771 (visited on 03/28/2023).

[94] Niclas P. Randt, Christoph Jessberger, and Kay O. Ploetner. “Estimating the Fuel Saving Potential of Commercial Aircraft in Future Fleet-Development Scenarios”. In: *15th AIAA Aviation Technology, Integration, and Operations Conference.* 15th AIAA Aviation Technology, Integration, and Operations Conference. Dallas, TX: American Institute of Aeronautics and Astronautics, June 22, 2015. ISBN: 978-1-62410-369-8. DOI: 10.2514/6.2015-2435. URL: https://arc.aiaa.org/doi/10.2514/6.2015-2435 (visited on 03/28/2023).

[95] Tomas Grönstedt et al. "Ultra Low Emission Technology Innovations for Mid-Century Aircraft Turbine Engines". In: *Volume 3: Coal, Biomass and Alternative Fuels; Cycle Innovations; Electric Power; Industrial and Cogeneration; Organic Rankine Cycle Power Systems*. ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition. Seoul, South Korea: American Society of Mechanical Engineers, June 13, 2016, V003T06A001. ISBN: 978-0-7918-4974-3. DOI: 10.1115/GT2016-56123. URL: https://asmedigitalcollection.asme.org/GT/proceedings/GT2016/49743/Seoul,%20South%20Korea/239480 (visited on 03/28/2023).

[96] Flávio D. Quadros, Mirjam Snellen, and Irene C. Dedoussi. "Recent and Projected Trends in Global Civil Aviation Fleet Average NO $_x$ Emissions Indices". In: *AIAA SCITECH 2022 Forum*. AIAA SCITECH 2022 Forum. San Diego, CA & Virtual: American Institute of Aeronautics and Astronautics, Jan. 3, 2022. ISBN: 978-1-62410-631-6. DOI: 10.2514/6.2022-2051. URL: https://arc.aiaa.org/doi/10.2514/6.2022-2051 (visited on 03/29/2023).

[97] Grewe Volker et al. "Climate Impact Evaluation for future Green Aircraft Technologies". In: (Oct. 2016).

[98] Roger Teoh. "Climate Forcing of Aircraft Contrails: Uncertainty Quantification and Mitigation Potential". In: ().

[99] Volker Grewe et al. "Evaluating the climate impact of aviation emission scenarios towards the Paris agreement including COVID-19 effects". In: *Nature Communications* 12.1 (June 22, 2021), p. 3841. ISSN: 2041-1723. DOI: 10.1038/s41467-021-24091-y. URL: https://www.nature.com/articles/s41467-021-24091-y (visited on 03/26/2023).

[100] E Terrenoire et al. "The contribution of carbon dioxide emissions from the aviation sector to future climate change". In: *Environmental Research Letters* 14.8 (Aug. 1, 2019), p. 084019. ISSN: 1748-9326. DOI: 10.1088/1748-9326/ab3086. URL: https://iopscience.iop.org/article/10.1088/1748-9326/ab3086 (visited on 03/26/2023).

[101] K. Seymour et al. "Fuel Estimation in Air Transportation: Modeling global fuel consumption for commercial aviation". In: *Transportation Research Part D: Transport and Environment* 88 (Nov. 2020), p. 102528. ISSN: 13619209. DOI: 10.1016/j.trd.2020.102528. URL: https://linkinghub.elsevier.com/retrieve/pii/S136192092030715X (visited on 02/06/2023).

[102] Ivan Jakovljević, Radomir Mijailović, and Petar Mirosavljević. "Carbon dioxide emission during the life cycle of turbofan aircraft". In: *Energy* 148 (2018), pp. 866–875. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2018.02.022. URL: https://www.sciencedirect.com/science/article/pii/S0360544218302500.

[103] Robert Sausen and Ulrich Schumann. "Estimates of the Climate Response to Aircraft CO2 and NOx-Emission Scenarios". In: *Climatic Change* 44 (Jan. 2000), pp. 27–58. DOI: 10.1023/A:1005579306109.

[104] R. Hein et al. "Results of an interactively coupled atmospheric chemistry – general circulation model: Comparison with observations". In: *Annales Geophysicae* 19.4 (2001), pp. 435–457. DOI: 10.5194/angeo-19-435-2001. URL: https://angeo.copernicus.org/articles/19/435/2001/.

[105] Ulrike Burkhardt and Bernd Kärcher. "Process-based simulation of contrail cirrus in a global climate model". In: *Journal of Geophysical Research* 114 (Aug. 2009), pp. 1–13. DOI: 10.1029/2008JD011491.

[106] Ulrike Burkhardt and Bernd Kärcher. "Global radiative forcing from contrail cirrus". In: *Nature Climate Change* 1 (Apr. 2011), pp. 54–58. DOI: 10.1038/nclimate1068.

[107] Ulrike Burkhardt, Lisa Bock, and Andreas Bier. "Mitigating the contrail cirrus climate impact by reducing aircraft soot number emissions". In: *npj Climate and Atmospheric Science* 1 (Dec. 2018). DOI: 10.1038/s41612-018-0046-4.

[108] Victoria Williams and Robert B. Noland. "Variability of contrail formation conditions and the implications for policies to reduce the climate impacts of aviation". In: *Transportation Research Part D: Transport and Environment* 10.4 (2005), pp. 269–280. ISSN: 1361-9209. DOI: https://doi.org/10.1016/j.trd.2005.04.003. URL: https://www.sciencedirect.com/science/article/pii/S1361920905000180.

[109] Volker Grewe, Sigrun Matthes, and Katrin Dahlmann. "The contribution of aviation NOx emissions to climate change: are we ignoring methodological flaws?" In: *Environmental Research Letters* 14.12 (Dec. 2019). Publisher: IOP Publishing, p. 121003. ISSN: 1748-9326. DOI: 10.1088/1748-9326/ab5dd7. URL: https://dx.doi.org/10.1088/1748-9326/ab5dd7 (visited on 08/29/2023).

[110] Douglas Irwin and Nina Pavcnik. "Airbus Versus Boeing Revisited: International Competition in the Aircraft Market". In: *Journal of International Economics* 64 (May 2003), pp. 223–245. DOI: 10.1016/j.jinteco.2003.08.006.

[111] Alan John Cook. "BOEING VERSUS AIRBUS: AN ECONOMIC ANALYSIS". In: (May 2008).

[112] Lockheed Martin. "A Merger of Equals". In: (Oct. 2020). URL: https://www.lockheedmartin.com/en-us/news/features/history/merger.html.

[113] James Morrison, Sgouris Sgouridis, and R. Hansman. "Game Theory Analysis of Aircraft Manufacturer Innovation Strategies in the Face of Increasing Airline Fuel Costs". In: (May 2011).

[114] Steven Pearlstein. "Boeing and Airbus, the new 'super duopoly'". In: *Washington Post* (Apr. 2018). URL: https://www.washingtonpost.com/news/wonk/wp/2018/04/25/boeing-and-airbus-the-new-super-duopoly/.

[115] Glennon J. Harrison. "Challenge to the Boeing-Airbus Duopoly in Civil Aircraft: Issues for Competitiveness". In: *Congressional Research Service* (July 2011). URL: https://sgp.fas.org/crs/misc/R41925.pdf.

[116] CAPA. "Bombardier aircraft: free cash flow a priority; sell-offs no surprise". In: (Nov. 2018). URL: https://centreforaviation.com/analysis/reports/bombardier-aircraft-free-cash-flow-a-priority-sell-offs-no-surprise-449054.

[117] Niraj Chokshi and Tiffany May. "Large Commercial Jet Is a Milestone for China." In: *The New York Times* (2023), B1–L.

[118] Michelle Toh. "China's answer to Boeing and Airbus isn't as 'homegrown' as it seems. Here's why". In: *CNN* (2023). URL: https://edition.cnn.com/2023/06/02/tech/comac-c919-china-aircraft-intl-hnk/index.html.

[119] Airbus. "Commercial Aircraft". In: (2023). URL: https://www.airbus.com/en/products-services/commercial-aircraft.

[120] BoeEurocontroling. "Aircraft Perofrmance Database". In: (2023). URL: https://contentzone.eurocontrol.int/aircraftperformance/default.aspx?.

[121] Boeing. "Commercial aircraft - Products in Boeing history". In: (2023). URL: https://www.boeing.com/history/products/.

[122] Volker Grewe and Katrin Dahlmann. "Evaluating Climate-Chemistry Response and Mitigation Options with AirClim". In: *Atmospheric Physics*. Ed. by Ulrich Schumann. Series Title: Research Topics in Aerospace. Berlin, Heidelberg: Springer Berlin Heidelberg, 2012, pp. 591–606. ISBN: 978-3-642-30182-7 978-3-642-30183-4. DOI: 10.1007/978-3-642-30183-4_36. URL: http://link.springer.com/10.1007/978-3-642-30183-4_36 (visited on 06/05/2023).

[123] Agnieszka Skowron, David S. Lee, and Ruben R. De León. "Variation of radiative forcings and global warming potentials from regional aviation NOx emissions". In: *Atmospheric Environment* 104 (Mar. 1, 2015), pp. 69–78. ISSN: 1352-2310. DOI: 10.1016/j.atmosenv.2014.12.043. URL: https://www.sciencedirect.com/science/article/pii/S1352231014009911 (visited on 08/31/2023).

[124] Agnieszka Skowron et al. "Greater fuel efficiency is potentially preferable to reducing NOx emissions for aviation's climate impacts". In: *Nature Communications* 12.1 (Jan. 25, 2021). Number: 1 Publisher: Nature Publishing Group, p. 564. ISSN: 2041-1723. DOI: 10.1038/s41467-020-20771-3. URL: https://www.nature.com/articles/s41467-020-20771-3 (visited on 08/29/2023).

[125] Thibaud M. Fritz et al. "Identifying the ozone-neutral aircraft cruise altitude". In: *Atmospheric Environment* 276 (May 1, 2022), p. 119057. ISSN: 1352-2310. DOI: 10.1016/j.atmosenv.2022.119057. URL: https://www.sciencedirect.com/science/article/pii/S1352231022001224 (visited on 08/31/2023).

[126] M. O. Köhler et al. "Latitudinal variation of the effect of aviation NOx emissions on atmospheric ozone and methane and related climate metrics". In: *Atmospheric Environment* 64 (Jan. 1, 2013), pp. 1–9. ISSN: 1352-2310. DOI: 10.1016/j.atmosenv.2012.09.013. URL: https://www.sciencedirect.com/science/article/pii/S1352231012008722 (visited on 08/31/2023).

[127] Marcus Köhler et al. "Impact of perturbations of nitrogen oxide emissions from global aviation". In: *Journal of Geophysical Research* 113 (June 2008). DOI: 10.1029/2007JD009140.

[128] International Air Transport Association IATA. "Net zero 2050: sustainable aviation fuels". In: (2021). URL: https://www.iata.org/en/iata-repository/pressroom/fact-sheets/fact-sheet---alternative-fuels/.

[129] Nurul Musfirah Mazlan, Mark Savill, and Timos Kipouros. "Evaluating NOx and CO emissions of bio-SPK fuel using a simplified engine combustion model: A preliminary study towards sustainable environment". In: *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 231.5 (2017), pp. 859–865. DOI: 10.1177/0954410016643980. eprint: https://doi.org/10.1177/0954410016643980. URL: https://doi.org/10.1177/0954410016643980.

[130] International Energy Agency IAE. "Are aviation biofuels ready for take off?" In: (2019). URL: https://www.iea.org/commentaries/are-aviation-biofuels-ready-for-take-off.

Appendix

A Aircraft ICAO codes

ICAO	Full name	ICAO	Full name	ICAO	Full name
A19N	A319 Neo	A345	A340-500	B748	B747-8
A20N	A320 Neo	A346	A340-600	B762	B767-200
A21N	A321 Neo	A359	A350-900	B763	B767-300
A319	A319 Ceo	A35K	A350-1000	B764	B767-400
A320	A320 Ceo	A388	A380-800	B772	B777-200
A321	A321 Ceo	B37M	B737-7 MAX	B773	B777-300
A332	A330-200	B38M	B737-8 MAX	B77L	B777-200 LR
A333	A330-300	B39M	B737-9 MAX	B77W	B777-300 ER
A338	A330-800	B737	B737-700	B788	B787-8
A339	A330-900	B738	B737-800	B789	B787-9
A342	A340-200	B739	B737-900	B78X	B787-10
A343	A340-300	B744	B747-400		

Table 8: Aircraft ICAO code names and their full names.

B Altitude conversion table

ft	hPa	ft	hPa	ft	hPa	ft	hPa
0	1013.25	13000	619.8169223	26000	360.3205757	39000	196.7656882
1000	977.430802	14000	595.3956502	27000	344.6272568	40000	187.9767973
2000	942.2789116	15000	572.2582138	28000	330.0669773	41000	179.1879065
3000	908.2653061	16000	549.1834981	29000	315.5066977	42000	170.3990156
4000	875.390117	17000	527.6966051	30000	300.9464182	43000	161.6101248
5000	843.2114073	18000	506.2097121	31000	288.1164209	44000	152.821234
6000	812.2132672	19000	485.9096314	32000	275.4067107	45000	145.4775543
7000	782.1449617	20000	466.091954	33000	262.6970005	46000	138.817104
8000	752.6812021	21000	446.5966691	34000	249.9892079	47000	132.1566538
9000	724.6231156	22000	428.493845	35000	239.1970645	48000	125.4962035
10000	696.8914647	23000	410.391021	36000	228.4049212	49000	118.8357533
11000	670.5479452	24000	393.0323847	37000	217.6127779		
12000	644.5571499	25000	376.6764802	38000	206.8206346		

Table 9: Conversion table for altitude, from feet to hPa.

C AirClim background emissions data

Units are [Tg/yr]

Year	CurTec	FP2050	Year	CurTec	FP2050	Year	CurTec	FP2050	Year	CurTec	FP2050
1940	16.3	16.3	1981	108.4	108.4	2022	570.1	542.0	2063	1264.8	316.2
1941	16.9	16.9	1982	108.8	108.8	2023	592.7	558.0	2064	1277.7	317.6
1942	17.6	17.6	1983	111.5	111.5	2024	613.9	572.6	2065	1290.6	319.0
1943	18.3	18.3	1984	117.8	117.8	2025	633.6	585.5	2066	1303.5	320.4
1944	19.0	19.0	1985	123.9	123.9	2026	652.9	597.7	2067	1316.4	321.8
1945	19.8	19.8	1986	129.5	129.5	2027	672.4	609.8	2068	1329.4	323.2
1946	20.6	20.6	1987	139.3	139.3	2028	692.0	622.0	2069	1342.3	324.6
1947	21.4	21.4	1988	147.1	147.1	2029	711.9	634.0	2070	1355.3	326.0
1948	22.3	22.3	1989	150.5	150.5	2030	731.8	646.0	2071	1368.3	327.4
1949	23.2	23.2	1990	158.0	158.0	2031	752.6	658.5	2072	1381.3	328.9
1950	24.1	24.1	1991	151.4	151.4	2032	773.4	670.8	2073	1394.4	330.3
1951	25.1	25.1	1992	155.7	155.7	2033	794.3	683.0	2074	1407.4	331.8
1952	26.1	26.1	1993	154.7	154.7	2034	815.2	695.0	2075	1420.4	333.2
1953	27.2	27.2	1994	163.9	163.9	2035	836.2	706.9	2076	1433.6	334.7
1954	28.3	28.3	1995	172.6	172.6	2036	856.7	718.1	2077	1446.7	336.3
1955	29.5	29.5	1996	183.6	183.6	2037	877.0	729.0	2078	1459.9	337.8
1956	30.7	30.7	1997	191.0	191.0	2038	896.9	739.5	2079	1473.0	339.3
1957	31.9	31.9	1998	191.9	191.9	2039	916.5	749.6	2080	1486.2	340.9
1958	33.3	33.3	1999	200.9	200.9	2040	935.8	759.3	2081	1499.3	342.4
1959	34.6	34.6	2000	214.5	214.5	2041	954.6	768.4	2082	1512.5	344.0
1960	36.1	36.1	2001	204.8	204.8	2042	973.0	777.1	2083	1525.6	345.6
1961	37.6	37.6	2002	206.6	206.6	2043	990.7	785.1	2084	1538.7	347.2
1962	39.2	39.2	2003	210.1	210.1	2044	1007.8	792.6	2085	1551.8	348.8
1963	40.8	40.8	2004	238.2	238.2	2045	1024.3	799.5	2086	1564.9	350.4
1964	42.5	42.5	2005	254.0	254.0	2046	1038.9	804.9	2087	1578.0	352.0
1965	44.3	44.3	2006	265.7	265.7	2047	1053.2	810.0	2088	1591.0	353.6
1966	46.1	46.1	2007	283.1	283.1	2048	1067.2	814.8	2089	1604.0	355.3
1967	48.1	48.1	2008	284.1	284.1	2049	1080.9	819.3	2090	1617.0	356.9
1968	50.1	50.1	2009	276.4	276.4	2050	1094.2	743.8	2091	1630.0	358.6
1969	52.2	52.2	2010	293.3	293.3	2051	1113.1	678.6	2092	1642.9	360.3
1970	54.4	54.4	2011	307.2	307.2	2052	1125.5	615.5	2093	1655.8	362.0
1971	56.7	56.7	2012	321.2	321.2	2053	1138.0	558.3	2094	1668.7	363.7
1972	63.1	63.1	2013	337.4	337.4	2054	1150.5	506.4	2095	1681.5	365.4
1973	67.6	67.6	2014	356.0	356.0	2055	1163.1	459.3	2096	1694.3	367.1
1974	69.7	69.7	2015	381.1	381.1	2056	1175.6	416.6	2097	1707.1	368.8
1975	74.7	74.7	2016	407.5	407.5	2057	1188.3	377.8	2098	1719.8	370.6
1976	80.5	80.5	2017	437.9	437.9	2058	1201.0	342.7	2099	1732.4	372.3
1977	84.7	84.7	2018	473.4	468.1	2059	1213.7	310.9	2100	1745.0	374.1
1978	95.3	95.3	2019	498.1	487.6	2060	1226.4	312.2			
1979	106.2	106.2	2020	522.4	506.4	2061	1239.2	313.5			
1980	107.3	107.3	2021	546.6	524.7	2062	1252.0	314.9			

Table 10: Background aviation fuel scenario ('CurTec' and 'FP2050') used for AirClim simulations.