thalesgroup.com

THALES
Building a future we can all trust

#2
Assessing the potential climate impact reduction of eco friendly operations

Towards eco-friendly operations
Acting now to reduce the climate impact of aviation

Towards eco-friendly operations

Acting now to reduce the climate impact of aviation

Day-to-day flight operations are perhaps the least easily understood field of air transport. Yet, it is one of the most relevant levers for short-term actions intending to reduce the climate impact of air transport, since it can affect all in-service aircraft without requiring major technological breakthroughs.

But reducing the climate impact of aviation requires understanding it:

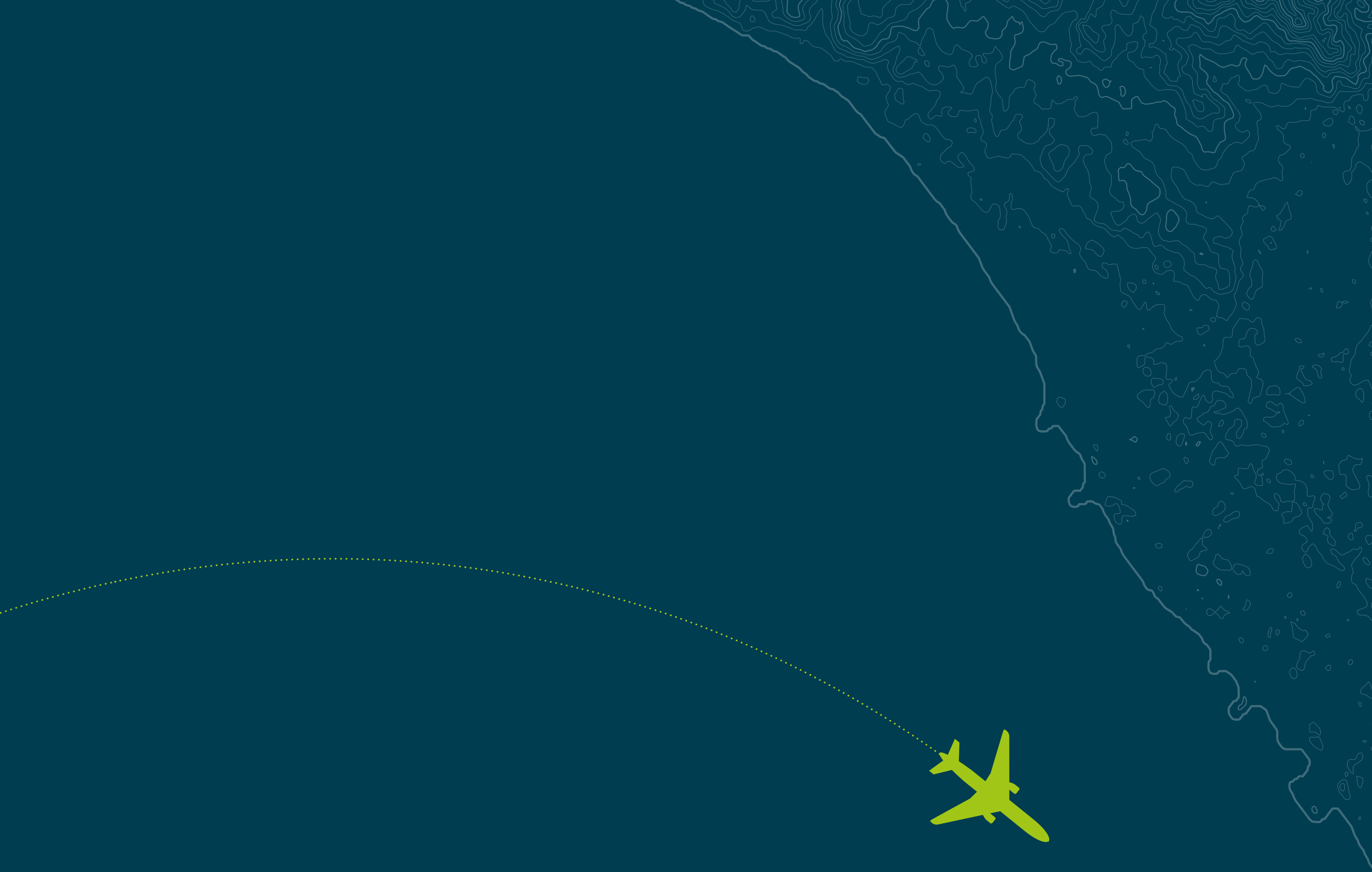
From this standpoint, climate science has made significant progress, allowing both to model and quantify the impact of carbon dioxide (CO_2) emissions, but also to better understand the effects of condensation trails their induced cirrus clouds, and to a lesser extent, those of nitrogen oxides.

Leveraging on these results, research in the field of flight optimisation shows that implementation of eco-friendly flight operations offers the potential to **reduce the climate impact of aviation by more than 10%** when considering only CO_2 effects, and over 20% when compounding all effects.

In order to achieve tangible gains as quickly as possible and take advantage of current air traffic conditions that are favourable to experimentation, reliance on **local ecosystems** willing to commit to the ecological transition of their operations is crucial.

TO MAKE THIS TRANSITION A SUCCESS, WE MAKE THREE MAIN PROPOSALS:

- First, **set up and disseminate a single source of truth**, reliable, neutral, objective, shared and transparent, enabling each party to assess the climate impact of its operations on each segment of each flight.
- Second, develop **operational and technological frameworks that enable continuous reduction of the environmental impact of these operations** by facilitating collaboration between pilots, airlines and air navigation services, starting through digital tools. To act quickly, deployment could be limited initially in space and/or time, and later extended to increase in scope.
- Third, for each local ecosystem, put in place as quickly as possible measures making such operations economically viable for each party, for example by **facilitating communications to passengers and investors** of the ecological performance of stakeholders' operations, or promote eco-friendly behaviour through **economic**.



#2

Assessing the potential climate impact reduction of eco friendly operations

Towards eco-friendly operations

Acting now to reduce the climate impact of aviation

Introduction

No one can deny the major role of aviation in the development of modern societies: it has brought people together and has contributed significantly to global economic growth.

However, like many human activities, air transport has an ecological footprint and more specifically a significant climate impact.

The International Council on Clean Transportation (ICCT) estimates the share of air transport at **2.4%** of 2018 global CO_2 emissions (Graver, Zhang, & Rutherford, 2018).

To reduce its environmental impact, the air transport community is thus actively working in four complementary directions:

- Develop low-carbon footprint aircraft: hydrogen, electric, hybrid...
- Introduce sustainable aviation fuels (SAF) compatible with existing aircraft: sustainable biofuels, synthetic fuels...
- Renew aging fleets with newer, more efficient in-production aircraft.
- ... and finally optimize flight operations of in-service aircraft in order to reduce their environment footprint.

ECO-FRIENDLY FLIGHT OPERATIONS: ACT NOW, EVERYWHERE, AND AT LOW COST

While the first two approaches are obviously the most promising since they enable truly low-carbon air transport, they must overcome several significant challenges:

- On one hand, development of low-carbon aircraft requires major technological and logistical breakthroughs and experts do not anticipate mass production to start before the end of the next decade.
- On the other hand, deployment of SAF will necessarily be gradual: initially limited[1] to SAF based on the sustainable exploitation/recycling of biomass, their use will grow with the development of synthetic fuel. However, large-scale deployment of low carbon synthetic fuel is not foreseen before 2035 at the earliest. The positive impact of fleet renewal on air transport environmental footprint no longer needs to be demonstrated[2]. However the cost of such renewal for airlines is very high – A320neo list price is $110M – in a time when airlines' investment capabilities are seriously hampered by the COVID crisis.

Therefore, the fourth approach seems to be the most accessible in the short term while being cumulative with the three first ones: optimizing the day-to-day flight operation of in-service aircraft to reduce their ecological impact. Throughout the following of this document, we refer to such operations as eco-friendly operations.

WHAT ARE FLIGHT OPERATIONS?

Flight operations are probably the area of air transport that is the least easily understood by the general audience.

This document focuses more specifically on the subset of these flight operations having an impact on aircraft emissions,

- Strategic and pre-tactical flight planning activities:
  - Strategic flight planning carried out by airlines (flight scheduling) and consolidated/adjusted by Air Navigation Service Providers (ANSPs), the result being a validated flight plan filed for each aircraft.
  - Flight preparation, including the determination of the quantity of fuel carried and more generally flight related operational planning (catering, supplies…).
- Tactical flight execution activities:
  - Taxiing (for departure and arrival), carried out in collaboration between air traffic control and the crew, possibly with the help of a pushback tug.
  - The actual flight and its integration into air traffic, carried out in collaboration between the crew, air traffic control and the airline, based on the filed flight plan and taking into account the conditions of the day: weather, load factor...

EVALUATE, EXPLORE, EXPERIMENT, DEPLOY...

This document thus aims at describing more precisely the challenges of the ecological transition of flight operations:

- We first summarize the methods for assessing the climate impact of aviation that has been developed by the scientific community and that are now widely recognized. We also show how the understanding of this impact itself is improving.
- Using these methods and state-of-the-art flight optimization research, we try to assess the order of magnitude of the potential for eco-friendly flight operations to reduce the climate impact of air transport.
- We then identify the challenges that air transport will have to face to deploy these eco-friendly operations.
- Finally, we introduce three proposals allowing to engage all air transport stakeholders in order to achieve these reductions as quickly as possible.

> **A few definitions**
> In the context of Air Traffic Flow Management, considering a D-day flight, the strategic phase includes dispatching and flight planning activities carried out between one year and D-7, the pre-tactical phase takes place between D-7 and D-1 and finally the tactical phase takes place on D-day.

[1] (EEA, EASA & EuroControl, 2020) estimates that, if the whole European biofuel production was dedicated to SAF, it would only account for 4% of kerosene consumption in Europe in 2019. It also states that the average use of SAF in Europe should not exceed 1% in the short term because of their high price.

[2] The latest generation A320neo is at least 15% more efficient than a classic A320 according to (Hensey & Magdalina, 2018). This number is probably underestimated as it doesn't take into account replaced aircraft's airframe and engine aging.

Assessing the potential climate impact reduction of eco friendly operations

While the previous section of this document allowed us to lay the foundations for an assessment of the climate footprint of aviation and to understand its mechanisms, the aim of this section is to quantify the reduction potential made possible by eco-friendly operations, both in terms of CO_2 and non-CO_2 effects.

> **Flight optimization, an area of research**
>
> Flight optimization research is often based on mathematical models and simulations – sometimes corroborated by local experiments – rather than actual measurements. Consequently, the results reported in this section intend only to provide orders of magnitude to support the remainder of the document. models involved.

1.
CO_2 EFFECTS: A REDUCTION POTENTIAL ABOUT 10%

To understand the reduction potential of eco-friendly operations in terms of CO_2 emissions, a simple method consists of characterizing a CO_2-perfect flight[3] and measuring the difference between this flight and an actual flight. This gives us a maximum theoretical gain, ignoring any constraints other than the departure and arrival airports and time of departure[4].

Since the reduction of CO_2 emissions depends directly on the reduction of fuel burn, we can benefit from the numerous works carried out with the aim of optimizing the operational (economic) efficiency of air transport.

We split this section in two parts:

- We first identify the different flight optimization strategies aiming at reducing CO2 effects.
- We then assess their reduction potential.

1.1. CO_2 REDUCTION LEVERS

The main means for flight optimization are:

- Flight trajectory optimization:
  we first determine a CO_2-perfect trajectory ignoring weather conditions, and then assess the weather impacts (wind in particular).
- Ground operations optimizations.

> CO_2 perfect flight, ignoring weather

While the idea of a CO_2-perfect flight is conceptually appealing, its real efficiency in terms of emission reduction is complex to evaluate. For example, since this trajectory ignores all conventional flight constraints except the safe flight envelope, it is difficult to implement under normal operating and traffic conditions. Science therefore focuses on simulations, corroborated in some cases by experiments with necessarily limited representativeness.

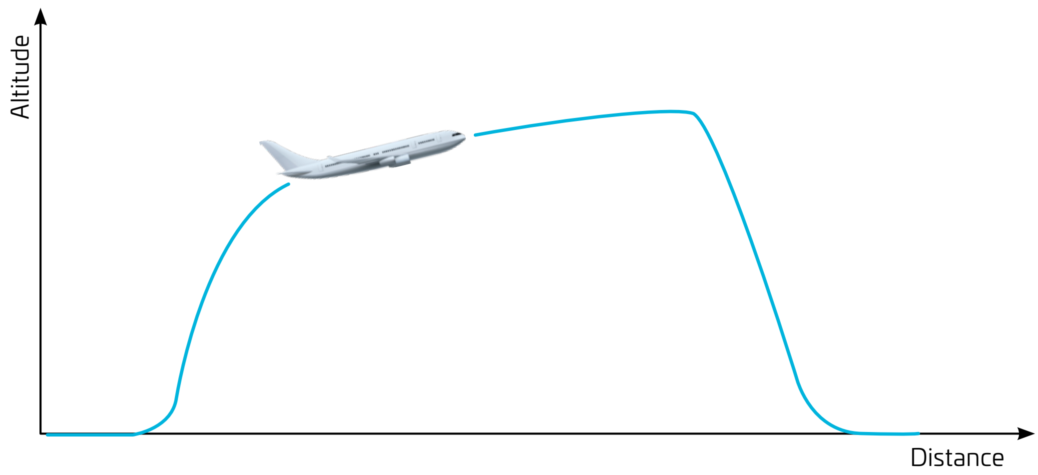
Practically, the characteristics of this CO_2-perfect trajectory in the vertical and horizontal planes are actually quite different. In the vertical plane (figure 1), it is essentially based on an optimal use of engines and on flight dynamics optimization.

Based on results largely taken from *Dalmau & Prats, 2015*, it can be characterized as follows:

- A continuous climb, progressively changing thrust level to adjust flight path angle according to aircraft performance and external conditions,
- A cruise phase with a thrust level that ensures optimum fuel efficiency at all times (see figure 4 below) also known as Maximum Range Cruise. Such thrust configuration induces therefore a shallow continuous climb until top of descent as aircraft weight decreases as flight progresses,
- A descent with idle thrust.

Figure 1

CO_2-perfect vertical trajectory, according to (Dalmau & Prats, 2015)

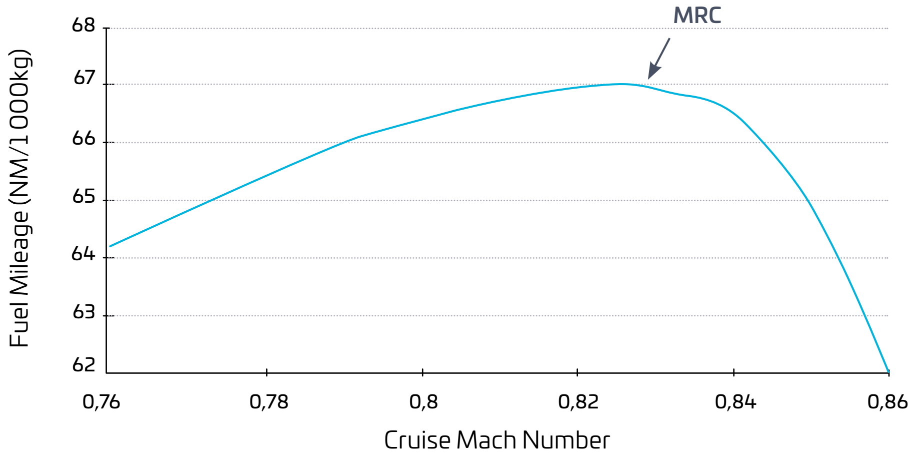


[3] *In this document, the term "-perfect" – for instance "CO2-perfect trajectory" – refers to an item – for instance a trajectory – that is associated to the smallest possible environmental impact.*

[4] *Among the constraints ignored by the CO2-perfect flight are air traffic interactions, potential nuisances in airport vicinity, flight duration and delays, economic efficiency…*

Figure 2

Maximum Range Cruise (MRC), optimal thrust level in terms of aircraft efficiency (Robertson, Root, & Adams, 2007)



Obviously, the relative importance of each flight phase varies with its total flight length: for example, cruise phase may be very short for a short-haul flight. This CO_2-perfect trajectory actually also varies with each flight, depending on variables such as aircraft and engine type, aircraft take-off weight but also aging of the airframe and engines.

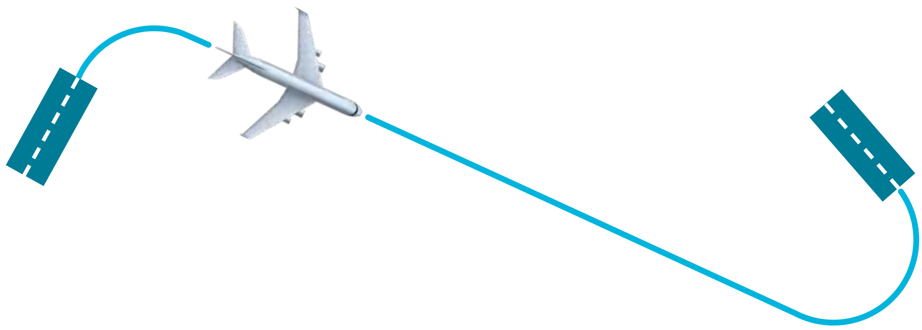
In the horizontal plane (figure 3), theoretical optimization is mostly geometric and consists of minimizing the overall flight distance.

The CO_2-perfect horizontal trajectory is thus composed of:

- Turn after take-off towards destination,
- A direct flight towards the arrival following the great circle route[5],
- A final turn during the approach to align the aircraft with the destination runway.

Figure 3

CO_2-perfect theoretical horizontal trajectory



Impact of weather on the CO_2 perfect flight

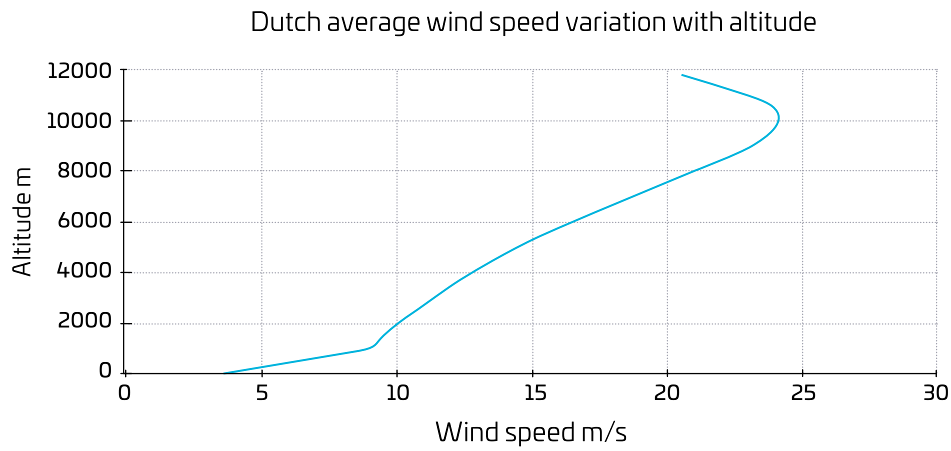
Winds are very important for flight optimization: a mere 5kt wind translates to around 1% fuel burn impact for an average commercial flight.

Indeed, while the aircraft is moving relative to the ground, it is actually moving inside an air mass, itself moving relative to the ground. The aircraft ground speed is thus the sum of its air speed and the wind speed, this wind speed varying with the altitude. As shown on figure 4, wind speed can reach very significant values – 25m.s^{-1} compared a typical aircraft speed of 250m.s^{-1} – at the usual flight levels of commercial airplanes – typically 10 000m.

[5] *A great circle route – also known as orthodromy – is the shortest path between two points at the surface of a sphere.*

Figure 4

Typical wind speeds over the Netherlands as a function of altitude (Mearns, 2016).



Weather can interact with the aircraft trajectory in two ways:

- As a disruptor to the execution of the CO_2-perfect trajectory, local weather events can significantly affect flight efficiency. In flight, a hazardous weather area may require a detour, and head winds can significantly increase fuel burn. During idle descent, wind gradients or icing may require the inefficient use of engines or speed brakes. During departure or arrival, low visibility may reduce the frequency of take-offs or landings, or even require flight cancellations or diversions.
- As a means for optimization taking benefits of better winds and temperature gradients is a simple way to increase ground speed, therefore reducing flight time and fuel burn.

Several works, such as *Palopo, Windhorst, Suharwardy, & Hak-Tae, 2010, Ng, Sridhar, & Grabbe, 2014 and Currie, Marcos, & Turnbull, 2016*, show that three-dimensional optimization (often called windsurfing) – constantly searching for the most favorable trajectory in the volume of air around the aircraft – can have a very significant effect on the duration of flights and therefore on their fuel burn.

While it may involve significant adjustments to the lateral trajectory, sometimes deviating by several hundred kilometers from the CO_2-perfect trajectory shown in figure 3, such windsurfing involves mostly small adjustments of flight levels – typically a few hundred meters.

Beyond flight: fuel load, taxi, and onboard energy usage

Apart from the flight itself, there are two global flight optimization contributors:

- The reduction of emissions on ground (departure and arrival) that could involve single-engine taxiing, towing using an electric vehicle part or all of the way, and when parking the aircraft, use of airport ground power rather than an onboard auxiliary power unit (APU).
- Optimization of fuel load[6]: it is common for an aircraft to carry significantly more fuel than is required by regulatory safety constraints, a practice that increases CO_2 emissions: the unnecessary fuel makes the aircraft heavier and increases fuel burn.

  An extreme example of such practice is tankering, which involves carrying excess fuel to a destination where fuel is more expensive, often aiming at reducing or eliminating the need to purchase fuel there[7].

> **Can reducing onboard consumption be a viable option?**
>
> Aircraft engines are not only a source of propulsive energy; they also provide bleed air and power onboard electrical systems: air conditioning, de-icing, avionics, cabin and so on… On the Airbus A320/A330 family, the consumption of onboard systems represents only 3 to 10% of the energy produced by the engines (Giraud, 2014). Therefore, even if they have merit, strategies for optimizing onboard consumption offer only limited potential for reducing aviation climate impact.

[6] *Fuel load has two distinct components:*
- A mandatory component corresponding to the kerosene necessary to carry out the flight given known forecast weather conditions, and regulatory reserves in case of random events such as unforeseen bad weather, arrival delays, and in flight diversion.
- A discretionary component under the responsibility of the pilot-in-command or the airline: this is the one at stake in this section.

[7] *According to (Eurocontrol Aviation Intelligence Unit, 2019), this practice does not seem economically viable beyond a flight distance of 1,100 km*

1.2. Evaluating the CO_2 reduction potential

To evaluate the potential induced by these different optimizations for reducing the CO_2 emissions of aviation, we deliberately consider two opposite situations:

- Short-haul flights where we can consider the impact of weather negligible on average[8].
- Long-haul flights where the impact of weather is significant compared to operations, climb and descent optimizations.

We then extrapolate from those two situations an assessment of the reduction potential for all flight distances.

The short haul situation

As previously mentioned, determining the reduction potential of a CO_2-perfect flight is complex since there are no exhaustive experimental results on which we could rely.

To consolidate an approximation of this reduction potential, we can use three different approaches:

- First, we can rely directly on the work of *Prats, Dalmau & Barrado, 2019*, the most comprehensive in this area. They estimate a potential reduction of around 14%, by fully modeling theoretically CO_2-perfect aircraft trajectories and comparing them to real traffic[9].
- Second, the work of *Nutt, 2012*, proceeds the same way with a more typical flight – climb and descent without intermediate level off, and optimum thrust cruise – and then advantageously consolidates theoretical results through an actual flight. The observed result is a potential 10% reduction in fuel burn. The works of *Dalmau & Prats, 2015* yield an expected additional potential reduction of around 3% by using continuous climb and cruise, leading to a total of around 13%.
- Last, performance evaluations by *Eurocontrol Performance Review Commission, 2019* estimate at 6% the inefficiencies of air traffic control in Europe. Considered sources of inefficiency are:
  - Lateral flight inefficiency, that is to say the increase in actual flight distance compared to a great circle route,
  - Vertical flight inefficiency through climb and descent without intermediate level off (Continuous Climb/Descent Operations).

  The main potential gains ignored here are:
  - First better optimization of engine thrust though relaxation of flight scheduling
  - Second allowing continuous climb and cruise profiles. *Prats, Dalmau, & Barrado, 2019* estimates their potential for additional between 4% and 8%, for an overall reduction potential ranging from 10% to 14%.

Ground operations may yield further reduction potential:

- The works of *Deonandan & Balakrishnan, 2010* and *Open Airlines, 2018* on taxiing show a potential ranging from 0.5 to 2% through single engine taxiing, and from 1.2% to 4% by using an electric towing device.
- The works of *Ryerson, Hansen, Hao, & Seelhorst, 2015* on fuel load show a potential of 1% through more eco-friendly fuel loading for short and medium haul flights.
- Last, *Eurocontrol Aviation Intelligence Unit, 2019* estimates the ecological impact of tankering as an over-consumption of kerosene between 2.2% (300NM flight) and 4.7% (600NM flight). However, including this data meaningfully would require overcoming the difficulty of quantifying this practice.

The following table summarizes the reduction potential of these optimizations and deduce from these values an overall reduction potential for a short-haul flight.

Table 1

Estimated potential for reducing the CO_2 emissions of short-haul flights.

Means	Potential	Comment
CO_2-perfect trajectory	11%	Lower end value obtained by the three approaches described in this section.
Taxi	0.5%	Single engine taxi (lower hypothesis).
Fuel load optimization	1%	Above landmasses and therefore without significant diversion stakes.
Elimination of tankering	2.2%	Data excluded from overall total (no statistics on frequency of occurrence).
Total potential	12.5%	Excluding tankering.
Confidence level	Average to high	

[8] *Indeed, the short duration of cruise phase makes it difficult to take advantage of cruise winds.*
[9] *Assessment carried out over two representative traffic days: one summer day, one winter day, in the FABEC zone consisting of Germany, Belgium, France, Luxembourg, the Netherlands and Switzerland,*

The long haul situation

The distinction between short and long haul flights arises mainly from the overwhelming predominance of cruise phase for the latter.

The first characteristic of a long-haul flight is thus to dilute several aspects of a CO_2-perfect flight: optimizations of ground operations, climb and descent have indeed a lower relative weight.

Furthermore, the potential for lateral trajectory optimizations is often limited:

- Large deviations relative to great circle route are generally due to safety considerations and thus cannot be optimized away (e.g. avoidance of conflict zones, see figure 5).
- Flights over remote areas (oceans, poles, uninhabited areas) are usually already optimized (see figure 7).

Figure 5

The significant deviation relative to great circle flight due to avoidance of Syria for safety reasons (FlightRadar24, 2020).

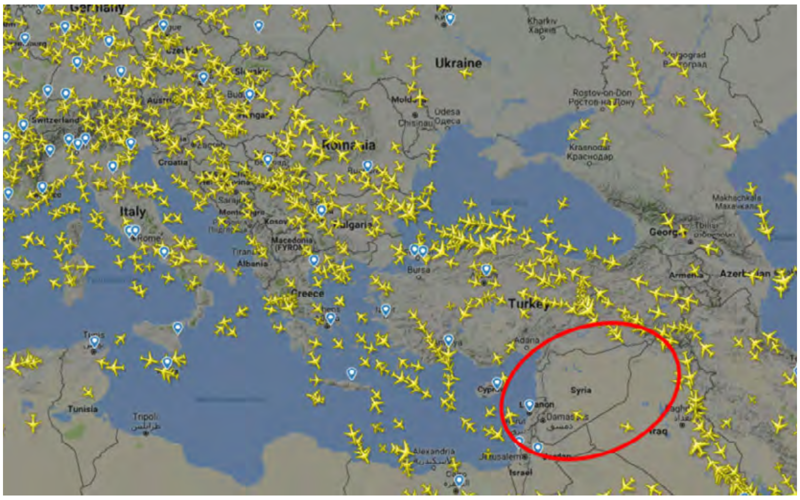
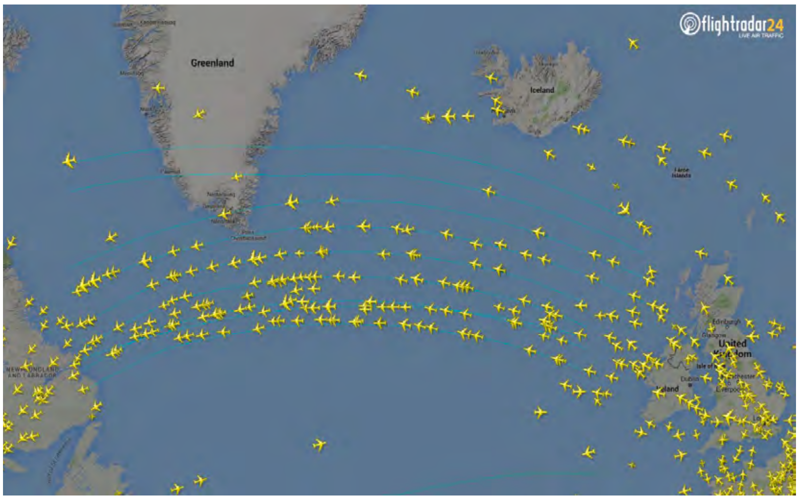


Figure 6

Flight trajectories are usually very close to the great circle route over the Atlantic (FlightRadar24, 2020).



To assess the “dilution” of the CO_2-perfect flight reduction potential, long haul could be approximated by considering them as a short-haul flight with an additional cruise segment that cannot be laterally optimized. Using this method and based on the works of *Robertson, Root, & Adams, 2007* and *Dalmau & Prats, 2015*, the estimated reduction potential on a typical long-haul flight (7600NM) is around 5%.

The second characteristic of long-haul flights is the obvious benefit of windsurfing, the benefit of which has been addressed through different approaches:

- Ng, *Sridhar, & Grabbe, 2014* shows that vertical windsurfing – based only on the modification of flight levels – has a reduction potential ranging from 3% to 10%.
- *Palopo, Windhorst, Suharwardy, & Hak-Tae, 2010* shows that lateral windsurfing – based only on modifications of the lateral trajectory – can reach a modest 0.5%.
- Finally, combining lateral and vertical optimizations *Currie, Marcos, & Turnbull, 2016* shows reduction potential ranging from 6% to 10%.

The table below summarizes the overall CO_2 reduction potential of a long-haul flight, using both theoretical and weather optimizations.

Table 2

Estimated potential for reducing the CO_2 emissions of long-haul flights.

Means	Potential	Comment
CO_2-perfect flight and ground operations	5%	Limited potential for lateral flight optimizations; diluted effect of climb/descent and ground optimizations.
Weather	6%	Lower hypothesis of works by *Currie, Marcos, & Turnbull, 2016*
Total potential	11%	
Confidence level	Average to high	

Extrapolating the reduction potential as a function of flight distance

Short- and long-haul flights are opposite operating scenarios in terms of the respective weights of their two means of optimization: theoretical and weather-based. It is however possible to combine their respective reduction potential estimates according to the statistical distribution of flights.

Figure 7 thus shows the estimated potential for reducing CO_2 emissions through eco-friendly operations as a function of flight distance.

Figure 7

Estimated potential for reducing CO_2 emissions as a function of flight distance in percentage.

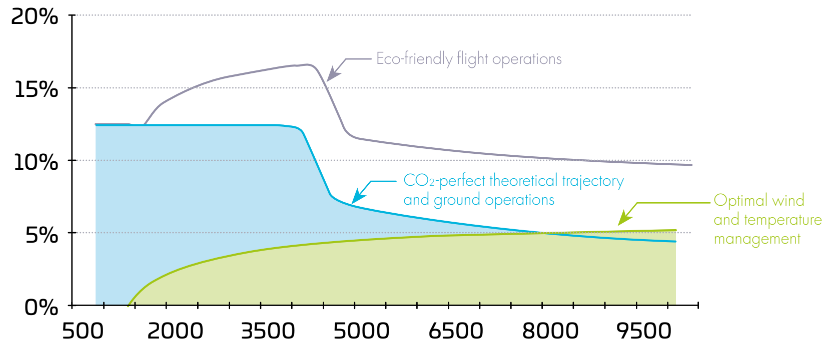
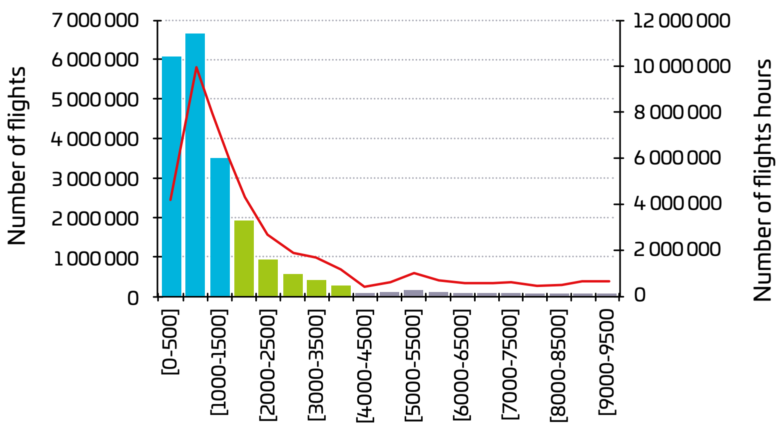


Figure 8 shows the statistical distribution of flights as a function of flight distance. Comparing it to the preceding figure, unsurprisingly the maximum potential arises for transcontinental flights in controlled airspaces – such as flights from Portugal to Norway or from Boston to New Orleans – where the potential of optimal wind management strategies adds up with that of a more direct flight.

Figure 7

Distribution of the number of commercial flights as a function of flight distance: blue bars are short-haul flights, green medium-haul, and purple long-haul, and of flight hours: red curve (Atmosfair, 2011)



Research estimates that the potential for **reducing CO_2 emissions** through eco friendly flight operations **is ranging from 10% to 15%.**

2.
NON CO_2 EFFECTS: A NOVEL AND COMPLEX RESEARCH AREA

The two most notable non-CO_2 climate effects are contrails with their artificial cirrus clouds, and Nitrogen oxides.

2.1. Contrails and induced cirrus: a very significant potential

As seen in section 1.2.2 on page 5, the effects of contrails and especially their induced artificial cirrus clouds are very significant and better understood. *Kärcher, 2018* shows that these artificial cirrus appear as the aircraft passes through areas particulary conducive to their formation – cold and humid air. Their intense greenhouse effect lasts for a few hours and is essentially nocturnal.

Research therefore focuses on two types of solutions to reduce their impact:

- Their impact being nocturnal *Stuber, Forster, Rädel, & Shine, 2006* proposes to modify aircraft take-off schedules to decrease the quantity of artificial cirrus created in the evening. However, this type of measure has a very high operational impact, and since induced cirrus clouds can reach a lifespan of several hours, their benefit is debatable.
- An alternative solution consists of aircraft avoiding areas conducive to contrail formation by adapting their vertical and horizontal trajectories. This approach appears to be very effective since several studies *Sridhar, Ng, & Chen, 2011, Grewe, et al., 2017, Teoh, Schumann, Majumdar, & Stettler, 2020*, show a significant effect on the creation of contrails (see table below).

Table 3

Reducing the effects of contrails and their induced cirrus through trajectory optimization.

Study	Potential	Comment
(Sridhar, Chen, & Ng, 2010)	53%	For US domestic flights, with an increase in overall fuel burn of 2%.
(Sridhar, Ng, & Chen, 2011)	70%	For US domestic flights, with an increase in overall fuel burn of 2%.
(Grewe, et al., 2017)	45%	For transatlantic flights, with an increase in overall fuel burn of 2%.
(Yin, Grewe, Fröming, & Yamashita, 2018)	40%	For transatlantic flights, with an increase in overall fuel burn of 2%.
(Teoh, Schumann, Majumdar, & Stettler, 2020)	59%	In Japan, by modifying 1.7% of flights.
Adopted value	40%	Adopted value is the lowest given the standard deviation of the studies.
Confidence level	Average to high	

2.2. nitrogen oxides, the complexity of antagonistic effects

NO_X effects are more complex to assess. As stated in section 1.2.3 on page 5, NO_X emissions are approximately proportional to fuel burn, but NO_X generates antagonistic effects that can result in warming or cooling depending on flight level, area of emission, and weather conditions.

While there is a great deal of research on each of the basic effects of NO_X, little of it allows understanding their interrelationships and inferring action strategies:

- *Fröming, et al., 2012* presents an assessment of the impact of cruising altitude: an average 2,000-foot increase is shown to increase NO_X-induced radiative forcing by 29%. Conversely, a 6,000-foot reduction is shown to reduce this radiative forcing by 125%, giving an overall cooling effect by reducing CH_4 in the atmosphere.
- However, *Lee, et al., 2020* questions NO_X optimization models suggesting that the NO_X-induced GWP_{100} reduction does not compensate for the increase in CO_2 emissions. They suggest focusing on CO_2 reductions instead, since this implies lower fuel burn, and corresponding lower NO_X emissions.

Table 4

Reducing GWP_{100} induced by NO_X

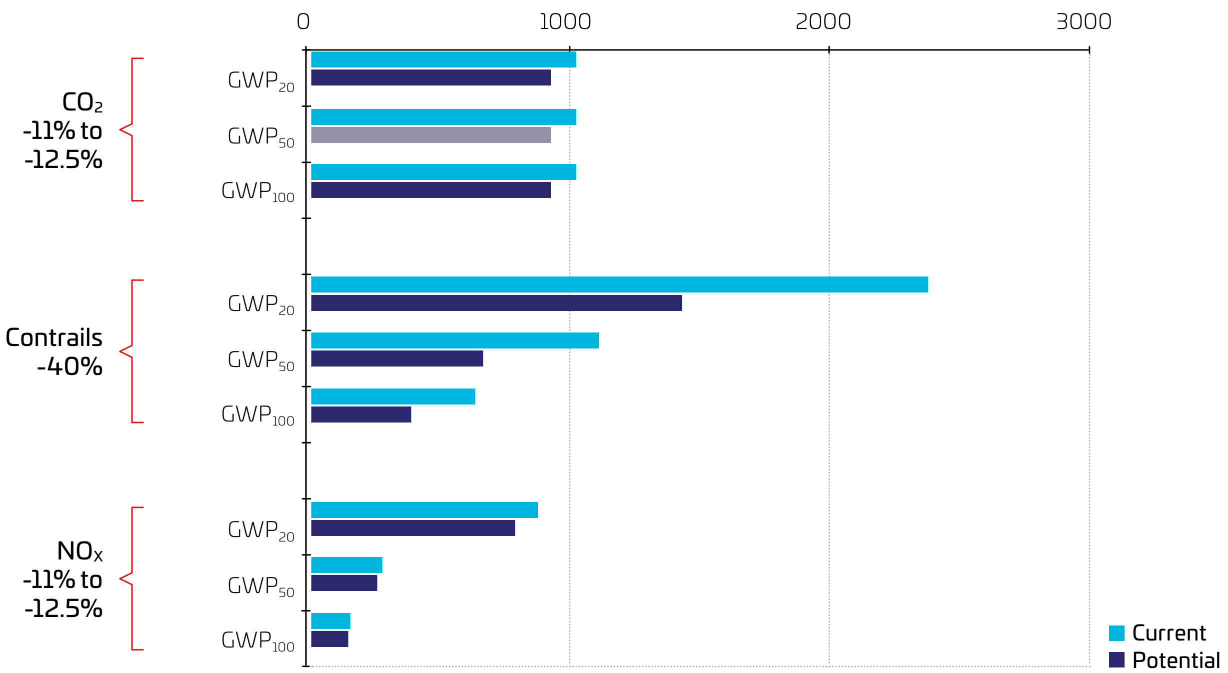
Study	Potential	Comment
(Fröming, et al., 2012)	53% (net contributor to climate cooling)	Reduce cruise altitude by 6,000 feet, at the expense of increased CO_2 emissions.
(Lee, et al., 2020)	11% - 12.5%	Based on the previously identified CO_2 gains.
Adopted value	11% - 12.5%	Conservative choice given the imprecision of the models.
Confidence level	Low to average	

Even if science has a lesser understanding of non CO_2 effects, **optimization of operations seems to be a very promising way** to reduce their impact, especially when dealing with **contrails and their induced cirrus.**

Figure 9

GWP reduction potential of each effect: CO_2, contrails, NO_X, for three timeframes: 20, 50 and 100 years, in CO_2-eq gigatons.

Calculations after one year of emissions. Blue bars show consequences of current emission levels, purple show potential consequences of the full deployment of climate-perfect flight. The potential of NO_X is indicative only, since this field of research is still in its infancy.



3.
EVALUATING THE COMBINED POTENTIAL OF A CLIMATE PERFECT FLIGHT

Based on the conclusions of the previous sections, figure 9 summarizes the potential for reducing the various climate impacts of aviation through eco-friendly operations.

3.1. Combining separate optimizations

The different approaches to the climate-perfect flight give sometimes-contradictory results because several of these effects are coupled. For example, a CO_2-perfect flight can be suboptimal from a contrail standpoint if it passes through an area conducive to their creation. The same flight may generate more O_3 because it requires flying at higher altitude to avoid these contrails while burning less fuel and thus reducing both CO_2 and NO_X emissions!

However, while these results are not directly cumulative, and if short-to-medium-haul flights and long-haul flights differ significantly, several articles provide clues for combining these effects:

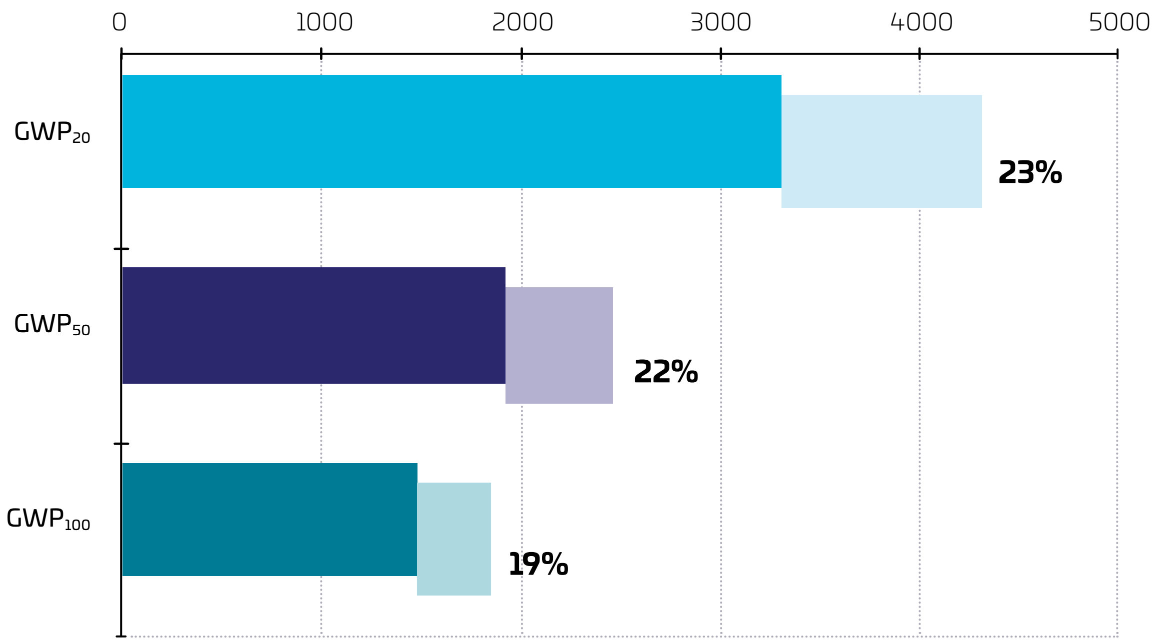
- The studies previously cited show that avoiding contrails and their induced cirrus increases CO_2 emissions by approximately 2% due to the increased fuel burn. Given their correlation, it seems reasonable to expect a similar effect with NO_X.
- As previous sections show, the trade-offs between CO_2-induced and NO_X-induced GWP_{100} reductions can be more complex to achieve. However, as proposed by *Lee, et al., 2020*, we can consider CO_2 optimization reduces NO_X by an equivalent magnitude.

Based on these hypotheses, figure 10 depicts tentative estimates of the potential for eco-friendly operations to reduce overall climate change effects (CO_2 and non-CO_2) with respect to the considered time scales (GWP_{20} to GWP_{100}).

Figure 10

Reduction potential to the climate effects of air transport (both CO_2 and non-CO_2) through eco-friendly flight operations. Horizontal scale is in CO_2-eq gigatons per year.

Light color shows GWP reduction potentials; dark color represents the resulting reduced GWP. The total of both corresponds to current state of affairs.



3.2. Combined optimizations: the climate cost functions

The most promising approach to combined optimization is the Climate Cost Functions (CCFs) developed by the DLR *Grewe, et al., 2014, Grewe, et al., 2014, Matthes, et al., 2017 and Matthes, et al., 2020.*

The CCFs aim at characterizing the climate impact of a specific emission at a given point on the globe for a given set of weather conditions. They allow the development of multi-criteria optimizations on all the dimensions of the climatic impact of a flight: CO_2, NO_X, contrails and induced cirrus clouds... Figure 11 (next page) shows examples of such optimized horizontal and vertical profiles.

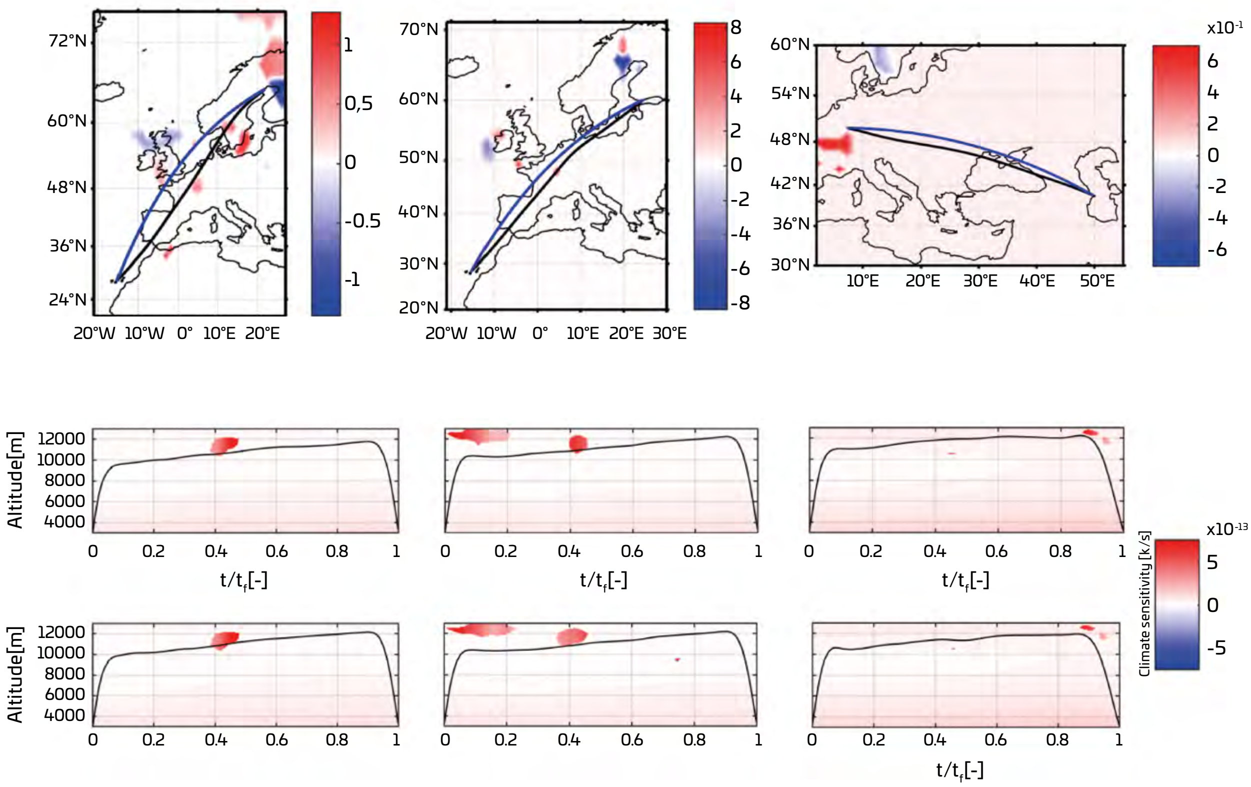
The result of these optimizations seems to confirm the conclusions of the previous sub-section, suggesting **a potential reduction of around 25% at the expense of a 5% increase** in fuel burn *Grewe, et al., 2014, Matthes, et al., 2017.* More recently, *Matthes, et al., 2020* shows more significant reductions for three sample flights, however estimated over a shorter timeframe of 20 years: 30% to 50% reduction at the expense of a 5% increase in fuel burn.

Science shows that the potential of eco friendly operations to reduce the climate impact of air transport induced by its **CO_2 and non CO_2 effects is ranging from 20% to 25%,** with a high degree of uncertainty concerning NO_X effects.

Figure 11

Example of optimization of three different flights using Climate Cost Functions in the horizontal plane (top) and in the vertical plane (bottom). In the horizontal plane, the blue trajectory corresponds to the great circle; the black trajectory corresponds to the optimal flight (Matthes, et al., 2020).

The sample flights are Lulea-Gran Canaria, Helsinki-Gran Canaria and Baku-Luxembourg.
The red areas have a positive CCF (warming); the blue areas have a negative CCF (cooling).
The lateral trajectory optimizes fuel burn; the vertical trajectory optimizes the climate impactat the expense of a 0.5% increase in fuel burn.



Appendices

BETTER UNDERSTANDING THE CLIMATE IMPACT OF AVIATION

This appendix describes in detail the different elements used to measure the climate impact of an emission and their mutual relationships: radiative forcing, effective radiative forcing, concentration trajectories, global warming and temperature change potential. It then introduces the reference climate models used to calculate the impact of CO_2, NO_X and contrails.

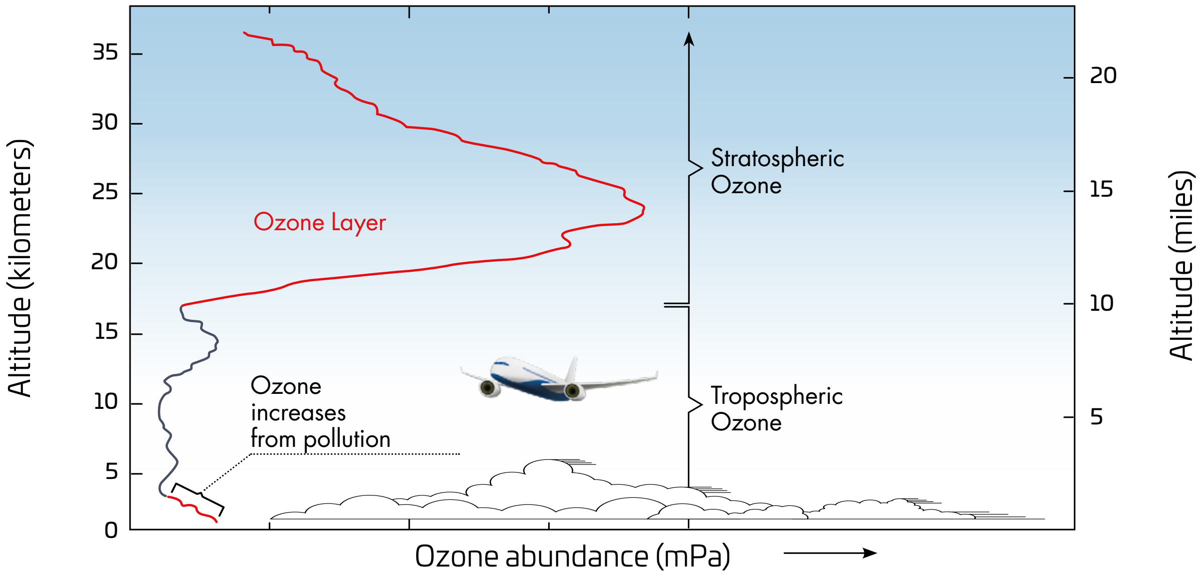
A.1. RADIATIVE FORCING

Radiative forcing (RF) can be conceptually defined as a change in the energy equilibrium of earth system, caused by a perturbation – gas or aerosol emission. It is a flux expressed in $W.m^{-2}$.

In a quantitative way, RF is therefore an incident flux difference caused by a perturbation on Top of Atmosphere (TOA) or at the tropopause.

Figure 12

Ozone abundance in the atmosphere as a function of altitude (Atmosphere Monitoring Service, 2020)

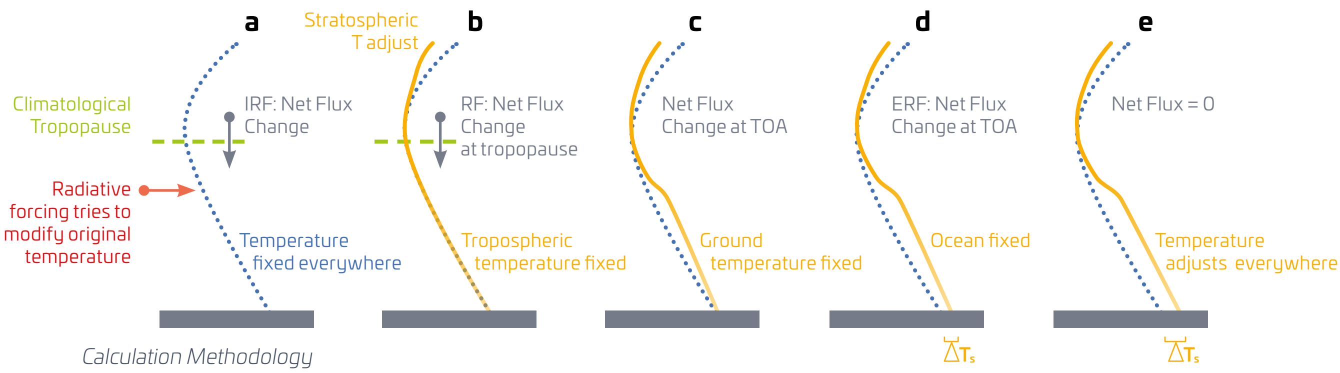


The energy state of the Earth's climate system results from the difference between the radiative power flux incoming from the sun and that reflected or emitted by the earth. Disturbances cause the system to shift towards a new equilibrium, with measurable changes in temperature at different altitudes.

The following figure shows different boundary conditions for the return to equilibrium.

Figure 13

Altitude vs. temperature graphs showing different boundary conditions for the return to equilibrium



Radiative Forcing (RF) and Effective Radiative Forcing (ERF) correspond to two types of boundary conditions, described in the table below.

Table 5

Boundary conditions corresponding to radiative forcing and effective radiative forcing.

	RF	ERF
Altitude	Tropopause	TOA
Free variables	Stratosphere temperature - Water vapor - Cloud cover - Surface temperature	- Atmosphere temperature
Fixed variables	- Surface temperature - Troposphere temperature - Water vapor - Cloud cover	- Surface temperature (partially)

The ERF/RF ratio is sometimes used to characterize which element is most disturbed, such as surface temperature.

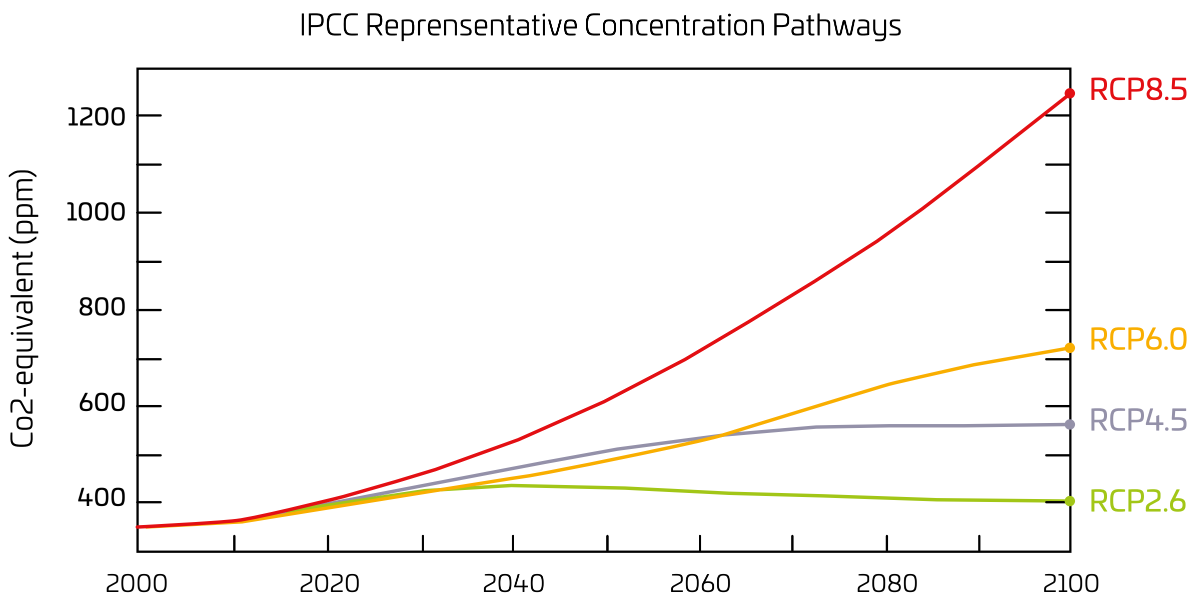
A.2. REPRESENTATIVE CONCENTRATION PATHWAY

In its fifth report, IPCC established four RCP (Representative Concentration Pathway) trajectory scenarios of radiative forcing to the 2100 horizon *Intergovernmental Panel on Climate Change, 2014.*

Each RCP scenario forecast climate changes likely to result from different assumptions regarding greenhouse gas emission over this century. Their names correspond to the predicted radiative forcing reached in 2100: the RCP2.6 scenario corresponds to a radiative forcing of +2.6 W.m^{-2}, the RCP4.5 scenario to +4.5 W.m^{-2}, and so on for RCP6 and RCP8.5 scenarios.spreading over wide areas (see figure below).

Figure 14

The four RCP scenarios considered by the IPCC (Intergovernmental Panel on Climate Change, 2014)



Each RCP scenario has different effects, as shown in the following table. The climate community widely deems the RCP8.5 scenario (also called "business as usual") as unlikely, because of climate actions already undertaken. RCP4.5 roughly matches current global warming trends, while climate agreements aim for RCP2.6 or better.

Table 6

Changes in temperature and sea level for each RCP scenario, according to IPCC (Intergovernmental Panel on Climate Change, 2014).

Scenario	Temperature change (°C)	Sea level rise (m)
RCP 2.6	+0,3°C to +1,7°C	+0,26m to +0,55m
RCP 4.5	+1,1°C to +2,6°C	+0,32m to +0,63m
RCP 6.0	+1,4°C to +3,1°C	+0,33m to +0,63m
RCP 8.5	+2,6°C to +4,8°C	+0,45m to +0,82m

A.3. CALCULATIONS

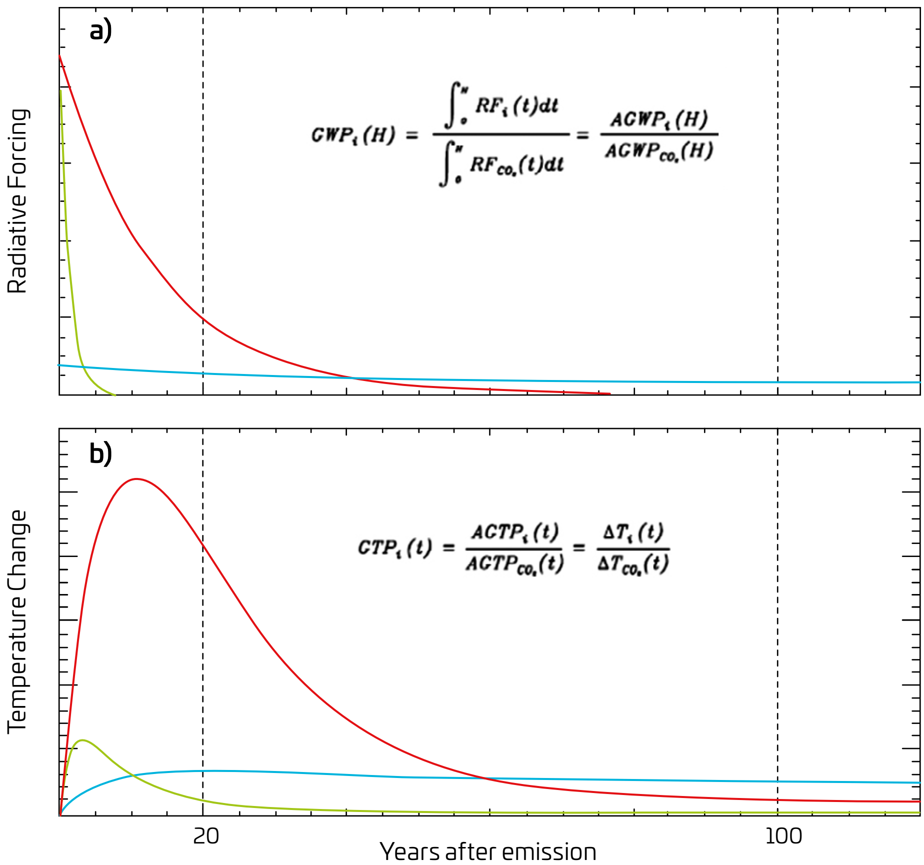
Climate change estimate can range over different time horizons, typically 20 to 100 years.

The Global Warming Potential (GWP) represents the overall energy added to the climate system because of pollution, compared to reference CO_2 emissions. In figure 6, the blue curve represents the radiative forcing of CO_2 in time, the green and red curves that of other pollution with shorter but more intense effects. GWP is the integration of radiative forcing over the considered period, and gives the equivalent CO_2 (CO_2-eq) emissions to various pollutions over a given period.

The Global Temperature change Potential (GTP) represents the global average change in surface temperature at a given time in response to a pulse of given type of emissions compared to CO_2.

Figure 15

Global Warming Potential (GWP) and Global Temperature change Potential (GTP) according to (Intergovernmental Panel on Climate Change, 2014)



A.4. APPLICATION TO AIR TRANSPORT

Air traffic emissions include emissions of CO_2, NO_X, water vapor, contrails cirrus, aerosols and soot. The RF can be calculated from changes in emission concentration in the atmosphere, or attenuation of solar radiation, especially when complex phenomena are involved (interactions, exchanges...).

RF calculation for CO_2 and associated uncertainty

The RF of CO_2 is a function of fuel burn, according to the stoichiometric coefficients of the combustion reaction[10]. The CO_2 dilutes in the atmosphere and results in a concentration measured in parts per million (ppm).

Natural sinks capture the CO_2 according to kinetics approximated by Impulse Response Function (IRF) models. The Beer-Lambert formula thus computes the RF:

$$RF = \alpha . \ln \left(\frac{C_0 + \Delta C}{C_0} \right)$$

Where C_0 is the reference concentration in 1940 and α is a constant equal to 5.35 W.m^{-2} *Myrhe, Highwood, Shine, & Stordal, 1998.*

For each year, given the quantity of fuel burn, we can deduce CO_2 emissions, the resulting CO_2 concentration in the atmosphere, and the IRF, which can predict CO_2 concentration over time. We can finally integrate the latter over the chosen duration.

When *Lee, et al., 2020,* identify an average RF of 34 mW.m^{-2}, it corresponds to the RF of CO_2 accumulated between 1940 et 2018 in the atmosphere, deduction made of the CO_2 captured by natural sinks.

In addition to fuel burn uncertainties, calculation uncertainties arise in the atmosphere carbon cycle and carbon capture impulse response models.

RF calculation for NO_X and associated uncertainty

In atmospheric chemistry, NO_X refers to the sum of NO and NO_2. In the presence of light, two cycles of coupled chemical reactions between NO_X and HO_X produce ozone (O_3) and consume methane (CH_4) and carbon monoxide (CO) - *Isaksen, et al., 2014.* These well-known phenomena lead to positive forcing for ozone and negative forcing for methane.

Models with different biases exist, to account for both short-term and long-term effects. They lead to a high degree of uncertainty in the estimates and the when combining the two effects.

RF calculation for contrails, and associated uncertainty

Aviation creates artificial clouds induced by the formation of contrails in an atmosphere supersaturated with ice[11] through nucleation, mainly on combustion soot particles. There are two disturbances: linear contrails and artificial cirrus resulting from their fusion.

Calculating the RF of contrails and the artificial cirrus clouds they induce relies on a global climate model. Required inputs include cloud cover, volume and length of the trail, the ice/water ratio and the concentration of ice crystals. A reference model is the ECHAM5-CCMod - *Bickel, Ponater, Bock, Burkhardt, & Reineke, 2020.* There are two types of uncertainties:

- The response of artificial cirrus clouds to solar illumination (flux transfer model in particular in the presence of ice crystals, cloud homogeneity, impact of the presence of soot),
- Mechanisms of formation of artificial cirrus from contrails (supersaturation rate, lifetime, interactions with natural clouds).

[10] *The commonly used ratio is 3.16kg of CO^2 emissions per kilogram of kerosene burned (Graver, Zhang, & Rutherford, 2018).*
[11] *Quenching a saturated solution results in a supersaturated solution.*

A.2. ABBREVIATIONS

AIC
Aircraft Induced Cloudiness (cloud formation induced by combustion soot)

ANSP
Air Navigation Service Providers

APU
Auxiliary Power Unit

ATAG
Air Transport Action Group

ATM
Air Traffic Management

ATSU
Air Traffic Service Unit

CDM
Collaborative Decision Making

CORSIA
Carbon Offsetting and Reduction Scheme for International Aviation

DLR
German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt e.V.)

EASA
European Aviation Safety Agency

EFB
Electronic Flight Bag

EMAS
Eco-Management and Audit Scheme

ERF
Effective Radiative Forcing

ETS
European Emission Trading System

FABEC
Functional Airspace Block – Europe Central

FMS
Flight Management System

GHG
Green House Gases

Gt
Gigatons (106 metric tons)

GTP
Global Temperature change Potential

GWP
Global Warming Potential

ICAO
International Civil Aviation Organization

ICCT
International Council for Clean Transportation

IPCC
Intergovernmental Panel on Climate Change

IRF
Impulse Response Function

KPI
Key Performance Indicator

LCC
Low-Cost Carrier

MODIS
Moderate Resolution Imaging Spectroradiometer

NM
Nautical Mile

RCP
Representative Concentration Pathway

RF
Radiative Forcing

RPK
Revenue Passenger Kilometers

RTK
Revenue Ton Kilometers

SAF
Sustainable Aviation Fuel

SESAR
Single European Sky ATM Research

SMS
Safety Management System

SSOT
Single Source of Truth

TOA
Top Of Atmosphere

A.3. REFERENCES

- **ADEME. (2020).** Base Carbone - Scope 3 - Aérien. Retrieved from Centre de ressources sur les bilans de gaz à effet de serre: https://www.bilans-ges.ademe.fr/documentation/UPLOAD_DOC_FR/index.htm?aerien.htm

- **Alligier, R., Gianazza, D., & Durand, N. (2015).** Machine Learning and Mass Estimation Methods for Ground-Based Aircraft Climb Prediction. IEEE Transactions on Intelligent Transportation Systems, 16(6), 3138-3149.

- **ATAG. (2020).** Tracking Aviation Efficiency: How is the Aviation Sector Performing in its Drive to Improve Fuel Efficiency, in line with its Short-Term Goal? Waypoint 2050.

- **Atmosfair. (2011).** Atmosfair Airline Index. Berlin.

- **Atmosphere Monitoring Service. (2020).** Ozone Layer and Ultra-Violet Radiation. Récupéré sur Copernicus.

- **Baumeister, S., & Onkila, T. (2017).** An Eco-Label for the Airline Industry? Journal of Cleaner Production, 142, 1368-1376.

- **Beyersdorf, A., Timko, M., Ziemba, L., Bulzan, D., Corporan, E., Herndon, S., . . . Anderson, B. (2014).** Reductions in Aircraft Particulate Emissions Due to the Use of Fischer–Tropsch Fuels. Atmospheric Chemistry and Physics, 14(1), 11-23.

- **Bickel, M., Ponater, M., Bock, L., Burkhardt, U., & Reineke, S. (2020).** Estimating the Effective Radiative Forcing of Contrail Cirrus. Journal of Climate, 33(5), 1991-2005.

- **Brasseur, G. P., Gupta, M., Anderson, B. E., Balasubramanian, S., Barret, S., Duda, D., . . . Zhou, C. (2016).** Impact of Aviation On Climate. American Meteorological Society, 561-583.

- **Carbon Trust. (2020).** Product Carbon Footprint Protocol. Part 1: Requirements for Certification.

- **Currie, C., Marcos, A., & Turnbull, O. (2016).** Wind Optimal Flight Trajectories to Minimise Fuel Consumption within a 3 Dimensional Flight Network. UKACC 11th International Conference on Control (CONTROL) (pp. 1-6). IEEE.

- **Dalmau, R., & Prats, X. (2015).** Fuel and Time Savings by Flying Continuous Cruise Climbs: Estimating the Benefit Pools for Maximum Range Operations. Transportation Research Part D: Transport and Environment(35), 62-71.

- **Dalmau, R., Prats, X., Ramonjoan, A., & Soley, S. (2020).** Estimating Fuel Consumption from Radar Tracks: A Validation Exercise using FDR and Radar Tracks from Descent Trajectories. CEAS Aeronautical Journal(11), 355-265.

- **Deonandan, I., & Balakrishnan, H. (2010).** Evaluation of Strategies for Reducing Taxi-out Emission at Airports. 10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference (p. 9370). Fort Worth, Texas: American Institute of Aeronautics and Astronautics.

- **EASA. (2020).** Updated Analysis of the Non-CO2 Climate Impacts of Aviation and Potential Policy Measures Pursuant to EU Emissions Trading System Directive Article 30(4). European Comission.

- **EEA, EASA & EuroControl. (2020).** European Aviation Environmental Report - 2019.

- **Eurocontrol Aviation Intelligence Unit. (2019).** Fuel Tankering: Economic Benefit and Environmental Impact. SESAR.

- **Eurocontrol Performance Review Commission. (2019).** Performance Review Report: An Assessment of Air Traffic Management in Europe. Eurocontrol.

- **Faber, J., Greenwood, D., Lee, D., Mann, M., Mendes de Leon, P., Nelissen, D., . . . van de Vreede, G. (2008).** Lower NOx at Higher Altitudes: Policies to Reduce the Climate Impact of Aviation NOx Emissions. CE Delft.

- **Flight Safety Foundation. (2020, Octobre).** Airliners Accidents Per 1 Million Flights 1977-2017. Récupéré sur Aviation Safety Network: https://aviation-safety.net/statistics/

- **Fröming, C., Grewe, V., Brinkop, S., Jöckel, P., Haslerud, A. S., Rosanka, S., . . . Matthes, S. (2020).** Influence of the Actual Weather Situation on Non-CO_2 Aviation: The REACT4C Climate Change Functions. Atmospheric Chemistry and Physics Discussions, 1-30.

- **Fröming, C., Ponater, M., Dahlmann, K., Grewe, V., Lee, D. S., & Sausen, R. (2012).** Aviation-Induced Radiative Forcing and Surface Temperature Change in Dependency of the Emission Altitude. Journal of Geophysical Research: Atmospheres, 117(D19).

- **Giraud, X. (2014).** Méthodes et Outils pour la Conception Optimale des Réseaux de Distribution d'Electricité dans les Aéronefs. Mémoire de thèse, INSA, Toulouse.

Gonenç, R., & Nicoletti, G. (2001).
Le Transport Aérien de Passagers : Réglementation, Structure du Marché

Graver, B., Zhang, K., & Rutherford, D. (2018).
CO_2 Emissions from Commercial Aviation, 2018. The International Council on Clean Transportation.

Graver, B., Zhang, K., & Rutherford, D. (2018).
CO_2 Emissions from Commercial Aviation, 2018. The International Council on Clean Transportation.

Grewe, V., Champougny, T., Matthes, S., Frömming, C., Brinkop, S., Sovde, O., . . . Halscheidt, L. (2014).
Reduction of the air traffic's contribution to climate change: A REACT4C case study. Atmospheric Environment, 94, 616-625.

Grewe, V., Frömming, C., Matthes, S., Brinkop, S., Ponater, M., Dietmüller, S., . . . Hullah, P. (2014).
Aircraft Routing with Minimal Climate Impact: the REACT4C Climate Cost Function Modelling Approach (V1.0). Geoscientific Model Development, 7, 175-201.

Grewe, V., Matthes, S., Frömming, C., Brinkop, S., Jöckel, P., Gierens, K., . . . Shine, K. (2017).
Feasibility of climate-optimized air traffic routing for trans-Atlantic flights. (I. Publishing, Éd.) Environment Research Letters, 12.

Haywood, J. M., Allan, R. P., Bornemann, J., Forster, P. M., Francis, P. N., Milton, S., . . . Thorpe, R. (2009).
A Case Study of the Radiative Forcing of Persistent Contrails Evolving into Contrail-Induced Cirrus. Journal of Geophysical Research: Atmosphere, 114(D24).

Helmore, E. (2020, janvier 15).
Activists Cheer BlackRock's Landmark Climate Move but Call for Vigilance. The Guardian.

Hensey, R., & Magdalina, A. (2018, Juillet 19).
A320 NEO vs. CEO Comparison Study. FPG Ametum.

ICAO. (2017).
ICAO Council Adopts New CO_2 Emissions Standard for Aircraft. Retrieved from International Civil Aviation Organization.

ICAO Air Transport Bureau. (2020).
Effect of Novel Coronavirus (COVID-19) on Civil Aviation: Economic Impact Analysis. Montréal, Canada.

Intergovernmental Panel on Climate Change. (2014).
IPCC Fifth Assessment Report. United Nations.

Isaksen, I., Berntsen, T., Dalsoren, S., Eleftheratos, K., Orsolini, Y., Rognerud, B., . . . Holmes, C. (2014).
Atmospheric Ozone and Methane in a Changing Climate. Atmosphere, 5(3), 518-535.

Kärcher, B. (2018).
Formation and Radiative Forcing of Contrail Cirrus. Nature Communications, 9(1), 1-17.

Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., . . . Wilcox, L. (2020).
The Contribution of Global Aviation to Anthropogenic Climate Forcing for 2000 to 2018. Atmospheric Environment, 117834.

Lopez-Leones, J., Polaina-Morales, M., Sanchez-Escalonilla, P., Ferrer-Herrer, D., Sanz-Bravo, M., Celorrio-Camara, F., & Martinez-Mateo, A. (2017).
User-Centric Cost-Based Flight Efficiency and Equity Indicators. 7th SESAR Innovation Days.

Materna, M. (2019).
Variants of Air Navigation Service Providers' Business Models. 13th International Scientific Conference on Sustainable, Modern and Safe Transport (TRANSCOM 2019).

Matthes, S., Grewe, V., Dahlmann, K., Fröming, C., Irvine, E., Lim, L., . . . Yin, F. (2017).
A Concept for Multi-Criteria Environmental Assessment of Aircraft Trajectories. Aerospace, 4(3), 42.

Matthes, S., Lührs, B., Dahlmann, K., Grewe, V., Linke, F., Yin, F., . . . Shine, K. P. (2020).
Climate-Optimized Trajectories and Robust Mitigation Potential: Flying ATM4E. Aerospace, 7(11), 156.

Mearns, E. (2016).
High Altitude Wind Power Reviewed.
Retrieved from Energy Matters: http://euanmearns.com/high-altitude-wind-power-reviewed/

Ministère de la Transition Ecologique. (2017).
Ciel Unique Européen. Retrieved from https://www.ecologie.gouv.fr/ciel-unique-europeen

Minnis, P., Ayers, J., Palinkonda, R., & Phan, D. (2004). Contrails, Cirrus Trends, and Climate. Journal of Climate, 17(8), 1671-1685.

Mooney, A., & Temple-West, P. (2020, Juillet 26).
Climate Change: Asset Managers Join Forces with the Eco-Warriors. Financial Times.

Myrhe, G., Highwood, E. J., Shine, K. P., & Stordal, F. (1998).
New Estimates of Radiative Forcing Due to Well Mixed Greenhouse Gases. Geophysical Research Letters, 25(14), 2715-2718.

Ng, H. N., Sridhar, B., & Grabbe, S. (2014).
Optimizing Aircraft Trajectories with Multiple Cruise Altitudes in the Presence of Winds. Journal of Aerospace Information Systems, 11(1), 35-47.

Nutt, C. (2012).
NATS Fuel Efficiency Metric. NATS.

Open Airlines.
(2018). What you need to know about Engine-Out Taxi-In. Retrieved from Open Airlines website: blog.openairlines.com/engine-out-taxi-in-eoti

Palopo, K., Windhorst, R. D., Suharwardy, S., & Hak-Tae, L. (2010).
Wind-Optimal Routing in the National Airspace System. Journal of Aircraft, 47(5), 1584-1592.

Prats, X., Dalmau, R., & Barrado, C. (2019).
Identifying the Sources of Flight Inefficiency from Historical Aircraft Trajectories. Thirteenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2019). Vienna, Austria.

Prats, X., Dalmau, R., & Barrado, C. (2019).
Identifying the Sources of Flight Inefficiency from Historical Aircraft Trajectories. Thirteenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2019).

Robertson, W., Root, R., & Adams, D. (2007).
Fuel Conservation Strategies: Cruise Flight. Aero, 22-27.

Ryerson, M. S., Hansen, M., Hao, L., & Seelhorst, M. (2015).
Landing on Empty:
Estimating the Benefits from Reducing Fuel Uplift in US Civil Aviation. Environment Research Letters, 10(9).

S&P Global. (2020).
Measuring Intangibles:
The SAM Corporate Assessment Methodology.

Shine, K. P., Bernsten, T., Flugestvedt, J. S., & Sausen, R. (2005).
Scientific Issues in the Design of Metrics for Inclusion of Oxides of Nitrogen in Global Climate Agreements. Proceedings of the National Academy of Sciences, 102(44), 15768-15773.

Sridhar, B., Chen, N. Y., & Ng, H. K. (2010).
Fuel Efficient Strategies for Reducing Contrail Formation in the United States Airspace. 29th Digital Avionics Systems Conference, (pp. 1-A 1-1-1 A. 1-9).

Sridhar, B., Ng, H. K., & Chen, N. Y. (2011).
Aircraft Trajectory Optimization and Contrails Avoidance in the Presence of Winds. Journal of Guidance, Control and Dynamics, 34(5), 1577-1584.

Stuber, N., Forster, P., Rädel, G., & Shine, K. (2006).
The Importance of the Diurnal and Annual Cycle of Air Traffic for Contrail Radiative Forcing. Nature, 441(7095), 864-867.

Sun, J., Hoekstra, J. M., & Ellerbroek, J. (2020).
OpenAP: An open-source aircraft performance model for air transportation studies and simulations. Aerospace, 7(8), 104.

Teoh, R., Schumann, U., Majumdar, A., & Stettler, M. E. (2020).
Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption. Environmental Science & Technology, 54(5), 2941-2950.

Tyler, L. (2013).
A Life Cycle Assessment of the Passenger Air Transport System using Three Flight Scenarios. Master Thesis, Institutt for Energi-og Prosessteknikk.

Yin, F., Grewe, V., Fröming, C., & Yamashita, H. (2018).
Impact on Flight Trajectory Characteristics when Avoiding the Formation of Persistent Contrails for Transatlantic Flights. Transportation Research Part D: Transport and Environment, 65, 466-484.

Also discover
our volume #3

#3

Challenges to overcome

Towards eco-friendly operations

Acting now to reduce the climate impact of aviation

THALES

Building a future we can all trust

Thales LAS France SAS
3, avenue Charles Lindbergh
BP 20351
94628 Rungis cedex
France

Tel. +33 (0)1 79 61 40 00
marketingams@thalesgroup.com

> Thalesgroup.com <

Come on board with us !