Simulation and evaluation of sustainable climate trajectories for aviation

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A B S T R A C T

In 2019, aviation was responsible for 2.6% of world CO_2 emissions as well as additional climate impacts such as contrails. Like all industrial sectors, the aviation sector must implement measures to reduce its climate impact. This paper focuses on the simulation and evaluation of climate scenarios for air transport. For this purpose, a specific tool (CAST for "Climate and Aviation - Sustainable Trajectories") has been developed at ISAE-SUPAERO. This tool follows a methodology for the assessment of climate impacts adapted to aviation. Firstly, models for the main levers of action, such as air traffic, aircraft energy consumption and energy decarbonization, are provided using trend projections from historical data or assumptions from the literature. Second, the evaluation of scenarios is based on aviation carbon budgets, which are also extended to non-CO_2 effects using the concept of GWP*. Several scenario analyses are performed in this paper using CAST allowing different conclusions to be drawn. For instance, the modelling of the scenarios based on the more recent ATAG (Air Transport Action Group) commitments shows that aviation would consume 6.5% of the world carbon budget for +1.5 °C. Some illustrative scenarios are also proposed. By allocating 2.6% of the world carbon budget to aviation, it is shown that air transport is compatible with a +2 °C trajectory when the annual growth rate of air traffic varies between −1.8% and +2.9%, depending on the technological improvements considered. However, using the same methodology for a +1.5 °C trajectory shows that a drastic decrease in air traffic is necessary. Lastly, analyses including non-CO_2 effects emphasize the importance of implementing specific strategies for mitigating contrails.

1. Introduction

Human activities generate GreenHouse Gas (GHG) emissions, in particular CO_2 due to the combustion of fossil fuels. These various emissions, as well as other physical phenomena such as the modification of the terrestrial albedo, cause the Earth's energy budget, defined as the difference between solar irradiance absorbed and radiated energy emitted, to become positive. This results in an increase in the global average temperature of the Earth. The consequences of these rapid and significant temperature variations are many and varied (Stocker et al., 2013). Melting ice, rising sea levels, water stress, declining agricultural yields, heat waves and the loss of biodiversity are examples, the extent of which will depend on the level of temperature anomalies. The Intergovernmental Panel on Climate Change (IPCC) studies these different questions through numerous reports such as (C.C. IPCC, 2007; W. IPCC, 2013). Due to climate change, the governments that have ratified the Paris Climate Agreement (Schleussner et al., 2016) have committed to limit global warming well below +2 °C above pre-industrial levels and to pursue efforts to limit the increase to 1.5 °C.

In order to comply with the Paris Agreement, it is therefore necessary to set up compatible trajectories, particularly in terms of GHG emissions. For example, at the global level, the IPCC defines trajectories to limit global warming to 1.5 °C or 2 °C using the concept of carbon budgets (Masson-Delmotte et al., 2018). Several tools for exploring the impact of key levers of action on the reduction of GHG emissions have been proposed to simulate global trajectories easily. For instance, the En-ROADS simulator generates trajectories using different economic, technical and social parameters (Sterman, 2012). Similarly, the Global Calculator tool can be used to generate trajectories based on energy, land and food scenarios (Strapasson et al., 2020). These different prospective scenarios can also be applied to specific sectors. The transportation sector is particularly interesting because of the rebound effect and the increase in travel speeds (Spielmann et al., 2008). For instance, transportation-specific transition scenarios are considered in such countries as France (Bigo, 2020), Nicaragua (Cantarero, 2019) and China (Zhang et al., 2020a). More specifically, these analyses can also be applied to the aviation sector.

Aviation has a significant impact on climate change through various emissions and physical phenomena (Lee et al., 2009), such as CO_2

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Nomenclature

ASK	Available Seat Kilometer
ATAG	Air Transport Action Group
BC	Black Carbon
BECCS	Bio-Energy with Carbon Capture and Storage
CAST	Climate and Aviation - Sustainable Trajectories
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DAC	Dual Annular Combustor
ERF	Effective Radiative Forcing
$EU-ETS$	European Union - Emissions Trading System
GHG	GreenHouse Gas
GWP	Global Warming Potential
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
RMS	Root Mean Square
RPK	Revenue Passenger Kilometer
SLSQP	Sequential Least SQuares Programming
TCRE	Transient Climate Response to cumulative carbon Emissions

emissions, condensation trails (contrails) and NO_x emissions. It can be assessed using the concept of effective radiative forcing (ERF) (Ramaswamy et al., 2019). This indicator can be estimated for CO_2 emissions but also non-CO_2 effects. Overall, aviation has generated a positive ERF of 100.9 mW/m^2 between 1940 and 2018 and thus global warming (Lee et al., 2020). Non-CO_2 effects, which represent 66.6 mW/m^2, are dominated by contrails, which are complex phenomena that depend on local atmospheric conditions (Grewe et al., 2017; Kärcher, 2018). From a quantitative point of view, aviation is responsible for about 2–3% of world CO_2 emissions (2.1% in 2019 according to Group (2020). In addition, by integrating non-CO_2 effects such as contrails, aviation's overall climate impact reached 3.5% of world ERF in 2011 (Lee et al., 2020). In addition, according to the Öko-Institut, due to the significant growth of the sector and the difficulty of easily and rapidly implementing technological solutions to reduce GHG emissions from aircraft, the aviation sector could account for up to 22% of global impacts on climate change by 2050 (Cames et al., 2015). These values involve significant uncertainties, and a study is in progress to refine the results (Linke et al., 2020). However, these results show that the aviation sector is responsible for significant effects on the climate and that the transition that has been initiated must be emphasized.

An aircraft generates environmental impacts at different stages of its life cycle such as the use, resource extraction or end-of-life phases. In order to better quantify the environmental impacts of aviation in the broadest sense, Life Cycle Assessment (LCA) type studies have been carried out. For example, a simplified LCA methodology for Airbus A320 aircraft has been developed (Johanning and Scholz, 2014). A study on other aircraft has been carried out and converges toward similar results (PinheiroMelo et al., 2020). Some studies focus more specifically on pollutant emissions near airports (Kurniawan and Khardi, 2011). All these studies show that climate impact is one of the major environmental issues for aviation with, however, some discrepancies in the evaluation of non-CO_2 effects. In particular, these LCAs show that the combustion and production of kerosene are the most impacting phases of the life cycle. Thus, the reduction of aircraft fuel consumption and the use of low-carbon fuels are the technological measures with the greatest impact on reducing CO_2 emissions from aviation.

Numerous studies have been conducted to evaluate new technologies for reducing aircraft fuel consumption. For example, hybrid-electric architectures are being studied for aircraft with different operating ranges (Ribeiro et al., 2020). These architectures are envisaged for short-range aircraft. The use of new fuels is also being studied. The main solutions being considered are biofuels (De Jong et al., 2017; Zhang et al., 2020b) and hydrogen (Yılmaz et al., 2012), but both face problems of energy availability.

Given aviation's climate impacts and potential improvements, work has focused on the evaluation of prospective scenarios. For instance, a 2005 study shows the need to stabilize the number of flights per inhabitant at levels slightly higher than those of the 2000s to limit the atmospheric concentration of CO_2 to 450 ppm (Åkerman, 2005). Moreover, the work of (Terrenoire et al., 2019) indicates that aviation would be responsible for 5.2% of total anthropogenic warming under an IPCC scenario named RCP2.6, considering International Civil Aviation Organization (ICAO) scenarios. Another study showed the difficulty of decarbonizing aviation (Sharmina et al., 2020). Lastly, a specific economic mechanism for allocating carbon emissions is considered in (Qiu et al., 2017) and different mechanisms such as CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) or EU-ETS (European Union - Emissions Trading System) are compared in (Scheelhaase et al., 2018).

Although forward-looking scenarios for the aviation climate transition exist, these studies do not address the problem in its entirety and leave open questions. First of all, non-CO_2 effects are often treated in an approximate way or not at all. Secondly, as far as we know, there are no reference models for simply constructing and analyzing aviation scenarios. Thirdly, the evaluation of these scenarios with regard to the Paris Agreement is scarcely carried out. Lastly, a specific tool for aviation is missing, like the En-ROADS or Global Calculator tools for world transition. Several actors such as ATAG propose simulated scenarios but without making specific models available.

The aim of the work reported here is to present methods and a tool which can help analyze sustainable scenarios for air transport in terms of climate change. The advantage of this tool, developed at ISAE-SUPAERO, is that it responds to some of the shortcomings mentioned above: it is a holistic and freely accessible simulation tool. It is based on tailored models for the main aviation levers of action, in order to model scenario transition trajectories, coupled with simplified and reproducible climate models. The contribution of the paper is to provide models for simulating different trajectories and evaluating them with an original method based on carbon budgets. The results obtained make it possible to quantify and identify general trends in aviation's climate transition and to integrate them into a single freely-accessible tool.

The paper is organized as follows. In Section 2, the overall methodology chosen for the tool is presented. Then, the models developed for estimating the impacts of aviation and assessing the sustainability of trajectories are the subject of Section 3. Subsequently, in Section 4, various scenarios are modelled, evaluated and criticized and a global analysis is carried out. Finally, Section 5 offers concluding remarks and an outline of future work.

2. Methodology

In this section, the methodology used to develop the CAST tool is outlined. First, the scope of the tool and the main data required for the implementation of the methodology followed for the tool are given. Then, the architecture of CAST is detailed as well as the main aspects of the software developments.

2.1. Scope and data

The scope of this work covers commercial aviation, which includes freight and passenger transport since freight is essentially carried out in an opportunistic manner (i.e. by filling the cargo compartments). In this paper, military and general aviation, which account respectively for 8% and 4% of the world kerosene consumption (Gössling and Humpe, 2020), are not taken into account.

Input data on global air transport are used by the software: number of passengers, Revenue Passenger Kilometer (RPK), total aircraft distance or mean aircraft load factor. For this study, they are taken from ICAO (I.C.A. Organization, 2020a). The kerosene consumption, 88% of which is for commercial aviation (Gössling and Humpe, 2020), is taken from (International Energy Agency, 2020) and it represented approximately 348 *Mtoe* in 2019. Consumption of other fuels such as biofuels is currently marginal and is not taken into account.

In order to convert this kerosene consumption into CO_2 emissions, European data from (ADEME, 2020) are used to get the emission factor estimated at 71.8 gCO_2/MJ if only emissions due to combustion are considered and 86.7 gCO_2/MJ if both kerosene production and combustion are taken into account. These values are close to the values used in American studies (Stratton et al., 2011). To take into account the other phases of the life cycle to obtain global aviation CO_2 emissions, based on mean results from (PinheiroMelo et al., 2020), these values are increased by 2%.

To correctly quantify the climate effects of aviation, it is necessary to also consider the non-CO_2 effects in addition to the CO_2 emissions. First, Table 1 gives the coefficients to obtain emissions from the consumed kerosene (Lee et al., 2020). To estimate the impact of these emissions in terms of ERF, coefficients, given in Table 2, are defined using data from (Lee et al., 2020). The impact of contrails is estimated in relation to the total distance flown by aircraft. The impact of CO_2 is considered cumulative over time, while the other phenomena are calculated annually.

Using all these data, direct CO_2 emissions from kerosene combustion for commercial aviation are computed and amounted to 921 Mt in 2019, i.e. 2.1% of world CO_2 emissions in 2019 (G. C. Project, 2020). For comparison, ATAG has estimated these emissions at 915 Mt in 2019, a difference of 0.7%. In terms of global emissions, CO_2 emissions due to the whole life cycle amounted to 1134 Mt, or roughly 2.6% (more accurate value: 2.635) of world CO_2 emissions in 2019. Also including non-CO_2 effects, while human activities generated 2290 mW/m^2 to 2011 (W. IPCC, 2013), commercial aviation generated 80.6 mW/m^2, i.e. 3.5%. Restricting the analysis to a more recent period (2005–2011), commercial aviation is responsible for 5.5% of the increase in anthropogenic ERF.

2.2. Architecture and development of the tool

The objectives of CAST are to generate climate trajectories (or prospective scenarios) for aviation and to evaluate their compatibility with temperature goals such as those defined in the Paris Agreement (Schleussner et al., 2016).

Fig. 1 shows the schematic diagram describing how CAST is built. CAST is based on models and scenarios, detailed in Section 3, whose input data can be divided into two categories:

- the main aviation levers of action, such as air traffic growth or fuel consumption efficiency, used to model the aviation sector;
- the climate parameters used to define climate scenarios targeted for aviation.

To assess the complexity behind the CAST process, the number of inputs and outputs is given here. From its first beta-version, CAST uses 26 input variables to allow users to define their own scenarios and trajectories. In addition, it uses 69 input parameters present in the models developed to perform the analyses proposed in CAST. These parameters are not meant to be modified by the user, but rather updated when more recent literature and data are available. The CAST methodology can then compute and provide 141 outputs along with 42 different graphs.

With regard to the software development of the tool, CAST was developed using the Python programming language. The tool is freely available. Providing a free tool that scientists, organizations, authorities and companies can interact with to define sustainable aviation trajectories is a great motivation. The data and models are mainly manipulated and implemented using the *Pandas* package (McKinney et al., 2010) but also use other scientific computing package like *Scipy* (Virtanen et al., 2020) for solving implicit models, for example. The user interface uses *ipywidgets* (JupyterDevTeam, 2020b) for the widgets and *ipympl* (JupyterDevTeam, 2020a) for the graphs. The CAST software is deployed as a web application thanks to *Voilà* (Quantstack, 2020).

Table 1
Emission factors for kerosene combustion.

Emissions	Value [unit]
CO_2	3.15 $[kgCO_2/kgFuel]$
H_2O	1.23 $[kgH_2O/kgFuel]$
NO_x	15.1 $[gNO_x/kgFuel]$
Aerosol (BC)	0.03 $[gBC/kgFuel]$
Aerosol (SO_x)	1.2 $[gSO_2/kgFuel]$

Table 2
ERF coefficients for aviation climate impacts.

Climate impact	Value [unit]
CO_2	0.88 $[mW/m^2/GtCO_2]$
H_2O	0.0052 $[mW/m^2/TgH_2O]$
NO_x	11.55 $[mW/m^2/TgN]$
Aerosol (BC)	100.7 $[mW/m^2/TgBC]$
Aerosol (SO_x)	−19.9 $[mW/m^2/TgSO_2]$
Contrails	$1.058.10^{-9}$ $[mW/m^2/km]$

3. Models

The purpose of this section is to present the main models used in CAST. First, the overall methodology for assessing climate trajectories is described. Subsequently, the models specific to aviation levers of action are detailed. Lastly, the main climate models used are given.

3.1. Definition of levers of action

To simulate different air transport scenarios, the main levers of action for aviation must be defined and interrelated. The approach chosen is based on the application of the Kaya equation to aviation. The Kaya equation (1) is used to link global CO_2 emissions to demographics (population POP), economics (GDP per capita GDP/POP) and technological parameters (energy intensity E/GDP which can be related to efficiency and energy content in CO_2 CO_2/E) (Kaya Yokoboriet al., 1997). The interest of this equation is that it shows the main levers for acting on CO_2 emissions (Friedl and Getzner, 2003). Different studies, often based on production decomposition analyses, justify the choice of the relevant factors for breaking down the emissions (Ang and Zhang, 2000; Wang et al., 2015). Some factors in the equation are interdependent, however, and the analyses can therefore be complex (Schandl et al., 2016).

$$CO_2 = POP \times \frac{GDP}{POP} \times \frac{E}{GDP} \times \frac{CO_2}{E} \qquad (1)$$

Equation (2) is a proposal for aviation. The choice of factors is justified by various works specific to aviation (Sharmina et al., 2020; Andreoni and Galmarini, 2012; Liu et al., 2017). The first factor is the Revenue Passenger Kilometer (RPK) which represents the level of air traffic, coupling the number of passengers and the distance flown. The increase in air traffic leads to an increase in CO_2 emissions. The second factor ASK/RPK is the ratio between the Available Seat Kilometer ASK and the Revenue Passenger Kilometer RPK. It therefore represents the inverse of the mean aircraft load factor. For a fixed RPK, the CO_2 emissions decrease if the load factor increases. Next, the third factor E/ASK is the ratio between the energy E consumed by aviation and Available Seat Kilometer ASK. It therefore represents the energy consumption per aircraft seat per kilometer and its improvement reduces

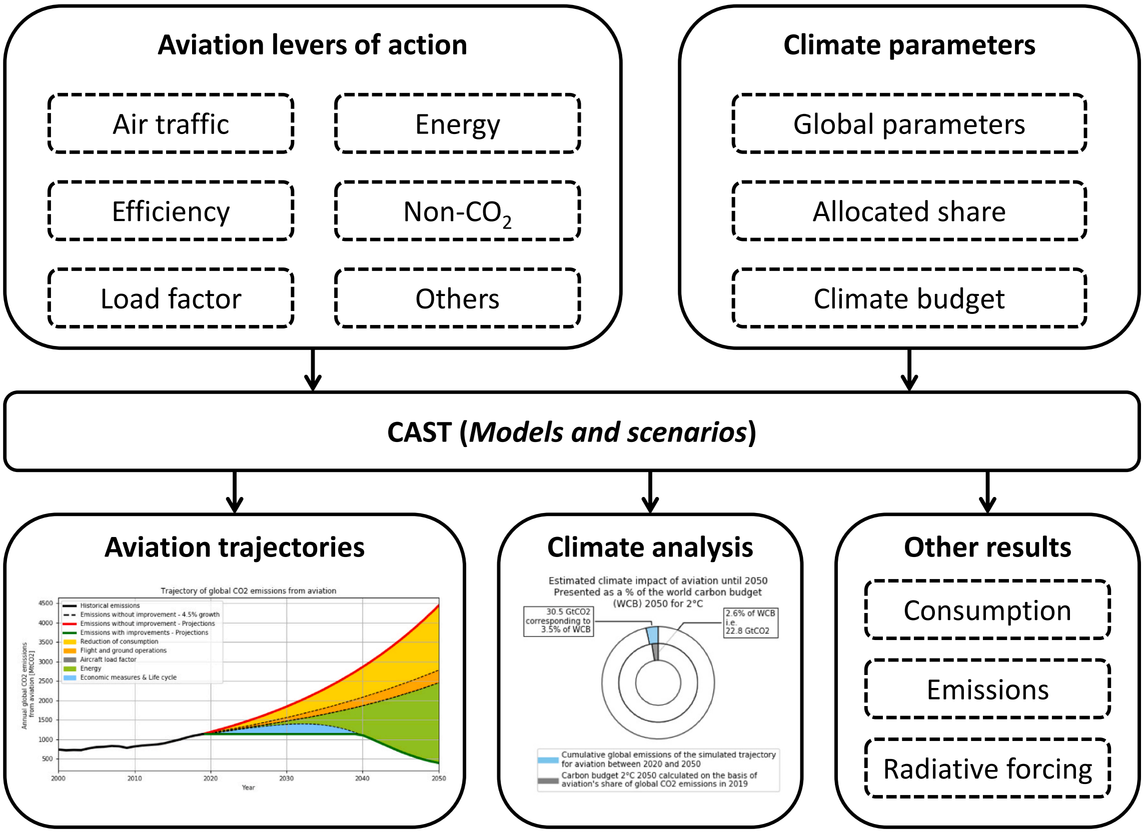

Fig. 1. CAST schematic diagram.

CO_2 emissions. Lastly, the last factor CO_2/E is the CO_2 content of the energy used by the aircraft. An improvement in this factor, for example through the use of biofuels or hydrogen produced with low-carbon energy, reduces CO_2 emissions. These different parameters represent the main levers of action for decarbonizing aviation.

$$CO_2 = RPK \times \frac{ASK}{RPK} \times \frac{E}{ASK} \times \frac{CO_2}{E} \quad (2)$$

As the Kaya equation for aviation is only a proposal, it can be simplified, modified or detailed. For example, additional coefficients can be added to take into account indirect emissions or non-CO_2 effects. Moreover, it is important to note that some factors are not totally independent. For example, fuel change may lead to an increase in energy consumption per seat-kilometer or the level of air traffic may affect the mean aircraft load factor. Nevertheless, assuming that these interactions are weak, these different levers of action make it possible to carry out initial analyses of different prospective scenarios.

Fig. 2 represents the evolution of the different parameters from equation (2). Despite the improvement in the mean aircraft load factor and energy consumption per seat-kilometer (divided by 2 in 30 years), aviation's CO_2 emissions have doubled in 30 years due to the strong increase in air traffic. It is interesting to note that due to the almost exclusive use of kerosene, the CO_2 energy content of aviation has remained constant.

If the historical study of the Kaya equation makes it possible to justify the importance of the different levers of action, it is interesting to perform a projection analysis to establish transition scenarios. As a consequence, modelling the future evolution of the different parameters can allow the development of transition scenarios for aviation's CO_2 emissions, and more globally for the climate impact of aviation.

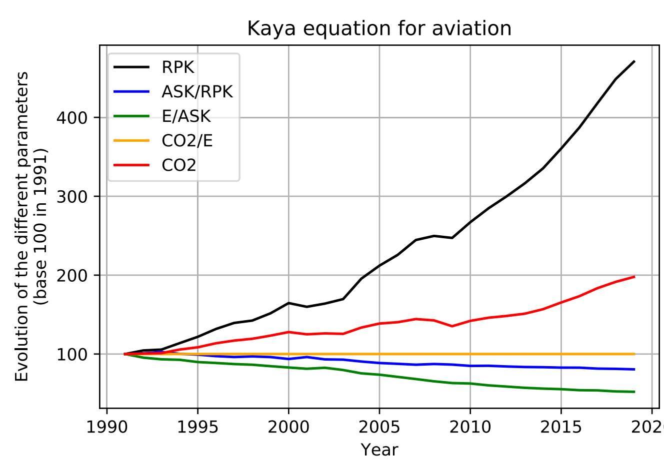

Fig. 2. Evolution of Kaya equation parameters for aviation since 1991.

3.2. *Modelling of the levers of action*

The objective of this section is to present the models for the various levers of action specific to aviation. The chosen levers of action are those from equation (2), with a distinction for operations and non-CO_2 effects. Two cases arise for establishing the models. Either historical data are available and deterministic historical models can be computed from these data – these models can be used to project the data into future years to determine trend models – or historical data is lacking and simple models are then computed on the basis of assumptions from the scientific literature.

In addition to the various levers of action presented, more specific options have been included in CAST. They are notably used to study specific effects due to the Covid-19 epidemic using IATA data (I. A. T.

Association, 2020a), as well as the impact of different economic, social, logistical and political measures.

3.2.1. Air traffic

The parameter corresponding to the lever of action on air traffic is *RPK*. To establish evolution scenarios, the approach consists in studying the historical evolution of this parameter. Fig. 3 represents the historical values since 1991 (I.C.A. Organization, 2020a) as well as the historical trend model. The latter was obtained using a simple exponential base function with a fixed growth rate as presented in equation (3) with RPK_{1991} the initial value in 1991, x the year and τ the smoothed growth rate over the period 1991–2019.

$$RPK(x) = RPK_{1991}(1+\tau)^{x-1991} \tag{3}$$

To determine the parameter τ, optimization was performed using the SLSQP method to minimize the Root Mean Square (RMS) error between the historical data and the model. This has the advantage of smoothing the values due to different crises (the 2001 September 11 attacks or the financial crisis of 2008). The optimal rate obtained is then 5.5% for the period 1991–2019, with an RMS error of 0.032. When the study is restricted to the evolution over the last 10 years, this rate reaches 6.5%, which shows an acceleration in air traffic growth trend as depicted in Fig. 3.

Nevertheless, due to the saturation of certain markets such as Europe, manufacturers anticipate a decline in this rate in the coming years. For example, with regard to the evolution of the total distance flown by aircraft, Boeing was counting on annual growth of 4.7% from 2017, compared with 4.4% for Airbus (Fichert et al., 2020). Moreover, ICAO has announced an average forecast for RPK of 4.1% per year between 2015 and 2045 (I.C.A. Organization, 2020b). Lastly, this growth rate could in the future decrease or even become negative due to the current crisis and the economic, political and health measures.

To model air traffic in the coming years, the exponential model with τ as a tuning parameter was kept for its simplicity and its good representation of the evolution in this lever of action. Equation (4) is used in CAST. The pre-Covid forecast growth rate is 4.5% and the post-Covid forecast growth rate is 3.0% (A. T. A. Group, 2020).

$$RPK(x) = RPK_{2019}(1+\tau)^{x-2019} \tag{4}$$

3.2.2. Efficiency

The second lever of action concerns the improvement of the energy efficiency per seat-kilometer, excluding the integration improvements in flight and ground operations, which will be treated separately. Contrary to air traffic trends, simple models do not adequately model historical trends. Indeed, technological limitations have led to reduced gains in recent years. For example, according to (Lee, (2010)), energy consumption per kilometer and per passenger (including the aircraft load factor) decreased by about 1.5% per year on average between 1975 and 2000, but less significantly afterwards. Similar results can be seen in Fig. 2.

To establish trend models for energy efficiency per seat-kilometer and scenarios, a three-step specific methodology has been developed based on historical data on energy consumption per seat-kilometer from (International Energy Agency, 2020; I.C.A. Organization, 2020a).

1. Synthesis of a past trend model from historical data.
2. Projection of the past trend model up to 2050 and modelling of this projection to obtain a trend model for future evolution.
3. Definition of different scenarios using the simplified projection model

The interest of this method is to separate the modelling of historical data from that of the projection. It provides an accurate model to represent the trend evolution and a simple model to simulate the projection and to define transition breaks.

The difficulty is to select a type of regression model that can represent the evolution of the historical data and that allows projection of the data into the future. Consequently, polynomial models are not considered because of their limits outside the field of study (Sanchez, 2017), and exponential models are preferred.

To perform the first step, three basic exponential models, more or less complex, given in equations (5)–(7), are considered here and compared over the period 2002–2019 due to the anomaly following the attacks of September 11, 2001. For each model, an optimization using the SLSQP method was performed on the coefficients in order to minimize the RMS error between the historical data and the model. Fig. 4 summarizes the models obtained. Model 3 provides the minimum RMS error, by a factor of 4 with respect to model 2 and by a factor of 7 with respect to model 1, which is a fixed decay rate model. Model 3 was therefore selected as the past trend model based on historical data.

$$f_1(x) = f_0(1-\tau)^{x-2002} \tag{5}$$

$$f_2(x) = \frac{f_f}{1-e^{-\varepsilon(x-x_0)}} \tag{6}$$

$$f_3(x) = \frac{\gamma}{\beta\ ln[\alpha(x-x_0)]} \tag{7}$$

with f_0, τ, f_f, ε, x_0, α, β, γ different coefficients. For selected model 3: $\gamma = 2.0$, $\beta = 0.72$, $\alpha = 0.35$, $x_0 = 1990$.

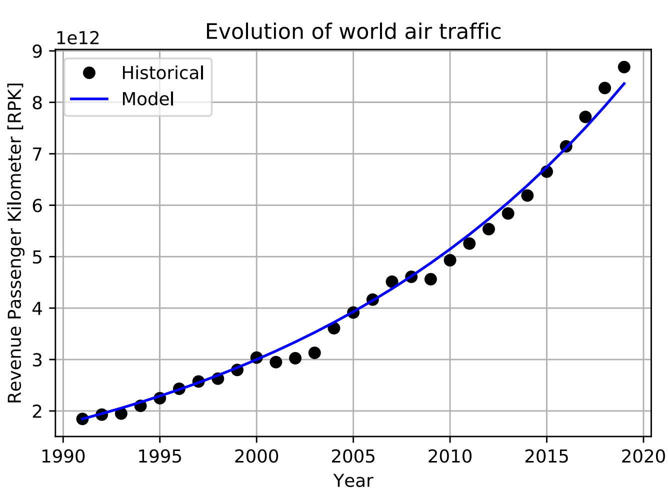

Fig. 3. Model of historical world air traffic.

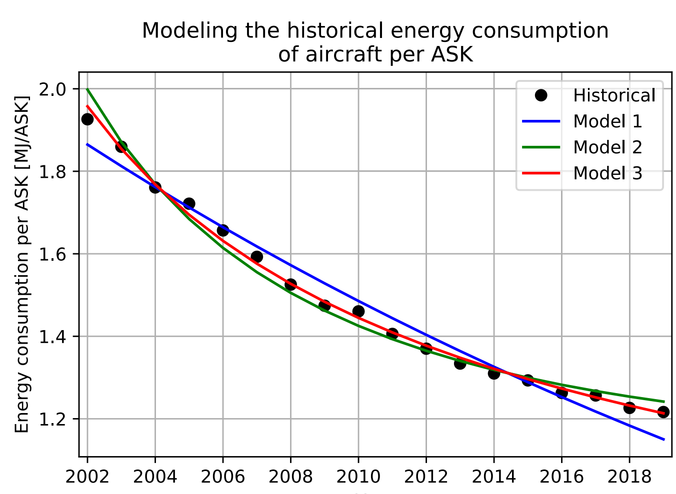

Fig. 4. Models of historical aircraft energy efficiency by ASK.

The second step consists in projecting the past trend model to obtain a trend model for future evolution. The projection of the historical model is represented by a dotted line on Fig. 5. In order to generate different scenarios on the evolution of this lever of action from 2020 to 2050, modelling for this projection is carried out by considering three different models in the same way as before. Fig. 5 shows that the optimizations of these models are very close. Therefore, the simplest model of trend efficiency per seat-kilometer *Ef*, given by equation (8), was selected. It provides simple modelling of the trend to 2050 with only one coefficient τ. If the trend is computed using data projected between 2020 and 2050, τ equals 1.0%.

$$Ef(x) = 1.22\ (1-\tau)^{x-2019}\ [MJ\ /\ ASK] \tag{8}$$

Lastly, the final step consists in defining different scenarios for the future by playing with the parameter τ. τ equals to 0 corresponds to the "Absence" scenario in which energy efficiency remains at the 2019 level. The value of $\tau = 1.0\%$ corresponds to the "Trend" scenario of Fig. 6. Other scenarios can be studied using the model developed in step 2 and different values of τ, extracted from historical data, which reflect more or less ambitious changes. The "Unambitious" scenario corresponds to a rate of 1.5%, which corresponds to the average annual improvements over the last 5 years calculated from historical data. Similarly, the "Ambitious" and "Very ambitious" scenarios correspond to a rate of 2.0% and 2.5%, respectively, which corresponds to the average annual improvements over the last 10 and 15 years. Fig. 6 summarizes the different scenarios considered.

3.2.3. Operations

Energy efficiency per seat-kilometer can also be enhanced by improving flight and ground operations, for instance by optimizing flight paths and designing better infrastructures for aircraft on the ground. This lever of action has been separated from the previous lever to better model these aspects, which are increasingly taken into consideration by the aviation sector. However, available historical data do not give a separate view of operations and efficiency. As a consequence, the model has been constructed considering that, until 2019, improvements in operations are included in efficiency improvements because of the preponderant impacts of engine and airframe improvements.

To overcome the lack of data and to model the evolution of operations, it is proposed to use sigmoid functions which can represent an evolution of implementation until a maximum level is reached. These models are present in many technological, sociological and economic fields (Kucharavy and De Guio, 2011; Jarne et al., 2007). Equation (9) represents the models used in this paper.

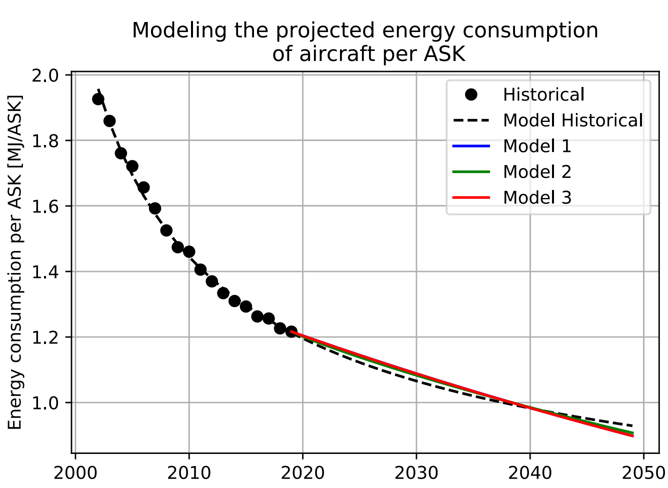

Fig. 5. Models of projected aircraft energy efficiency by ASK.

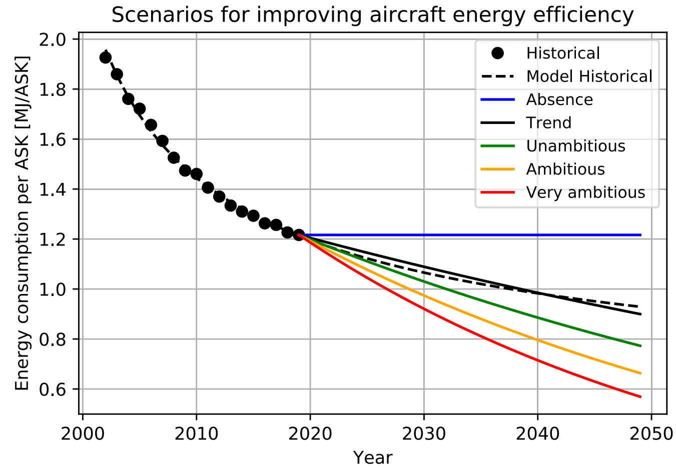

Fig. 6. Scenarios for aircraft energy efficiency by ASK.

$$s(x) = \frac{V_f}{1+e^{-\alpha(x-x_0)}} \tag{9}$$

where s is the sigmoid model, x the year, V_f the final value of the model, α a coefficient to set the speed of change and x_0 the reference year for the inflection.

In the case of operations modelling, sigmoid functions are used to model the effect of specific measures to reduce consumption. The choice of coefficients for the model makes it possible to introduce several scenarios. These scenarios have been established from industrial data from the ATAG Waypoint 2050 report (A. T. A. Group, 2020). For each scenario, it is assumed that $\alpha = 0.2$ and $x_0 = 2030$.

- Absence: no new operations are considered;
- Pessimistic: operational improvements are only marginally implemented and give a 4% reduction in consumption compared to the 2019 values, which means that $V_f = 0.96$;
- Realistic: operational improvements are developing and give an 8% reduction in consumption;
- Optimistic: operational improvements are widespread and give a 12% reduction in consumption;
- Idealistic: improvements in operations are generalized and optimized, giving a 15% reduction in consumption.

3.2.4. Load factor

To model the evolution of the aircraft load factor, an approach similar to that of efficiency is used. Indeed, historical data are available from 1991 (I.C.A. Organization, 2020a) and enable trend models to be produced for describing the behavior of the data observed. The model of the aircraft load factor, based on a sigmoid and given in equation (10) as a function of the year x, is obtained by minimizing the RMS error between the historical data and the model. It is interesting to note that this model converges to an aircraft load factor of about 90%, which is an ambitious value already reached by several airlines.

$$g(x) = 51.3 + \frac{38.7}{1+e^{-0.072(x-2000)}}\ [\%] \tag{10}$$

Sigmoid functions are then also used to model the projections. The aircraft load factor is modelled using equation (11) with α, β, x_0 coefficients. The trend model for projected data is described with coefficients $\alpha = 0.081$, $\beta = 0.15$ and $x_0 = 2030$. Different settings for these coefficients lead to the different scenarios presented in Fig. 7. One of the limits is the jump in value observed in 2020 due to a punctual discontinuity in the chosen modelling function. However, the sigmoid model can reproduce the trend curve well and can be used to modify the rate of change for the aircraft load factor.

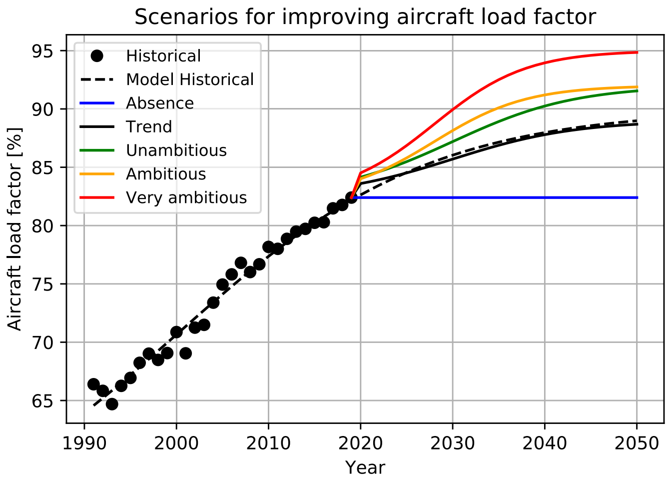

Fig. 7. Scenarios for aircraft mean load factor.

$$LF(x) = 82.4\left(1 + \frac{\alpha}{1 + e^{-\beta(x - x_0)}}\right)\ [\%] \tag{11}$$

3.2.5. Energy

One lever of action concerns the decarbonization of energy, i.e. the reduction of the CO_2 content in the energy used. In the same way as for operations, this lever of action is currently used marginally and modelling using sigmoid functions can be applied.

To estimate the maximum decarbonization rate of biofuels, average values of different production pathways are considered from De Jong et al. (2017). Whereas some of these pathways can lead to emission reductions of over 90% compared to kerosene, the average decarbonization rate of biofuels is 75%, which leads to an emission factor of about 22 gCO_2/MJ. Estimates for hydrogen are comparable, although major challenges remain (Khandelwal et al., 2013). The decarbonization rate of alternative fuels compared to kerosene is therefore assumed to be 75%. However, this value could increase in future years.

The scenarios focus on the proportion of the aircraft fleet that will operate on alternative fuels in the future. The regulatory limits of the incorporation rates of alternative fuels are not taken into account here, as they are expected to be overcome. For these scenarios, only the overall decarbonization rate is modified. The latter can take values between 0% (no aircraft has access to low-carbon fuels) and 75% (the entire fleet has access to low-carbon fuels). The coefficients of equation (9) are set to $\alpha = 0.4$ and $x_0 = 2040$ to obtain trajectories consistent with the industrial data (A. T. A. Group, 2020; I. A. T. Association, 2020b).

However, two limits can be mentioned in this model. On the one hand, unlike drop-in fuels, some alternative fuels such as hydrogen require redesigning aircraft airframes and engines. This could change aircraft energy consumption (Cell and Undertaking, 2020), which is not considered in this paper. On the other hand, these scenarios do not take into account the constraints on the availability of global energy resources.

3.2.6. Non-CO_2 effects

The last major lever of action for reducing aviation's climate impacts concerns the mitigation of non-CO_2 effects. In this paper, only specific strategies against contrails are considered.

Many strategies to prevent the formation of contrails are being considered, both from a technological and an operational point of view (Noppel and Singh, 2007; Gierens et al., 2008). The technological measures mainly considered are the reduction of the quantity and size of emitted particles (Noppel and Singh, 2007). From an operational point of view, modifying the flight altitude for certain atmospheric conditions is studied (Gierens et al., 2008). Quantitative studies have been performed to estimate the potential gains for these strategies. For example, different scenarios are studied in (Teoh et al., (2020)) and lead to contrail reductions between 20% and 91.8%. Similar analyses are also found in (Matthes et al., (2020)).

The impact of alternative fuels on non-CO_2 effects is not considered in this paper. For instance, the use of hydrogen also leads to the formation of contrails, so comparison with conventional fuels is subject to uncertainties (Noppel and Singh, 2007; Marquart et al., 2005).

As with previous models, the modelling of this lever of action is based on the use of sigmoids. The scenarios considered here are extracted from (Teoh et al., (2020)) and are given below. They are based on changes in flight altitude and the use of more efficient combustion chambers, called Dual Annular Combustor (DAC). There is still room for significant improvement in this type of technology.

- Absence: no strategies on contrails;
- Pessimistic: slight changes in altitude, which do not lead to overconsumption, are implemented on conventional engines;
- Realistic: more significant altitude changes, which result in slight overconsumption, are implemented on conventional engines;
- Optimistic: widespread use of improved DAC engines;
- Idealistic: more significant altitude changes, which result in slight overconsumption, are implemented on improved DAC engines.

3.3. Models for climate analysis

To evaluate scenarios for aviation obtained from the models defined above, the concept of carbon budget is introduced and generalized in a simplified way to non-CO_2 effects in this section. The assumptions for allocating carbon budgets are also given and analyses are carried out until 2050.

3.3.1. Carbon budget

A carbon budget is a remaining quota of CO_2 emissions that can still be emitted globally to remain below a chosen limit temperature. This makes it possible to relate the increase in average temperature to the cumulative quantity of CO_2 emissions (W. IPCC, 2013). It is an interesting concept for estimating the impact of greenhouse gases on the average global temperature (Matthews et al., 2009) and is used to study the ability of trajectories to reach climate targets (Friedlingstein et al., 2014).

Several methodologies can be applied to estimate carbon budgets (Matthews et al., 2017), which leads to numerous estimates (Rogelj et al., 2016). These estimates depend for instance on how the non-CO_2 effects are taken into account and on the climate models considered (Matthews et al., 2021). There are uncertainties regarding the value of the Transient Climate Response to cumulative carbon Emissions (TCRE) which is a metric that relates cumulative CO_2 emissions to global mean temperature change (MacDougall, 2016). Carbon budgets are then expressed for different percentiles of TCRE. Table 3 summarizes world carbon budgets estimated by IPCC (Masson-Delmotte et al., 2018). To take Earth system feedback into account, 100 $GtCO_2$ must be subtracted from these budgets.

In this paper, the model used to calculate carbon budgets is given by equation (12) extracted from (Rogelj et al., (2019)). The advantage of this method is that the different terms are clearly specified, especially for non-CO_2 effects. CB represents the carbon budget, T_{lim} the limit temperature rise, $T_{hist} = 0.97°C$ the temperature rise already achieved until

Table 3
Remaining carbon budgets from 01.01.2018 (without Earth system feedback).

Percentiles of TCRE	1.5 °C carbon budget	2 °C carbon budget
33%	840 $GtCO_2$	2030 $GtCO_2$
50%	580 $GtCO_2$	1500 $GtCO_2$
67%	420 $GtCO_2$	1170 $GtCO_2$

a considered year (here 2015), T_{non-CO_2} the temperature rise due to non-CO_2 effects (equal to 0.1 °C for 1.5 °C and to 0.2 °C for 2 °C), T_{ZEC} the zero-emissions commitment (here 0 °C), $TCRE = 0.45°C/TtCO_2$ (for median value) and $ESF = 100\ GtCO_2$ Earth system feedback.

$$CB = \frac{T_{lim} - T_{hist} - T_{non-CO_2} - T_{ZEC}}{TCRE} - ESF \tag{12}$$

IPCC has also taken into account the possible deployment of carbon capture and storage strategies, known as BECCS (Bio-Energy with Carbon Capture and Storage). Four scenarios are defined in (Masson-Delmotte et al., 2018). P1 does not consider BECCS while P2 considers a storage capacity of 151 $GtCO_2$, P3 of 414 $GtCO_2$ and P4 of 1191 $GtCO_2$, all by 2100.

3.3.2. Aviation carbon budget

A corrected carbon budget $CB_{c,2100}$ is defined to take into account BECCS and past emissions. It can be estimated with equation (13) using the carbon budget CB, carbon storage $BECCS$ and past CO_2 emissions $E_{CO_2,past}$ (between the historical year considered for the calculation of BC and today).

$$CB_{c,2100} = CB + BECCS - E_{CO_2,past} \tag{13}$$

This budget is assumed to be consumed by 2100. As a consequence, this budget is equal to the world cumulative CO_2 emissions between now and 2100, which gives equation (14) with $E_{CO_2,k}$ the annual world CO_2 emissions.

$$CB_{c,2100} = \sum_{k=2020}^{2100} E_{CO_2,k} \tag{14}$$

A model with a fixed annual rate of decrease x is selected to compute a reference trajectory for $CB_{c,2100}$. Equation (14) is reformulated with this assumption and gives rise to equation (15) which can be written as the closed-form solution of a geometric series. This equation can then be solved implicitly to determine the annual rate of decrease x.

$$CB_{c,2100} = \sum_{k=2020}^{2100} E_{CO_2,2019}(1-x)^{k-2019} = E_{CO_2,2019}\frac{(1-x) - (1-x)^{82}}{x} \tag{15}$$

To limit the analysis to 2050, x being known, CAST uses equation (16) to compute the corrected world carbon budget until 2050 $CB_{c,2050}$.

$$CB_{c,2050} = E_{CO_2,2019}\frac{(1-x) - (1-x)^{32}}{x} \tag{16}$$

To compute the carbon budget allocated to aviation until 2050 for a target of 1.5 °C or 2 °C, the world carbon budget must be shared. If F is the rate of the carbon budget allocated to aviation, then the corrected carbon budget given to aviation until 2050 is $F.CB_{c,2050}$. F is set by default in CAST to aviation's share of world CO_2 emissions in 2019, i.e. 2.6%, but can be modified. Indeed, the choice of this share results from a political choice. For instance, increasing this share gives more flexibility to aviation to the detriment of other sectors, and conversely.

Applying this methodology with median IPCC values and without BECCS gives world carbon budgets until 2050 of 378 $GtCO_2$ and 865 $GtCO_2$ for 1.5 and 2 °C, respectively. With an allocation of 2.6% for aviation, the aviation carbon budgets are therefore 10.0 $GtCO_2$ and 22.8 $GtCO_2$, respectively.

This aviation carbon budget can be compared to the cumulative CO_2 emissions from aviation between 2020 and 2050.

3.3.3. Aviation equivalent carbon budget

The approach described above is extended to non-CO_2 effects to compute corrected equivalent carbon budgets. Adapting the equations for carbon budgets, a corrected equivalent carbon budget until 2100 $ECB_{c,2100}$ is estimated with equation (17), where $E_{GHG,\ past}$ is the past GHG emissions given in (ONU, 2020). The term T_{non-CO_2} from equation (12), which eliminates non-CO_2 effects in the previous computation, is now deleted to integrate them.

$$ECB_{c,2100} = \frac{T_{lim} - T_{hist}}{TCRE} - ESF + BECCS - E_{GHG,past} \tag{17}$$

The approach to compute the corrected equivalent carbon budget until 2050 $ECB_{c,2050}$ is then the same as before, this time considering annual GHG emissions $E_{GHG,k}$. Equation (18) gives $ECB_{c,2050}$, to which a share F must be allocated for aviation. In this case, F is set by default in CAST to the recent share of aviation in the world ERF, i.e. 5.5% (2005–2011).

$$ECB_{c,2050} = E_{GHG,2019}\frac{(1-x) - (1-x)^{32}}{x} \tag{18}$$

Applying this methodology with median IPCC values, without BECCS and considering an allocation of 5.5%, leads to equivalent carbon budgets for aviation until 2050 of 19.9 $GtCO_2$-*we* and 54.2 $GtCO_2$-*we* for 1.5 and 2 °C, respectively.

This equivalent carbon budget for aviation can be compared with cumulative equivalent CO_2 emissions from aviation between 2020 and 2050.

The climate metric GWP* is used to estimate the (warming) equivalent CO_2 emissions (Allen et al., 2018; Cain et al., 2019; Lynch et al., 2020). In comparison to standard GWPs, it provides a better estimate of the impact of short-lived pollutants on temperatures over a wide range of timescales (Allen et al., 2018). This approach is also used in Lee et al. (2020) to estimate equivalent carbon emissions from aviation. For a given non-CO_2 effect, the model of the annual equivalent CO_2 emissions E_{CO_2-we} is given in equation (19) with ΔF the ERF change (smoothed over 5 years) of the non-CO_2 effect over a period $\Delta t = 20$ *years*, $H = 100$ *years* the time horizon and $AGWP_H = 88$ *year* $mW/m^2/GtCO_2$ the absolute global warming potential of CO_2 over 100 years. The different assumptions are derived from Allen et al. (2018) and Lee et al. (2020). It is interesting to note that this value, expressed in $GtCO_2$-*we*, can be negative depending on the evolution of the non-CO_2 effect. Using this annual rate of equivalent CO_2 emissions computed for all non-CO_2 effects and the annual rate of CO_2 emissions, cumulative equivalent CO_2 emissions from aviation between 2020 and 2050 are estimated.

$$E_{CO_2-we} = \frac{\Delta F}{\Delta t}\frac{H}{AGWP_H} \tag{19}$$

4. Results and discussion

In this part, CAST is used on some scenarios in order to check their compatibility with the objectives of the Paris Agreement in terms of CO_2 emissions or CO_2-*we* emissions (including non-CO_2 effects). First, the ATAG commitments proposed by aviation stakeholders are analyzed using CAST. Then, various illustrative scenarios are developed by selecting a set of levers of action and assessed with respect to the 2019 situation to highlight the potential for decreasing aviation's climate impact.

4.1. Analysis of ATAG commitments

A study was carried out on ATAG commitments to detail the methodology for analyzing a scenario using CAST. The objectives of these commitments are to stabilize carbon emissions from 2020 with carbon-neutral growth and to reduce emissions by 50% relative to 2005 levels by 2050. For the analysis, BECCS were not considered and the IPCC carbon budgets with a 50% probability of remaining below the targeted temperature increase (1.5 °C or 2 °C) were taken into account.

A modelling of ATAG commitments of 2009 is shown in Fig. 8, representing the trajectory of global CO_2 emissions for aviation. In this scenario, a 4.5% annual growth in RPK air traffic is considered as well as a 1.5% annual improvement in fuel efficiency (yellow part) and an

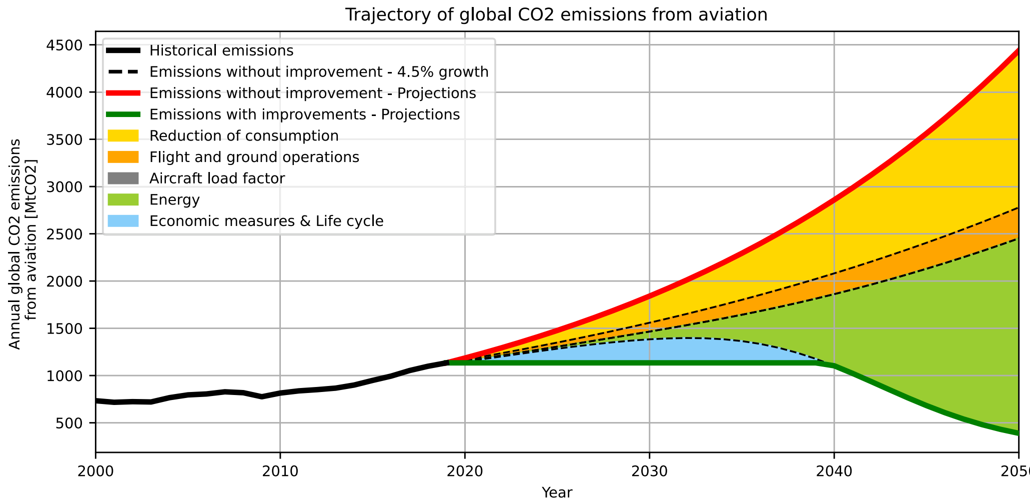

Fig. 8. Modelling of 2009 ATAG commitments.

optimistic improvement in operations (orange part). The evolution of the load factor is not considered and its value is therefore that of 2019. Concerning the energy decarbonization, using the models developed in the article, a final decarbonization rate of 93% for alternative fuels is necessary to obtain the trajectory defined by ATAG (green part). It is interesting to note that this value is much higher than the 75% decarbonization rate estimated to be achievable for biofuels or hydrogen. Lastly, to cushion the transition, economic carbon offsetting measures are being put in place to compensate for CO_2 emissions above the 2019 level (blue part).

The analysis of this scenario shows that the cumulative global emissions of CO_2 for aviation until 2050 are equal to 30.5 $GtCO_2$. As stated before, the world carbon budgets until 2050 for 1.5 °C and for 2 °C are equal to 378 $GtCO_2$ and 865 $GtCO_2$, respectively. Therefore, considering this scenario, aviation would consume 8.1% of the world carbon budget for 1.5 °C and 3.5% of the world carbon budget for 2 °C until 2050. Since aviation accounted for 2.6% of global CO_2 emissions in 2019, it would consume more than this share in this scenario.

Air traffic was severely disrupted in 2020 due to Covid-19 and will be impacted for years to come. ATAG has updated its commitments to take into account the impacts of Covid-19. The return of air traffic to the 2019 level is only envisaged for 2024 and the annual growth rate for the following years is estimated at 3.0%. To model this update in CAST, the forecasts for improvements in energy efficiency and operations are kept to the 2009 commitments. The final decarbonization rate obtained is decreased to 78%, which is which is close to the expected value of 75%.

Using the same type of analysis as for the ATAG commitments of 2009, the cumulative global emissions of CO_2 until 2050 are about 24.7 $GtCO_2$, which corresponds to 6.5% of the world carbon budget for 1.5 °C and 2.9% of the world carbon budget for 2 °C until 2050. In the same way as for the previous scenario, aviation would consume more than the 2.6% share in this scenario.

In terms of equivalent carbon budget, the ATAG commitments of 2020 result in cumulative global equivalent emissions of CO_2 until 2050 of 96.7 $GtCO_2$-we. In this scenario, aviation would consume 26.8% and 9.9% of the world equivalent carbon budgets in 2050 for 1.5 °C and 2 °C, respectively. Since aviation accounts for 5.5% of recent global ERF (2005–2011), this scenario would consume more than this share. This large budget overshoot is especially due to the fact that the impact of contrails, which represents more than half of aviation's climate impacts, is not mitigated in the ATAG commitments. However, the possible impact of alternative fuels on non-CO_2 effects has not been considered.

4.2. *Simulation and analysis of three illustrative scenarios*

The objective of this part is to use CAST to simulate and analyze illustrative scenarios. For all these case studies, BECCS are not considered and the IPCC carbon budgets with a 50% probability of remaining below the temperature targets are taken into account. The studies carried out for these scenarios are limited to fixed allocated shares for aviation that correspond to current impacts, i.e. 2.6% for global CO_2 emissions and 5.5% for the equivalent carbon budget (including non-CO_2 effects).

4.2.1. *Presentation of illustrative scenarios*

Three illustrative scenarios are defined according to different levels of technological development. The settings for these scenarios are based on the models for the levers of action in Section 3.

1. *Trend scenario for aircraft efficiency and load factor considering a kerosene-fueled fleet without new operations*: Trend scenarios are considered for the evolution of aircraft energy consumption (1% annual improvement) and load factor. Improvements in operations are not considered. Moreover, it is assumed that only kerosene continues to be used as aircraft fuel. Using these assumptions, the global CO_2 emissions per RPK would be 89 gCO_2/RPK in 2050.
2. *Trend scenario for aircraft efficiency and load factor including low-carbon fuels and new operations*: Trend scenarios are considered for the evolution of aircraft energy consumption (1% annual improvement) and load factor. For operations, a realistic improvement is taken into account, in accordance with the models in the previous section. Moreover, a transition to low-carbon fuels (75% reduction compared to kerosene) for half of the fleet by 2050 is considered. This corresponds in the models to total energy decarbonization for of 37.5% the entire fleet. Using these assumptions, the global CO_2 emissions per RPK would be 52 gCO_2/RPK in 2050.
3. *Technology-based scenario*: Technologies are pushed forward with optimistic assumptions. First, the annual rate of improvement in aircraft fuel efficiency is 1.5%, which corresponds to the average value for the last 5 years. Next, it is assumed that the entire fleet will be able to be fueled by alternative low-carbon fuels (75% reduction compared to kerosene) by 2050. Using these assumptions, the global CO_2 emissions per RPK would be 17 gCO_2/RPK in 2050. In comparison, this scenario is more ambitious than the ATAG commitments.

The level of air traffic, modelled using the annual growth rate of RPK,

Table 4
Results for the analysis of illustrative scenarios in terms of carbon budgets.

Scenario description	Illustrative scenario 1	Illustrative scenario 2	Illustrative scenario 3
	Trend scenario excluding low-carbon fuel	Trend scenario including low-carbon fuel	Technology-based scenario
CO_2 emissions per RPK in 2050	89 gCO_2/RPK	52 gCO_2/RPK	17 gCO_2/RPK
Share of the 1.5 °C world carbon budget consumed for a 3% growth rate	10.2%	8.2%	6.0%
Share of the 2 °C world carbon budget consumed for a 3% growth rate	4.5%	3.6%	2.6%
Annual air traffic growth rate to comply with a 2.6% share for aviation for 2 °C	−1.8%	−0.1%	2.9%

is considered variable in these scenarios. Three distinct cases are studied: estimated trend of traffic growth before Covid-19 (4.5%), estimated trend of traffic growth after Covid-19 (3%) and traffic necessary to equal the carbon budget for 2 °C. The effects of Covid-19 are included in the last three cases for the level of traffic.

4.2.2. *Analysis for CO_2 emissions*

In this section, illustrative scenarios are analyzed in terms of CO_2 emissions and carbon budgets. Table 4 summarizes the main results.

Firstly, the analysis is done for the trend scenario excluding low-carbon energy. With the estimated growth of air traffic before Covid-19, cumulative CO_2 emissions amount to 60.0 $GtCO_2$. This largely exceeds the carbon budgets allocated to aviation for 1.5 °C and 2 °C, which are respectively 10.0 $GtCO_2$ and 22.8 $GtCO_2$. Similarly, considering the projections after the Covid-19 crisis, cumulative CO_2 emissions are equal to 38.8 $GtCO_2$, which also exceeds the carbon budgets allocated to aviation and correspond to 4.5% of the 2 °C world carbon budget for 2050. Air traffic growth projections must therefore be reduced in order to respect a trajectory compatible with the Paris Agreement for this scenario with an allocated share of 2.6%. To respect 2 °C carbon budget, air traffic must be reduced by 1.8% per year in the trend scenario excluding low-carbon energy.

Secondly, the same methodology is applied to the trend scenario including low-carbon energy. This scenario leads to cumulative CO_2 emissions of 47.3 $GtCO_2$ for a RPK growth of 4.5% and 31.1 $GtCO_2$ for a RPK growth of 3%, which also exceeds the carbon budgets allocated to aviation. However, the carbon budget for 2 °C is respected considering a small annual decrease of 0.1% in air traffic. This represents a 3% reduction in air traffic by 2050. The latter scenario is shown in Fig. 9.

Thirdly, the approach is used for analyzing the technology-based scenario. This scenario leads to cumulative CO_2 emissions of 33.8 $GtCO_2$ for an annual RPK growth of 4.5%, which exceeds the budgets. However, the carbon budget for 2 °C can be respected considering an annual RPK growth of 2.9%, which allows an increase in air traffic close to the trend in RPK growth after Covid-19.

Lastly, for 1.5 °C, all illustrative scenarios lead to a drastic decrease in annual air traffic, at least 7% for the most ambitious scenario, if the allocated share for aviation is kept at the 2019 level.

4.2.3. *Analysis for CO_2-we emissions*

In this part, illustrative scenarios are analyzed in terms of equivalent carbon budgets, including non-CO_2 effects.

The three illustrative scenarios, set with a traffic level compatible with a +2 °C trajectory, result in equivalent cumulative emissions ranging from 26.8 $GtCO_2$-*we* (scenario 1) to 91.3 $GtCO_2$-*we* (scenario 3). Without even mitigating non-CO_2 effects, illustrative scenario 1 would be compatible with a +2 °C trajectory due to the decrease in air traffic which reduces the ERF of aviation and thus its equivalent emissions. However, illustrative scenario 3 would consume 9.3% of the world equivalent carbon budget in 2050.

Illustrative scenario 3 can be made compatible with a +2 °C trajectory by generalizing significant altitude changes, which reduces contrail formation by around 60%. In this case, this scenario would consume 27.0 $GtCO_2$-*we* (Fig. 10), i.e. 2.7% of the world equivalent carbon budget. For illustrative scenario 1, this measure would even reduce the climate impact of aviation by decreasing ERF, which corresponds to negative cumulative equivalent CO_2 emissions of −2.4 $GtCO_2$-*we*.

This result shows the importance of integrating strategies against contrails in the future. In this case, the restrictive budget is not the

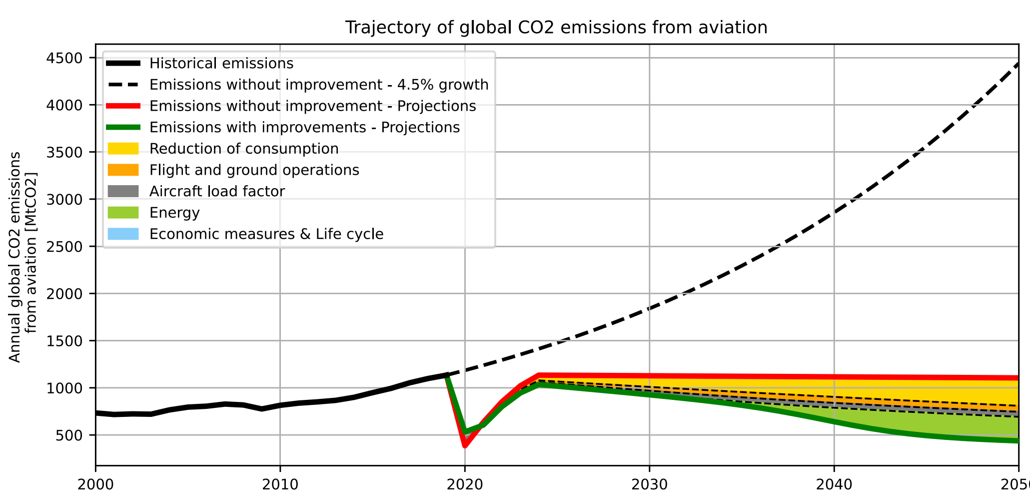

Fig. 9. Annual CO_2 emissions for the trend scenario including low-carbon energy with an annual decrease of 0.1% in air traffic.

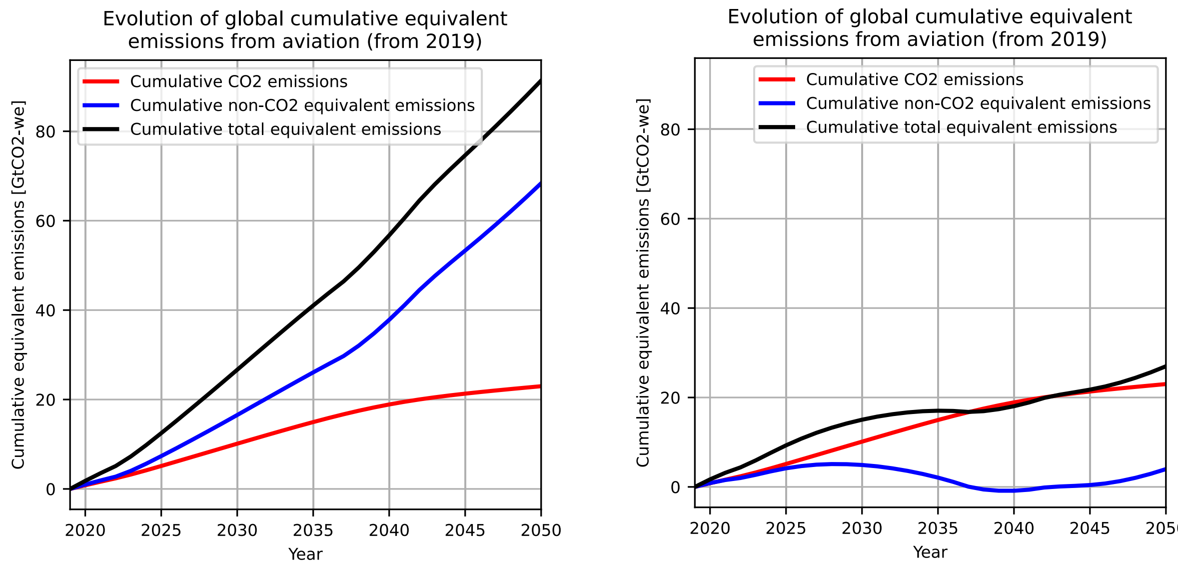

Fig. 10. Cumulative equivalent CO_2 emissions from aviation for illustrative scenario 3 (left) and for illustrative scenario 3 including strategies against contrails (right).

equivalent carbon budget (including non-CO_2 effects), but rather the carbon budget. However, even if the equivalent carbon budget is met, ambitious CO_2 emission strategies are still needed to limit long-term temperature (Lynch et al., 2020).

5. Conclusions and future work

In this paper, the methodology and models used to develop the CAST tool for simulating and assessing climatic scenarios for the aviation industry are presented. This tool is used to simulate scenarios concerning the future climate impacts of aviation, and to assess their compatibility with the Paris Agreement.

Regarding the methodology and the models, two main themes are addressed. Firstly, the evolution of aviation is modelled via different levers of action, such as the levels of air traffic, fuel consumption efficiency and use of low-carbon fuel, that are linked via an adapted Kaya-type equation. Several strategies are used to model these different levers of action. For those with historical data, deterministic models are developed to define trend scenarios. For the others, hypotheses from the scientific literature are taken into account and projections are made. Different assumptions are considered in order to establish multiple scenarios. Secondly, climate models are used both to assess the compatibility of the trajectories with the Paris Agreement but also to estimate aviation's climate impact. The evaluation of the scenarios is based on the concept of carbon budgets. In addition to CO_2 emissions, non-CO_2 effects are considered using aggregated models from the scientific literature to estimate the impacts in terms of ERF. The concept of carbon budget is extended to non-CO_2 effects and the equivalent CO_2 emissions are estimated using GWP*, a climate metric used to equate these effects with CO_2 emissions.

As examples, several scenarios are assessed with CAST. First of all, the ATAG commitments are modelled and compared with trajectories compatible with the Paris Climate Agreement. The most recent ATAG commitments would result in a consumption of 2.9% and 6.5% of the world carbon budgets for limiting the temperature increase to 2 °C and 1.5 °C, respectively. This represents more than the 2.6% share of global CO_2 emissions from aviation in 2019. Note that, non-CO_2 effects are not taken into account in these commitments, even though they currently account for about 2/3 of the global ERF of aviation. Then, different scenarios are simulated to take into account different levels of technological improvements. Regarding the compatibility of these scenarios with the Paris Agreement with the 2 °C target for CO_2 emissions and considering a 2.6% share for the allocated carbon budget, the evolution of world air traffic is expected to be between an annual traffic decrease of 1.8% (trend scenario without new fuels) and an annual growth of 2.9% (ambitious scenario including low-carbon fuels). However, air traffic would have decrease drastically to be compatible with a +1.5 °C trajectory, with an annual decrease of more than 7%. Lastly, additional studies on non-CO_2 effects show the importance of implementing specific strategies to refine scenarios for aviation.

Although CAST is already a mature tool for simulating and assessing climate scenarios, there are still some limitations to making a full analysis of the scenarios. First, regarding the decarbonization of alternative fuels, constraints on the availability of energy resources (land available for biofuels, low-carbon electricity available for hydrogen production) are not addressed. These aspects will be taken into account in a future version of CAST. Second, some models represent the future evolution in a simplified way. For instance, the different scenarios considered for the evolution of the different levers of action are projected models taking into account current trends and knowledge. A better link between these projections and the future technologies envisaged will be implemented in a future version of CAST using a bottom-up approach. This would provide more accurate modelling of the impacts of technologies and fleet renewal. Subsequently, modelling for other strategies to mitigate non-CO_2 effects is envisaged, as well as the impact of alternative fuels on the latter. Lastly, for most of the scenarios studied, climate constraints are based on an allocated share corresponding to the current aviation's impacts. This share could be determined by coupling these studies with social-economic parameters in order to make trade-offs regarding the distribution of carbon budgets.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary material

CAST is available at: https://cast.isae-supaero.fr/, https://nam03.safelinks.protection.outlook.com/?url=https%3A%2F%2Fcast.isae-supaero.fr%2F&data=04%7C01%7CA.Achuthan%40elsevier.com%7Cb6ec3e8ea2db4876de4108d92f1e1aa7%7C9274ee3f94254109a27f9fb15c10675d%7C0%7C0%7C637592630140802224%7CUnknown%7CTWFpbGZsb3d8eyJWIjoiMC4wLjAwMDAiLCJQIjoiV2luMzIiLCJBTiI6Ik1haWwiLCJXVCI6Mn0%3D%7C1000&sdata=n9RuPNYyLRipBTQ%2BePJkoBkkqFAQcda2kpFB72zBEIo%3D&reserved=0.

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