Calculating the Greenhouse Gas Emissions of Flights: A Comparative Study of Existing Protocols

N Iken¹ and F-X Aguessy²

¹ R&D Manager, the Treep, Paris, France
² Innovation Manager, the Treep, Paris, France
E-mail: nabila.iken@thetreep.com

Abstract. To better understand the climate issues associated with aviation, several protocols for assessing greenhouse gas emissions from flights have been developed by various organisations. This multiplicity leads to variable and inconsistent results from one method to another. Yet few comparative studies exist in the grey and academic literature to highlight and understand this variability. This paper focuses on 6 calculation protocols (myclimate, atmosfair, and ICAO among others) and compares the methodological choices of each of them to partly explain the variability of results. We found that for most of the parameters that influence the outcomes, the 6 protocols all have different methodological choices, some of which (such as those of ICAO and DGAC) lead to underestimation of CO₂ emissions. We conclude that the most appropriate protocol depends on the purpose of the calculation (carbon offsetting, comparison of different modes of transport or influence on travel behaviour).

1. Introduction
The climate impact of air traffic is at the heart of many discussions in the political, industrial, and scientific spheres. Indeed, CO₂ emissions due to burning fuels for aviation contributed to 2.4 % of global carbon dioxide emissions in 2018 [1]. This contribution is even higher if other greenhouse gases are considered: it was estimated at 3.5 % in 2011 (Ibid).

Furthermore, air traffic has fallen sharply due to COVID-19 pandemic: according to Eurocontrol, the European air traffic decreased by 57 % between 2019 and 2021. However, estimates predict that it will return to its 2019 level during 2023 and will continue to grow [2]. The same trend is expected for global air traffic, which should be restored during 2024 according to IATA [3]. Given the Paris Agreements that entail planetary carbon neutrality in the second half of the century, this raises the need to better understand the scale of air traffic greenhouse gases (GHG) emissions, using robust and internationally recognised methods. To this end, several GHG emissions calculation protocols – with different assumptions and outcomes – have been developed, whether by governmental or international institutions, offsetting companies, or other organisations such as NGOs and foundations. Indeed, these assessment tools are needed for environmental reporting of organisations, but also for individuals who wish to assess, reduce, or offset their own emissions.

Nevertheless, the multiplicity of assessment protocols led to a high variability of results. While variability and lack of standardisation is a classic problem in environmental assessment, it is even more exacerbated for the aviation sector. Indeed, aviation entails complex physical and chemical processes and involves non-CO₂ effects, which makes challenging their aggregation to assess climate impact and leaves much uncertainty.

And yet, there have been few comparative studies that highlight and explain the existing variability between the outcomes of these different methods, particularly in recent years. Jardine for example
conducted a comparative study on 4 assessment methods (DEFRA, ICAO, ClimateCare, SABRE Holdings), but the age of the study (2009) makes it impossible to see the updates of the latter [4]. Moreover, it does not include two of the most used carbon offsetting organisations’ protocols: those of myclimate and atmosfair. Same observation for the study conducted in 2008 by Kollmuss and Lane, which compares 3 CO2 calculation protocols (atmosfair, TRX Travel Analytics, and Virgin Atlantic) and supplements the documentation-based data with interviews with the organisations concerned [5].

More recently, Barret highlighted the variability of the results of different protocols (DEFRA, ICAO, myclimate, atmosfair, French Ministry of Ecology, and KLM) and compared them according to some parameters such as consideration of non-CO2 effects or seating configuration [6]. However, his study does not go into detail about the parameters used by each protocol. Indeed, the aim of the study was rather to combine the different protocols into one tool (intended for the calculation of GHG emissions from academic conferences). In addition, this study does not include the protocol of the French Civil Aviation Department (DGAC), which is a reference in flight CO2 calculation in France [7] and does not suggest a way to select a method for more varied uses.

To help fill this gap, we analyse in this paper 6 flight CO2 assessment protocols that were developed by different organisations. Indeed, our study explores a range of parameters that influence total emissions with the most recent information published by each protocol. The aim is to understand what factors influence the GHG emissions of flights, but also the underlying assumptions of protocols and their methodological choices to explain (partly) the gaps between the results and provide insights into the process of selecting the most appropriate method for the intended use.

2. Method

In this study, we analyse 6 publicly available CO2 assessment protocols for flights, which were developed by the following institutions:

- The International Civil Aviation Organization (ICAO): the organisation provides one of the most used on-line carbon calculators, and a description of its main assumptions in a methodological document [8] of which the 11th version was published in 2018. The ICAO methodology is used for example by the global distribution system (GDS) AMADEUS.

- myclimate: the Swiss carbon offsetting foundation provides an online calculator available on its website, as well as an associated methodological document [9]. In this document, myclimate describes the equation on which the calculation tool is based, but also each parameter used. This calculator is used by the airline Lufthansa for example [10].

- atmosfair: specialising in carbon offsetting, this German NGO proposes a detailed online GHG calculation tool. The main assumptions are exposed in a short methodology document available on the website [11], but have more detailed technical documents available on request. They also propose a business solution co-developed with the German business travel association VDR, used by KAYAK for example.

- The UK Government Greenhouse Gas Conversion factors for Company Reporting: the UK Department for Business, Energy, and Industrial Strategy (DBEIS) proposes a set of emission factors for business reporting, also used in different policies [12]. This database is publicly available and can be downloaded on the government website [13].

- The French Department for civil aviation (DGAC): this institution provides an online CO2 calculator called TARMAAC [14], co-developed with the French centre for the study of atmospheric pollution (CITEPA). The tool’s website contains some information on methodological assumptions, but the DGAC does not provide more detailed technical documentation. It should be noted that this calculator only supports flights from France.

- The French Agency for the environment and energy management (ADEME): this organisation has built a database called Base Carbone® which gathers greenhouse gases emission factors for different activities, including air passenger transport. It provides mean emission factors according to flight distance or aircraft capacity. Moreover, ADEME partly bases its calculation on the DGAC CO2 calculator, which is mentioned in its methodological documentation [15].
This selection was not based on a systematic and exhaustive literature review. Indeed, there are many other assessment protocols that were not included. For example, those of airlines such as Air France [16] or Scandinavian Airlines System (SAS) [17], but also those of other GDS such as SABRE. We have retained protocols that are publicly available, free of charge, and that provide a minimum of detail on their methodology. Moreover, the protocols selected are among the most used, especially in France. Input and output parameters of each protocol studied are summarised in table 1.

Table 1. Input and output data of protocols studied (✓ means required; ~ means optional).

| Protocol          | ICAO | myclimate | atmosfair | DBEIS | DGAC | ADEME |
|-------------------|------|-----------|-----------|-------|------|-------|
| **Input parameter** |      |           |           |       |      |       |
| City pair         | ✓    | ✓         | ✓         | ✓     |      |       |
| Round trip or one way | ✓    | ✓         | ✓         |       |      |       |
| Aircraft type     | ✓    | ✓         | ✓         |       |      |       |
| Scheduled or charter | ✓    | ✓         | ✓         |       |      |       |
| Seat class        | ✓    | ✓         | ✓         |       |      |       |
| Number of flights | ✓    | ✓         | ✓         |       |      |       |
| Number of passengers | ✓    | ✓         | ✓         |       |      |       |
| Stop over         | ✓    | ✓         | ✓         |       |      |       |
| Plane capacity    | ✓    | ✓         | ✓         |       |      |       |
| Distance          | ✓    | ✓         | ✓         |       |      | ✓     |
| **Output parameter** |      |           |           |       |      |       |
| Distance          | ✓    | ✓         | ✓         |       |      | ✓     |
| Fuel burn         | ✓    | ✓         | ✓         |       |      | ✓     |
| Emissions with RFI | ✓    | ✓         | ✓         |       |      | ✓     |
| Emissions without RFI | ✓    | ✓         | ✓         |       |      | ✓     |
| Aircraft          | ✓    | ✓         | ✓         |       |      | ✓     |

3. Results

3.1. The determinants of CO2 emissions per passenger

The CO2 emissions calculation protocols are based on the same principles. The basic input data are mainly the departure and arrival points, the number of passengers, and the type of flight (one way or round trip). Some protocols such as myclimate propose to specify the flight class (economy or premium), and others such as atmosfair allow to specify the aircraft, but also whether the flight is scheduled or charter. In all cases, external data such as fuel consumption or mass of cargo transported must be used. The CO2 emissions per passenger are then calculated according to the distance travelled, considering the share of emissions allocated to the cargo.

In the following subsections, we introduce each parameter and the methodological choices associated with each calculation protocol where possible, based on their methodology documents.

3.1.1. Flight distance

The Great Circle Distance (GCD) between the origin and the destination points (also called orthodromic distance) can be calculated through the latitude and longitude of each airport. But it does not represent the actual distance travelled, because of the deviations, the holding patterns, and inefficiencies in the air traffic control systems. For this reason, some methods consider a distance correction factor (see table 2).
Moreover, some protocols (such as ADEME, DBEIS or myclimate) associate the emissions factors with distance categories such as short-haul, medium-haul and long-haul. However, there is no international standard definition for these different distance categories. Table 3 shows this variability in the distance categories. The DGAC, the ICAO and atmosfair, on the other hand, do not use this concept in their tools.

### Table 3. Short-haul, medium-haul and long-haul distance categories.

| Protocol   | ICAO | myclimate | atmosfair | DBEIS       | DGAC       | ADEME       |
|------------|------|-----------|-----------|-------------|------------|-------------|
| Short-haul distance | /     | <1500km   | /         | <3700km     | /          | <1000km     |
| Medium-haul distance | /     | /         | /         | /           | /          | 1000-3500 km|
| Long-haul distance   | /     | >2500km   | /         | >3700km     | /          | >3500km     |

3.1.2. Fuel consumption

The calculation of the distance (based on origin and destination airports) allows to determine the aircraft type – or a representative aircraft type – and to deduce the fuel burn. Indeed, the fuel consumption of flights depends on numerous parameters such as the aircraft and the engine type – knowing that the same aircraft can be equipped with different types of engines –, but also other parameters that are more difficult to predict, like the setting of the thrust according to the aircraft's fill rate, the weather, etc. In addition, the fuel consumption during the LTO (landing and take-off) phase does not depend on the distance. That explains why the specific fuel consumption of short-haul flights is bigger than that of medium or long-haul flights, and why fuel consumption of aircraft is not a linear function of distance as it might be for trains or cars [4] (see figure 1). This highlights the limitations of methods based on average emission factors (such as ADEME and DBEIS), which therefore model total emissions as a linear function of distance in the form $y=ax$ over a distance range (see table 3).

![Exemple of fuel consumption of some aircrafts (ICAO 2016 data)](image)

**Figure 1.** Fuel consumption of different aircraft (based on ICAO 2016 data).

myclimate proposes instead an interpolation of fuel consumption in the form $f(x) + LTO = ax^2 + bx + c$, based on EMEP/EEA air pollutant emission inventory guidebook [18], where $a$, $b$ and $c$ are different constants depending on whether it is a short or long-haul flight [9]. The DGAC also mentions
the use of the EMEP inventory method, in addition to ICAO data and real data. As mentioned earlier, its results serve as a basis for ADEME protocol.

To calculate fuel consumption, ICAO starts with data published by aircraft manufacturers, then corrects these data based on available in-service fuel consumption data [8]. atmosfair uses the Piano-x software to calculate the fuel consumption of a specific aircraft. Indeed, the NGO considers 121 different aircraft models and the corresponding variations, which covers 97% of the market [11]. It should be noted that atmosfair also considers the influence of winglets (or wingtips) on fuel consumption. Indeed, these are devices that reduce drag, and thus fuel burn by up to 3% according to the NGO. But not all aircraft can be fitted with winglets, and it is not always possible to distinguish between those that are and those that are not fitted within the same model. Therefore, atmosfair uses a "winglet rate" factor in its equation.

Once fuel consumption is estimated, it is then converted into CO2 emissions through the emission factor of the fuel, which is chemical constant. While most protocols (such as DGAC and ICAO) use an emission factor of 3.16 kgCO2/kg which only covers fuel burn GHG emissions, some protocols (such as DBEIS and myclimate), also consider the upstream emissions due to the production (extraction, transformation, transport, etc.) of the fuel – so called well to tank emissions –, which is indicated by a different emissions factor (see table 4).

**Table 4.** Emissions factor of jet A1 fuel (kgCO2-equivalent per kg fuel). Source: ADEME, 2018.

| Emissions covered | CO2  | CH4   | N2O | Total |
|-------------------|------|-------|-----|-------|
| Upstream          | 0.601| 0.0642| 0   | 0.665 |
| Downstream        | 3.15 | 3.96E-03| 7.02E-03 | 3.16 |
| Total             | 3.751| 0.06816| 0.00702 | 3.825 |

### 3.1.3. Allocation between freight and passengers

Because most flights also transport cargo, part of the CO2 emissions from flights is due to the mass of the freight transported. This raises the question of the distribution of emissions between passengers and cargo, which gives rise to different allocation options according to DBEIS [12]:

- **Option 1**: No allocation. From this point of view, all the emissions are allocated to the passengers, because it is considered that passengers are the main reason why aircraft fly.
- **Option 2**: Allocation based on freight and passengers’ weight.
- **Option 3**: Same as option 2, but by considering the weight of passengers’ specific on-board equipment such as seats and galleys as well.

The protocols do not always state clearly which allocation method they use. But based on the reported passenger equivalent masses, most seem to use allocation option 2. For example, DGAC, ADEME, and myclimate attribute a mass of 100kg to each passenger, which is an IATA standard. While ICAO (as well as DBEIS) uses the allocation option 3 and assigns a mass of 150kg to each passenger (100kg for the passenger and his luggage, 50kg for the on-board equipment associated with him). atmosfair assigns a specific value to each airline but does not specify whether the allocation between passengers and cargo is based on the weight of passengers only or of on-board equipment as well.

Moreover, the breakdown between cargo and passengers is based on statistical data from airlines, which also gives access to another data: the occupancy rate. Indeed, this indicator (also called Passenger Load Factor, or PLF) measures the percentage of available seats that have been occupied by passengers. myclimate uses an average PLF of 82% for generic flights derived from ICAO data, regardless of aircraft type and flight distance. DGAC uses its own statistical data on commercial flights, and DBEIS uses detailed UK Civil Aviation Authority statistics for UK registered airlines and considers different PLF according to the aircraft and the type of flight (domestic, short-haul, long-haul or international). This makes these two protocols more specific to France and the UK respectively. Finally, as for the cargo, atmosfair considers specific airlines PLF.
3.1.4. Seating class
In addition to the occupancy rate, seating configuration is also a factor affecting total emissions. Indeed, premium seats occupy much more space in the aircraft than economy seats and therefore reduce the total number of passengers that can be carried, which increases the average CO2 emissions per passenger-km. According to DBEIS, there is no agreed methodology for determining suitable scaling factors that are representative of average flights [12]. Therefore, different seat class factors are used by the assessment protocols (see figure 2). It should be noted that ICAO considers only 2 seating classes (economy and premium). Moreover, this factor is applied for flights of more than 3000km, and only for flights that support the differentiation economy versus premium [8]. On the other hand, the ADEME and DGAC protocols do not mention a seating class adjustment factor in their methodological documents or in their tools.

![Multiplication factor versus economic class](image)

**Figure 2.** multiplication factors to account for premium seating classes.

3.1.5. Accounting for non-CO2 effects
When emissions occur in high altitude, this induces specific effects which lead to a higher contribution of aviation to global warming than just the emission of CO2 from burning fuels. To take this into account, the IPCC introduced an index in 1999 to assess the role of aviation in climate change: the radiative forcing index (RFI). It represents the ratio of total radiative forcing (including direct emissions and indirect atmospheric responses) to that of CO2 emissions alone. The IPCC had initially estimated this factor to be between 2.2 and 3.4 [19], but more recent studies range from an RFI of 1 to 2.7 for the total CO2 emissions of the aircraft, to an RFI of 1 to 8.5 only for emissions in the higher atmosphere [20]. An RFI of 2 is recommended based on recent scientific publications (Ibid). Figure 3 shows the RFI used by each protocol studied. It appears that non-CO2 effects are ignored by the DGAC and ICAO protocols, that the ADEME, myclimate and DBEIS protocols apply an RFI to all CO2 emissions of flights, while atmosfair considers an RFI of 3 only for emissions that occur at an altitude above 9km.

![Radiative forcing index (RFI) used by each protocol](image)

**Figure 3.** Radiative forcing index (RFI) used by each protocol.
3.1.6. Accounting for upstream GHG emissions

As well as upstream emissions from fuel production, it is also possible to consider upstream emissions associated with the production of aircraft and infrastructure (airports). Of all the protocols studied, only myclimate considers the production phase, which makes it a method that covers a larger part of the aircraft life cycle. To account for aircraft production, a factor which attributes emissions to the total number of kilometres travelled is added to the calculation formula [9]. Moreover, a factor of 11.68kgCO2 from a life cycle inventory study of transport services [21] is also considered to account for infrastructure.

3.2. Synthesis and comparison of protocols

This section compares the 6 protocols studied regarding different parameters reported in table 5.

Table 5. comparative table of protocols studied.

|                           | ICAO         | myclimate    | DBEIS        | atmosfair    | DGAC         | ADEME        |
|---------------------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Emissions model (Where x is the distance) | $y=ax+b$     | $y=ax+bx+c$  | $y=ax$       | $y=ax+b$     | Not specified| Not specified|
| Passenger Load factor     | 65 to 84.9%  | 82%          | 52.6 to 73.8%| Depending on route group and aircraft | Not specified| Not specified|
| Short-haul; business class adjustment | 1            | 1.3          | 1.5          | 1.9          | /            | /            |
| Long-haul; business class adjustment | 2            | 1.9          | 2.9          | 1.9          | /            | /            |
| Short-haul; first class adjustment | 1            | 2.5          | 1.5          | 2.6          | /            | /            |
| Long-haul; first class adjustment | 2            | 3            | 4            | 2.6          | /            | /            |
| GCD correction            | +50 to 125 km| +95km        | +50km        | 8%           | 0            | 0            |
| RFI                       | 1            | 2            | 1.9          | 3 above 9km  | 1            | 2            |

Figure 4 shows examples of calculation results for the studied protocols and for different flight distances. It suggests that the gap between the results widens as the flight distance increases. This is partly due to the altitude dependent RFI used by atmosfair. For the flight OLY-NCE (694km) for example, the difference factor between atmosfair’s and ICAO’s results is approximately 2, while it rises to 4.6 for the flight CDG-MEX (9193km) for instance, which exceeds the RFI factor of 3 that partially explains this difference. Indeed, some of the variability is attributable to other differences in methodological choices. Barret observed a variability of a factor of 2 to 3 between the protocols included in his study, even after removing all RFI factors [6]. Nevertheless, for the set of flights illustrated by figure 4, atmosfair, myclimate, DBEIS and ADEME seem to give rather comparable results (especially for short distances). ICAO and DGAC give the lowest results, which can be partially explained by the fact that the method ignores non-CO2 effects, and does not systematically apply a class correction factor.
Figure 4. CO2 or GHG emissions (kgCO2 or kgCO2-equivalent) per passenger-km for various one-way flights in economy class where possible. The distances on the diagram are great circle distances.

4. Conclusion
Environmental assessment entails many methodological choices (boundaries, allocation…) and approximations which may be questionable from a certain point of view, but still inevitable. In addition, there will always be a gap between the emissions calculated and real-world emissions. Indeed, fuel consumption for example depends on numerous parameters such as filling rates and meteorological conditions, as mentioned earlier. Therefore, the relevance of a protocol does not necessarily derive from the precision and accuracy of the results in absolute terms, but rather from their relevance to an objective. For example, if the aim is to induce or promote behavioural change (in terms of seat class or airline choice), the protocol should capture the influence of these parameters, which is not the case of some average values like those of ADEME. If, on the other hand, the objective is to compare the average emissions of different modes of transport (e.g. air versus rail), the variability of the results may not be a problem, since air is currently the most emissive mode. In this case, ease of use as a criterion of choice may be relevant. Finally, if the objective is to obtain a result that is as close to reality as possible, for example for carbon offsetting purposes, myclimate and atmosfair methods seem to be more relevant among the protocols studied, due to their granularity.

To continue this work, it would be interesting to extend the scope of the study to include airline and GDS tools (such as SABRE’s) that have access to real data. Moreover, a multilinear regression based on a meta-analysis of existing protocols would make it possible to highlight the influence of each parameter and to deduce a general calculation formula.

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