Towards a Refined and Open Model for Calculating Flight Specific Greenhouse Gas Emissions

Nabila Iken* and François-Xavier Aguessy

***Abstract*—There are many tools available for calculating greenhouse gas (GHG) emissions from aviation. However, not all of them are transparent about their methodological choices and not all of them are relevant for certain purposes (e.g., comparison between different flights with the same origin-destination). In this paper, we propose an improved and open protocol (*The Treep* protocol), based on the improvement of existing protocols (principally *myclimate* protocol). In *The Treep* method, we replace the generic parameters in *myclimate* formula with aircraft or flight specific parameters and rely on more recent recommendations for the consideration of non-CO_2 effects. The results show the relevance of greater granularity in GHG emissions calculations, and the variability of these results depending on the flight and the aircraft, among others.**

Index Terms*—Greenhouse gas (GHG), aircraft, myclimate, *The Treep

I. Introduction

Aviation accounts for about 4% of anthropogenic global warming observed to date and is expected to induce a warming of about 0.1 ℃ by 2050 [1]. Despite continuous improvements in aircraft fuel efficiency, CO_2 emissions have increased by 42% between 2005 and 2019 due to air traffic growth alone [2], knowing that the share of the world's population that traveled by air in 2018 was only 11% [3]. In this context, the International Air Transport Association (IATA) has drawn up a strategic plan to achieve carbon neutrality by 2050 using new technologies, Sustainable Aviation Fuels (SAFs), carbon offset, etc. However, these estimates are made based on a measurement method for CO_2 emissions from aviation that does not meet with consensus.

This is manifested through the proliferation of flight CO_2 calculators, whether they are developed by international institutions like the International Civil Aviation Organization (ICAO), NGOs like *Atmosfair* or *myclimate*, or various airlines. These greenhouse gas (GHG) emissions calculation tools all have different levels of granularity, transparency, and give different outcomes [4].

Indeed, many calculation protocols are black boxes that do not provide their equations, assumptions, and data sources, making it difficult to compare them and judge their relevance to the user. Moreover, most protocols have very basic input data: sometimes only origin and destination such as in Air France CO_2 calculator [5]. This leads to the same calculation results for all flights between the same origin and destination regardless of the flight parameters (aircraft type, altitude, etc.). While such protocols are sufficient for some purposes (e.g., an estimate of the annual carbon footprint at country or company levels), they are not relevant in some situations. An example of a situation where more detailed results are needed is when a transport comparator wants to show the GHG emissions of different flights between two airports, to enable the travelers to book the least emissive flight.

To help build a transparent, comprehensive, and adaptable methodology for calculating flight GHG emissions, we propose an approach called *The Treep* protocol. The latter is based on various existing protocols and open access data: *myclimate*, *Atmosfair*, ICAO and *seatguru*. Our added value is the improvement of these methods by using specific rather than average parameters (for aircraft, non-CO_2 factor, passenger load factor, etc.), while using freely available data. More generally, our objective is also to provide a critical look at existing methods. This can help each actor to adapt the calculation parameters according to the dataat their disposal, their scope, and their final objective.

II. Method

Based on a previous comparative study of existing flights GHG calculation protocols [6], we selected *myclimate* method as our starting point for several reasons. First, *myclimate* gives a detailed description of its Eq. (1) in its methodological document [7].

Secondly, it describes and details the values given to its different parameters (Table I), which allows them to be modified. Finally, it is the only method that considers other life cycle phases than the use phase of the aircraft: the production phase of the aircraft and the infrastructure [7].

It should be noted that *myclimate* equation is very typical and close to what is proposed by other methods such as ICAO and *Atmosfair*. However, assumptions, data sources, and parameters are different from one method to another [6]. As mentioned earlier, *myclimate* has the advantage of giving the values used for each parameter.

$$E = \frac{ax^2 + bx + c}{S \times PLF} \times (1 - CF) \times CW \times (EF \times M + P) + AF \times x + A \quad (1)$$

With:

$$x = GCD + DC \quad (2)$$

The different parameters included in Eq. (1) and Eq. (2) are defined in Table I. Their numerical values are provided in Table II.

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Nabila Iken and François-Xavier Aguessy are with The Treep, Paris, France.

*Correspondence: nabila.iken@thetreep.com (N.I.)

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TABLE I: DEFINITION OF THE PARAMETERS INCLUDED IN MYCLIMATE FORMULA

Parameter	Definition	Unit
E	GHG emissions per passenger for a given flight	kg CO_2eq
x	Flight distance	km
GCD	Great Circle Distance	km
DC	Distance correction for extra mileage	km
S	Average number of seats (total across all cabin classes)	/
PLF	Passenger load factor	/
CF	Cargo factor	/
CW	Cabin class weighting factor	/
EF	Emissions factor for jet fuel combustion (kerosene)	kg CO_2eq/kg
M	A multiplier accounting for potential non-CO_2 effects	/
P	GHG emission factor for pre-production jet fuel, kerosene	kg CO_2eq/kg
AF	Emissions factor for aircraft production, maintenance, and end of life	kg CO_2eq/km
A	Emissions factor for infrastructures (airport operations)	kg CO_2eq

In Eq. (1), the flight distance *x* (and more precisely the Great Circle Distance) is the only variable parameter. All other parameters having one to two constant values, depending on whether it is a long-haul flight ($x > 2500\, km$) or short haul flight ($x < 1500\, km$). When $1500\, km < x < 2500\, km$, *myclimate* protocol uses linear interpolation to estimate GHG emissions.

TABLE II: VALUES OF THE PARAMETERS INCLUDED IN *MYCLIMATE* FORMULA

Parameter	Generic short haul	Generic long-haul
Average seat number (S)	153.51	280.21
Passenger load factor (PLF)	0.82	0.82
Detour constant (DC)	95	95
1 - Cargo factor (1 - CF)	0.93	0.74
Economy class (CW)	0.96	0.8
Business class weight (CW)	1.26	1.54
First class weight (CW)	2.4	2.4
Emission factor (EF)	3.15	3.15
Preproduction (P)	0.54	0.54
Multiplier (M)	2	2
Aircraft factor (AF)	0.00038	0,00038
Airport/Infrastructure (A)	11.68	11.68
a	±0.0000	0.0001
b	2.714	7.104
c	1166.52	5044.93

Equation (1) contains several methodological choices that can be discussed and potentially improved. In what follows, we analyze the methodological choices concerning certain calculation parameters and proposeavenues for improvement. At the end of this procedure, this leads to a new calculation protocol that we called *The Treep* protocol, more adapted to a comparison between flights with the same origin-destination and using freely available data.

A. Analysis and Determination of the Potential for Improvement in Myclimate Formula

Eq. (1) shows the variables and parameters considered by *myclimate*. Each parameter is the result of a methodological choice and is based on data processed in a certain way. In the following, we discuss the assumptions related to each parameter described in Table I, except the parameters related to the production phase of the aircraft and infrastructures, which require a separate study. Emissions factors for preproduction and combustion of jet fuel are also not discussed, as they are chemical constants.

1) Flight distance

GHG emission calculations for flights are based on the great circle distance (GCD), which is defined as the shortest distance between two points of a sphere (in this case between two airports). However, this geometrical distance doesn't reflect exactly the effective distance flown by an aircraft. Indeed, due to detours, traffic inefficiencies, meteorological conditions, etc., the effective distance flown is bigger. To account for this additional distance, *myclimate* adds a constant distance of 95 km to the GCD, regardless of its magnitude. For comparison, ICAO protocol uses three different distance correction values depending on the distance range: 50 km for flights below 550 km, 100 km for flights between 550 km and 5500 km, and 125 km for flights above 5500km [8].

This highlights the need to investigate the relevance of *myclimate* assumption. To do so, we calculated the effective distance (*x*) flown for a set of 96 flights to compare it with the GCD. For this purpose, we used *flightradar24* [9], which provides various live and historical air traffic data such as latitude and longitude of aircraft at various points of time. Using these geographical coordinates, we calculated the effective distance flown for different flights with different great circle distances.

Fig. 1 shows the distance correction (*DC*) for different flights based on real data and on *myclimate* protocol. Here, we define *DC* as the difference between effective distance (*x*) and GCD.

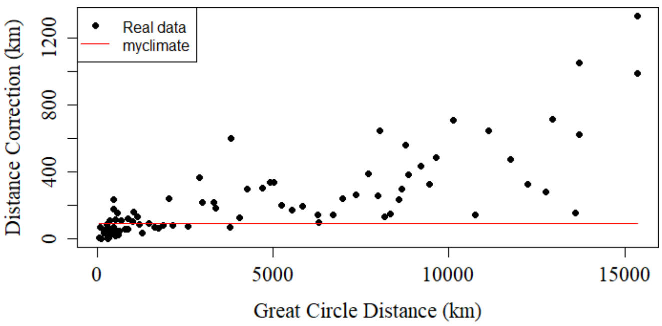

Fig. 1. Relationship between distance correction and great circle distance for different flights.

This demonstrates that Distance Correction tends to increase with GCD, and the limits of *myclimate* assumption. Moreover, Fig. 2 shows the evolution of effective distance (*x*) in function of the GCD. It is possible to describe this relationship with the linear model described with (3):

$$x = 32.04 + 1.043 \times GCD \qquad (3)$$

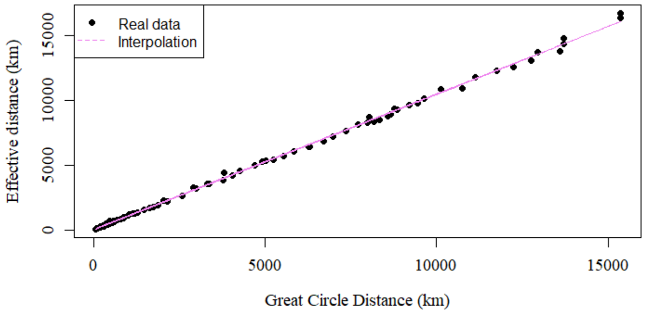

Fig. 2. Relationship between effective distance and great circle distance for different flights.

The components of this linear model are given in Table III, and Fig. 3 shows the distribution of residuals. The latter demonstrates that the interpolation model reduces the difference between predicted and actual values on average compared to *myclimate* model, but also that the effective distance is less predictable for large distances.

TABLE III: COMPONENTS OF THE LINEAR MODEL DESCRIBING EFFECTIVE DISTANCE IN FUNCTION OF GREAT CIRCLE DISTANCE

Parameter	Estimate	Standard error	t value	Pr(>|t|)
Intercept	32.034	20.480078	1.565	0.121
GCD	1.043366	0.003428	304.323	<2e−16
Residual standard error	148.1 on 94 degrees of freedom			
Multiple R-squared	0.99			
F-statistic	9.261e+04 on 1 and 94 DF			
p-value	<2.2e−16			

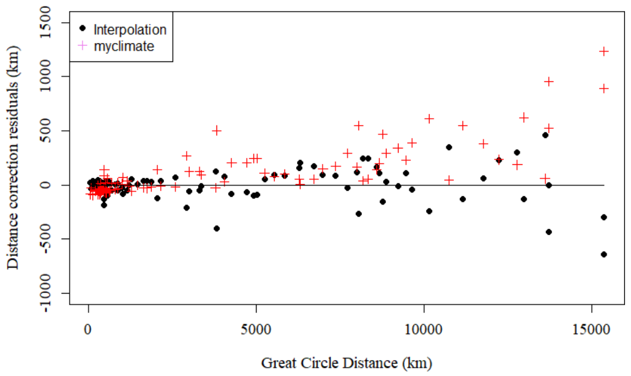

Fig. 3. Distribution of the linear model describing effective distance in function of great circle distance.

2) *Concerning fuel consumption*

To assess the fuel consumption of flights, *myclimate* uses a nonlinear approximation with Eq. (4):

$$fuel\ consumption = ax^2 + bx + c \qquad (4)$$

where the factors *a*, *b* and *c* each have two values: one for long haul and one for short haul. The constant parameter *c* represents the Landing and Takeoff (LTO) fuel consumption. Fig. 4 shows the resulting values for average fuel consumption by distance. According to *myclimate* methodology document, this approximation is based on EMEP/EEA airpollutant emission inventory guidebook [10].

Indeed, EMEP/EEA guidebook gives tools to assess fuel consumption and emissions for LTO cycles, according to the available information at country level. However, *myclimate* formula doesn't allow comparison between different flights with the same origin-destination (i.e., the same x), which is essential for a flight comparator for example, or a traveler wishing to choose the least emissive flight.

Based on a grey literature review, we have identified only one open database providing fuel consumption by aircraft type, which is the ICAO database [8]. To build this database, ICAO assessed fuel consumption for each airline, on each sector of a scheduled flight, using airline information for their scheduled operations. The methodology used to generate the data consisted of using the fuel consumption figures published in the aircraft manufacturers' manuals as a basic estimate of fuel consumption per distance flown. These figures were then corrected according to available in-service fuel consumption data. These data were then grouped in a table that provides the fuel consumption for different aircraft and different flight distances.

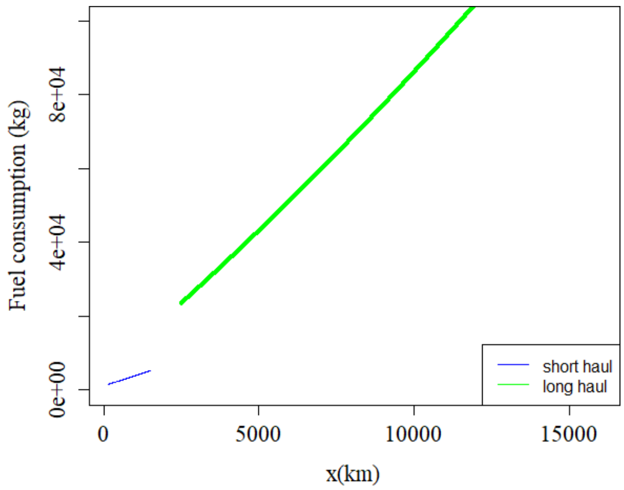

Fig. 4. Fuel consumption calculated with *myclimate* formula.

Indeed, ICAO database gives fuel consumption of 312 types of aircraft, for up to 20 flight distances. Fig. 5 illustrates the difference in fuel consumption between different aircraft types for a 5835 km flight (e.g: CDG-JFK) according to ICAO database, compared to the average value from *myclimate*. In this case, flying a B77W instead of a B789 increases fuel consumption by 59%.

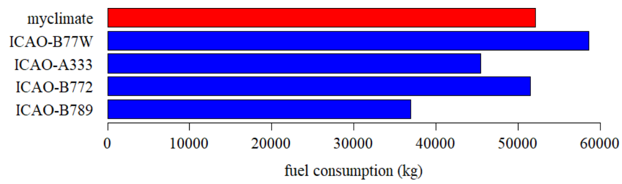

Fig. 5. Fuel consumption calculated with ICAO database for different CDG-JFK flights.

However, these data are expected to be updated annually, but the last publication was in 2018. Moreover, they do not offer much granularity in terms of flight distance, although the fuel consumption corresponding to any flight distance can be calculated by interpolation between the two closest distance points. Indeed, to obtain this data for a given distance, it is possible to interpolate between the two closest distances by using Eq. (5):

$$f_d = \frac{(f_{long} - f_{short}) \times (d - d_{short})}{d_{long} - d_{short}} + f_{short} \quad (5)$$

where f_d is the fuel consumption corresponding to the distance d, d_{long} and d_{short} are respectively the distance just above and the distance just below the distance d available in ICAO database, f_{long} and f_{short} are the fuel consumption corresponding to the distances d_{long} and d_{short} respectively.

Furthermore, the database does not distinguish between aircraft fitted with winglets and those without, which is a parameter considered by *Atmosfair* in its formula. Indeed, according to the latter, fitting an aircraft with winglets can reduce CO_2 emissions by 3%.

3) Concerning non-CO_2 effects

There is a consensus that the impact of flights is greater than their contribution to direct CO_2 emissions from burning kerosene. Indeed, there are specific effects related to the fact that the emissions are at high altitude [11]. This is reflected in the contrail trails, also designated as condensation trails or non-CO_2 effects. The latter are caused by the condensation of water vapor emitted by engines at high altitudes (the upper troposphere and the lower stratosphere) if the surrounding air is sufficiently cold and humid.

However, some CO_2 emissions calculation protocols such as ICAO do not take these non-CO_2 effects into account.

Moreover, several studies have shown that the climate impact of flights depends on the emissions altitude [12]. Yet many methods do not include this dependence in the calculation of greenhouse gas emissions. Indeed, methods that take condensation trails into account usually consider a constant multiplication factor (called RFI for Radiative Forcing Index) with a value of 2. This is the case of *myclimate* protocol, but also the UK Department for Business, Energy and Industrial Strategy [13] and ADEME [14] protocols.

In contrast, *Atmosfair* uses an altitude-dependent multiplication factor that is calculated with Eq. (6):

$$nCO_2 = CO_2 \times falt \times fnCO_2 \quad (6)$$

where nCO_2 is the non-CO_2 emissions per passenger, CO_2 is the carbon dioxide emissions per passenger, $falt$ is the proportion of the flight distance flown at altitude over 9 km in relation to the total flight distance, $fnCO_2$ is a factor for the climate effect of non-CO_2 emissions. For this last parameter, *Atmosfair* has chosen a value of 3, justifying it as follows: "*This actual value of 3 is exactly in the middle of the old IPCC bandwidth of the RFI, which was indicated to be 2-4 by the IPCC in 1999*" [15].

Furthermore, a recent literature review showed that RFI values proposed in the literature vary between 1 and 2.7 if emissions from the whole flight are considered, and between 1 and 8.5 if only emissions in the upper atmosphere are considered [11]. The authors of the study recommend a factor of 5.2 in the higher atmosphere because it is based on most recent scientific publications. This illustrates both the enormous impact that non-CO_2 effects could have on the climate impact of flights, but also the dispersion of possible values in the scientific literature. In all cases, research shows that if flight altitude data is available, it is preferable to multiply the share of emissions that happens in higher atmosphere by a factor. However, the determination of the fraction of flight that occurs at high altitude can be difficult. Therefore, we have designed a model that aims to provide this information based on flight distance.

Indeed, to calculate the percentage of flight distance that occurs above 9 km, we used *flightradar24* data for 92 flights with various GCDs. Indeed, *flightradar24* provides aircrafts altitude at regular time intervals (at least every two minutes), which allows to calculate the ratio of effective distance flown in the relevant altitude range. Fig. 6 shows the relationship between effective distance travelled over 9 km (let's name it EF_{alt}) and Effective Distance (x) is linear. By focusing on short distances, Fig. 7 shows that this linear relationship takes place above a certain distance. Below this critical distance, the effective distance flown above 9 km of altitude is zero.

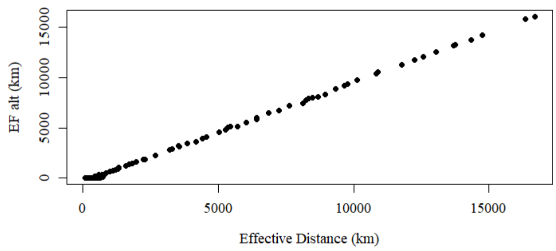

Fig. 6. Distance above 9 km of altitude in function of GCD.

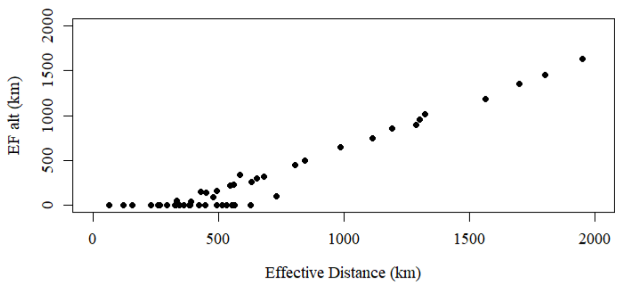

Fig. 7. Distance above 9 km of altitude in function of GCD with a focus on small GCDs.

By determining the intersection of the trend line with the x-axis, we find a critical distance of 392 km. The relationship between EF_{alt} and x can be then described with the following linear model:

$$\begin{cases} EF_{alt} = 0.9907 \times x - 391.2;\ x > 392km \\ EF_{alt} = 0;\ x \leq 392km \end{cases} \quad (7)$$

Table IV shows the components of the linear model given by the first equation in Eq. (7):

TABLE IV: COMPONENTS OF THE LINEAR MODEL DESCRIBING EFFECTIVE DISTANCE ABOVE 9 KM OF ALTITUDE IN FUNCTION OF GREAT CIRCLE DISTANCE

Parameter	Estimate	Standard error	t value	Pr(>|t|)
Intercept	−3.912e+02	1.427e+01	−27.42	<2e−16
GCD	9.907e−01	2.089e−03	474.20	<2e−16
Residual standard error	85.84 on 75 degrees of freedom			
Multiple R-squared	0.9997			
F-statistic	2.249e+05 on 1 and 75 DF			
p-value	<2.2e−16			

This means that f_{alt} defined as the fraction of the effective distance flown above 9 km to the total effective distance flown, can be described with the following formula:

$$\begin{cases} f_{alt} = \dfrac{0.9907 \times x - 391.2}{x} : x > 392km \\ f_{alt} = 0;\ x \leq 392km \end{cases} \quad (8)$$

Which can be expressed using Eq. (3) as follows:

$$\begin{cases} f_{alt} = \dfrac{1.033 \times GCD - 359.46}{32.04 + 1.043 \times GCD} ; GCD > 348km \\ f_{alt} = 0; GCD \leq 348km \end{cases} \quad (9)$$

Fig. 8 shows the f_{alt} values obtained with Eq. (8) compared with those calculated based on real data and the obtained residuals. This shows a larger error for short distances.

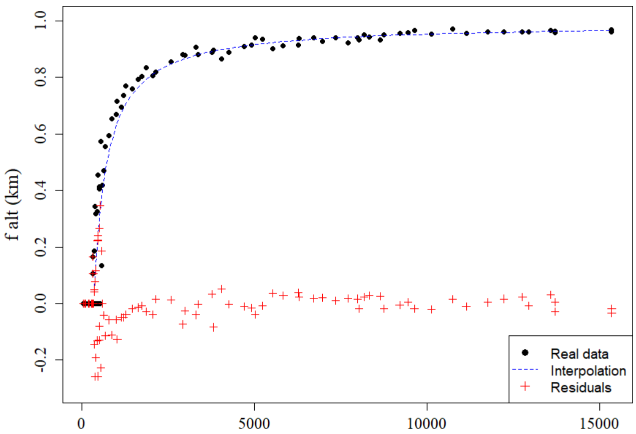

Fig. 8. Distance above 9km of altitude in function of GCD with afocus on small GCDs.

It should be noted that very high uncertainties are associated with flights with a GCD situated in the interval [300–[600]km. Indeed, in this distance range, some aircraft fly above 9km while others fly below 9 km, with no clear correlation between the distance flown above 9 km and the GCD. This is probably partly due to the uncertainty in estimating aircraft altitude as a function of GCD (since altitude is also determined by other factors), which appears more clearly for short distances. This makes it impossible to estimate the exact GCD above which the altitude exceeds 9 km, since the transition zone between the altitudes below and above 9 km is wide. This explains the area of high uncertainty when approaching 9km altitude.

1) Concerning total number of seats and seat class

To calculate GHG emissions per passenger, it is essential to know the number of seats available on the aircraft. *myclimate* uses two constant values of 153.51 for short haul flights and 280.21 for long haul flights. Knowing that this number depends on the type of aircraft, but also on the configuration chosen by the airline, it varies from one flight to another. For example, a 789 can hold 231 seats with the airline Etihad, while it can hold 344 seats with Norwegian Air Sweden Airline [16]. This factor therefore adds significant uncertainty to the calculation of GHG emissions per passenger. Indeed, the higher the number of seats, the lower the carbon footprint per passenger.

Furthermore, to allocate a quantity of GHG emissions to each passenger, it is important to consider the type of seat occupied by the passenger. In general, seat class is considered by flight GHG calculation protocols through multiplication factors. This is because higher class seats take up more space on the aircraft than economy class seats, which increases the carbon emissions per passenger. As shown in Table II, *myclimate* considers six class adjustment factors: three factors for short haul flights and three other factors for long haul flights, for economy, first and business classes. Emissions are allocated to individual seats according to the average seat area in the selected cabin class, based on data from *seatguru* [7, 16]. The cabin class adjustment factor is calculated for each aircraft type and then an average factor is calculated by weighting according to the most common aircrafts.

As shown in Table V, several other methods like those of *Atmosfair* and the Department for Business, Energy and Industrial Strategy (DBEIS) [13, 15] use different factors and sometimes additional seat classes (such as premium economy). To build these figures, *Atmosfair* based on a 2007 study on the seating design of the 40 biggest airlines worldwide but doesn't specify whether this study can be consulted or not. Same for DBEIS that mentions a 2008 study about the seating configuration of 16 major airlines.

TABLE V: SEAT CLASS FACTORS FROM ATMOSFAIR AND DBEIS PROTOCOLS

Economy class equivalence	*Atmosfair*	DBEIS
Business class-short haul	1.9	1.5
First class- short haul	2.5	1.5
Premium economy- short haul	1.3	/
Business class-long haul	1.9	2.9
First class- long haul	2.5	4
Premium economy- long haul	1.3	1.6

4) Concerning Passenger load factor and passenger to freight factor

When it comes to allocating the aircraft's GHG emissions to each passenger, four factors are important. The number of seats and the seat class factor discussed earlier are part of it, but the other two are the Passenger Load Factor (PLF) and the passenger to cargo ratio. The first provides information on the occupancy rate of the aircraft, while the second allows to allocate part of the GHG emissions to the transport of freight that takes place on most commercial flights.

As shown in Table II, *myclimate* uses a constant PLF of 82%. This figure is based on ICAO data, weighted according to a scheme that is not explained. Indeed, *myclimate* methodology document mentions a weighting scheme based on the most frequent aircrafts and the number of kilometers flown, but ICAO data in terms of PLF depend rather on route groups.

Indeed, ICAO passenger load factors per route group shows that this factor can vary by 31% between the lowest PLF (from Africa to South America) and the highest PLF (from Europe to South America). Fig. 9 below compares PLFs from ICAO database with the constant value of *myclimate* for different route groups.

The same applies to the passenger to cargo ratio. Indeed, *myclimate* uses two constant values: 0.93 for short haul and 0.74 for long haul. The source of these figures is not given in the methodology document, but it is mentioned that they are based on an allocation by weight. As well as for the PLF, ICAO provides different passenger to freightfactors that vary between 62.38% and 96.12%, dependingon the route group.

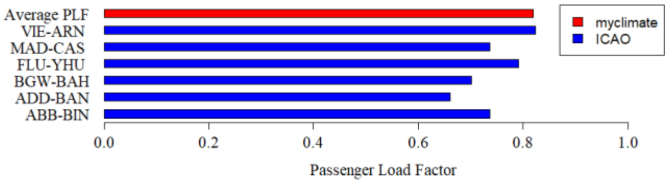

Fig. 9. Passenger load factors from ICAO database for different flights.

B. Analysis and Determination of the Potential for Improvement in Myclimate Formula

In view of the various points for improvement seen in the previous section, we propose a calculation formula based on the following elements.

1) Flight distance

For each flight, the effective distance flown (x) is calculated using the Great Circle Distance and the interpolation Eq. (4).

2) Fuel consumption

For each flight, the aircraft-specific fuel consumption is calculated with Eq. (5), depending on aircraft type and on the effective distance flown, and based on ICAO fuel data base.

3) Non-CO_2 effects

For each flight, emissions that occur above an altitude of 9 km are multiplied by a factor of 5.2 as recommended by a recent literature review [11]. The fraction of distance flown above 9 km is calculated with Eq. (9).

4) Seat class factors and number of seats

To account for the type of seat and the total number of seats in economy class equivalent (i.e. the number ofseats in economy class that the aircraft could carry), we propose the following three strategies based on the available data.

Situation A: the seat map of the aircraft with the relevant airline is available on *seatguru* statistics database. In this case, the class factor for the different classes is calculated by dividing the area of a seat in each class by the area ofa seat in economy class. The total number of seats in economy class equivalent is then calculated considering these class factors.

Situation B: the seat map of the aircraft is available, but not for the relevant airline in *seatguru* statistics database. In this case, we do the same calculation as above, but take the median seat area and median number of seats for all airlines available in the database.

Situation C: if any of the data needed for the calculation in Situation B is not available, we use *Atmosfair* seat class factors (see Table V), because they have a wider range of seat classes.

5) Passenger load factor and passenger to freight factor

For each flight with a corresponding route group, PLF and passenger to freight factor from ICAO database are used (see Table VII in the Appendix).

6) The Treep method summary

Thus, integrating the different modified parameters, CO_2 emissions per passenger due to fuel combustion for a given flight can be calculated with the following formula:

$$CO_{2_{flight}} = \frac{f_{aircraft}}{S_{aircraft} \times PLF_{route}} \times (1-CF)_{route} \times CW_{aircraft} \times EF \quad (10)$$

With:

$$S_{aircraft-y} = S_y + S_{busi} \times CW_{busi} + S_{prem-y} \times CW_{prem-y} + S_{first} \times CW_{first} \quad (11)$$

where $f_{aircraft}$ is the fuel consumption of the aircraft from ICAO database calculated with Eq. (5), PLF_{route} and $(1-CF)_{route}$ are the passenger load factor of the passenger to freight factor respectively of the concerned route group from ICAO database, $CW_{aircraft}$ is the seat class factor of the aircraft calculated from *seatguru* database (seat area of the concerned class compared to economy seat area), $S_{aircraft}$ is the number of seats in equivalent economy class, S_y, S_{busi}, S_{prem-y}, and S_{first} are the numbers of seats in economy, business, premium economy and first classes respectively, CW_{busi}, CW_{prem-y} and CW_{first} are the class factors for business, premium economy and first classes respectively (each factor is a ratio of the seat area of the class concerned to the seat area in economy class).

Moreover, to consider non-CO_2 effects, fuel preproduction, airport and infrastructures production, the following formula can be used:

$$E_{flight} = CO_{2_{flight}} \times \left[(1-f_{alt}) + f_{alt} \times RFI + \frac{P}{EF} \right] + AF \times x + A \quad (12)$$

where, E_{flight} are the greenhouse gas emissions per passenger for the given flight, f_{alt} is the fraction of distance flown above 9 km calculated with Eq. (9), *RFI* is a constant factor of 5.2, *x* is the effective distance calculated with Eq. (3), *P*, *EF*, *AF*, and *A* have the same definition and values as for *myclimate*: they are emissions factors for fuel preproduction, fuel combustion, aircraft production and airport production respectively.

It should be noted that the term $\frac{P}{EF}$ is because we considered that fuel preproduction emissions don't depend on flight altitude, as well as emissions from aircraft and airport production.

III. Results

To illustrate our method, we applied *The Treep* calculation model to a set of randomly selected flights. Table VI details the selected flights and the corresponding parameters. In the following, we illustrate the results obtained following the application of our recommendations and compare them with the results of other calculation protocols (*myclimate*, *Atmosfair*, and ICAO tools).

TABLE VI: PARAMETERS OF SELECTED FLIGHTS

Origin city	IATA code	Destination city	IATA code	GCD (km)	Aircraft	Airline
Valencia	VLC	Barcelona	BCN	295	B738	ASL
Amsterdam	AMS	Birmingham	BHX	443	B738	KLM
Paris	CDG	Nice	NCE	602	A320	Air France
Paris	CDG	Dublin	DUB	786	A320	Air France
Madrid	MAD	Casa Blanca	CMN	868	73H	Royal Air Maroc
Budapest	BUD	Geneva	GVA	1009	A320	EasyJet
Paris	ORY	Madrid	MAD	1030	B738	Transavia
Lyon	LYS	Oran	ORN	1222	B738	Air Algérie
Vienna	VIE	Stockholm	ARN	1285	A320	Austrian Airlines
Paris	CDG	Ankara	ESB	2583	B738	Air France
Paris	CDG	Tbilissi	TBS	3364	A320	Air France
Paris	CDG	New-York	JFK	5835	B772	American Airlines
Paris	CDG	Mexico	MEX	9213	B789	Aeroméxico

A. *Fuel Consumption*

Fig. 10 compares the fuel consumption calculated by *myclimate* formula (for an average aircraft) and that calculated with *The Treep* method from the ICAO database (specific to the aircraft type). It shows that the two values are close for short haul flights but can be very different for some long-haul flights. This can be explained by the variability in fuel consumption between different aircraft types, and what is considered the most representative aircraft by *myclimate*.

B. *Non-CO_2 Effects*

By applying the methodological choices exposed in Section II.B.3 to a set of flights selected, we obtain the results illustrated by Fig. 11. The latter shows multiplication factors for non-CO_2 effects obtained for the selected flights of Table VI, both with real data from *flightradar24* and with interpolation Eq. (7), using an RFI of 5.2. The constant multiplication factor used in *myclimate* is also illustrated for comparison.

C. *Seat Class Factors*

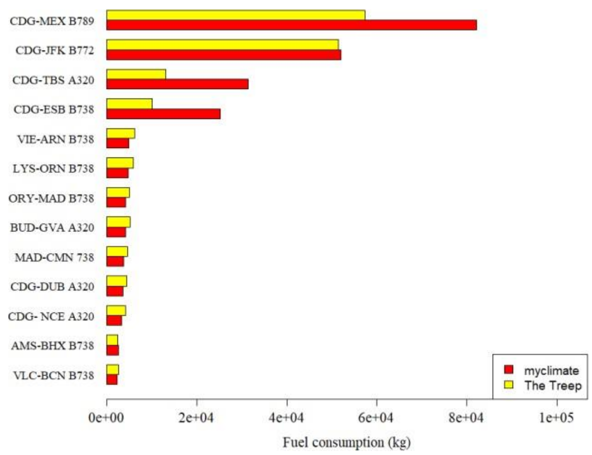

Fig. 10. Fuel consumption for different flights. Data used in ourmethodology are ICAO data.

Fig. 12 compares the average class factors from *myclimate* and *Atmosfair* with the actual class factors calculated from *seatguru* for CDG-HND flights with a Boeing 787-9 and with two different airlines. Seat class factors have been calculated based on the seat area (seat pitch multiplied by seat width) for these specific airlines, which is available in *seatguru* database. In this case, business seat class factor for example is underestimated by *myclimate* and *Atmosfair* for flights with Japan Airlines, but premium economy seat class factors are close.

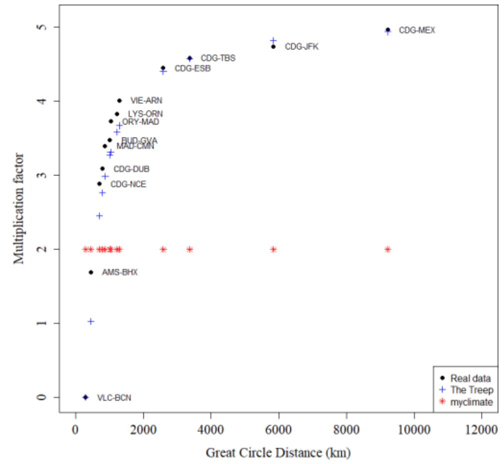

Fig. 11. Non-CO_2 effect multiplication factor for selected flights.

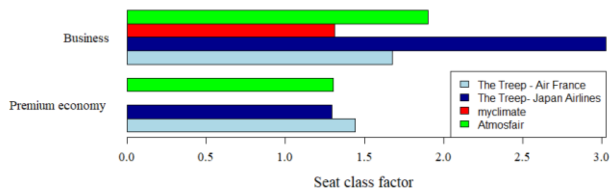

Fig. 12. Seat class factors for CDG-HND flights with a Boeing 787-9with two different airlines.

D. *GHG Emissions*

Finally, by applying all the parameters explained above, we obtain a GHG emission value for each selected flight. The results are summarized in Fig. 13 for a passenger in an economy seat and in Fig. 14 for a passenger in abusiness seat. Some values are missing from the second figure because the business class seat does not exist on all aircraft (e.g. for the CDG-MEX flight). The figures compare the values obtained by *myclimate*, *Atmosfair* and ICAO with those obtained using our method, and this with two possible RFIs: 5.2 and 3. Indeed, as the multiplication factor has a strong influence on the results, it is interesting to visualize the outcomes of our calculation using a factor close to that of the other methods to estimate the influence of the other parameters.

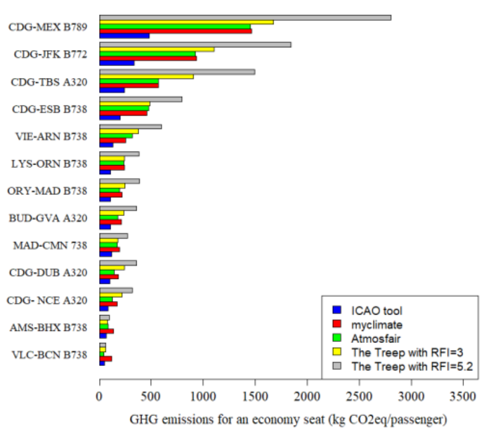

Fig. 13. GHG emissions by passenger in economy seat for differentflights calculated with different protocols.

Moreover, Fig. 15 shows the variability of GHG emissions for a passenger in economy class in different flights with the same origin-destination (in this case CDG-NCE flights).

Here, flying from CDG to NCE with an A321 rather than an A318 for example increases GHG emissions by 30%, which is equivalent to 58 kg per passenger.

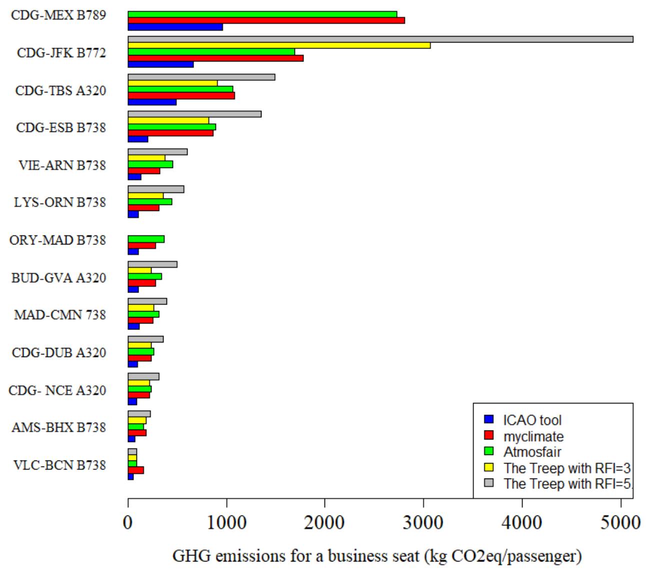

Fig. 14. GHG emissions by passenger in business seat for different flights calculated with different protocols.

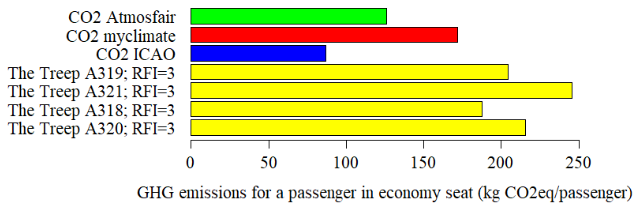

Fig. 15. GHG emissions by passenger in economy class for the flight CDG-NCE.

TABLE VII: VARIATION IN GHG EMISSIONS DUE TO VARIATION OF DIFFERENT PARAMETERS

Parameter variation	$f_{aircraft}$	PLF	S	x	f_{alt}
−80%					−61%
−50%		99%			−38%
−40%		66%			−31%
−30%		43%		−18 %	−23%
−10%		11%		−9%	−8%
10%	10%	−9%	−9%	9%	
20%	20%	−17%	−17%	18%	
30%	30%		−23%	26%	
40%	40%		−28%		
50%	50%		−33%		
80%			−44%		

IV. DISCUSSION

Through our study, we wanted to obtain a protocol for calculating GHG emissions from flights that distinguishes between flights with the same origin-destination, using open and freely available data. The interest is to open the black box of calculation methods, to allow the user to adapt the data used to the final objective and to have a critical look at the methodological assumptions often imposed by existing protocols.

Thus, we have identified some data sources such as ICAO database, which provides fuel consumption, PLF and passenger to cargo ratio specific to the aircraft or route groups.

We also used *seatguru* statistics to determine the seat class factors and the number of seats on each aircraft, and *flightradar24* data to assess the fraction of distance flown above 9km for each flight studied to calculate an altitude-dependent non-CO_2 effects factor. Because the latter calculation can be tedious, we have proposed an interpolation formula giving the multiplication factor as a function of the GCD.

Finally, the results obtained show the relevance of a calculation protocol with greater granularity, since the difference in GHG emissions between one aircraft and another for the same origin-destination may be significant.

However, several limitations and areas for improvement remain. The first one concerns the difficulty to calculate uncertainties. Indeed, data such as fuel consumption are not accompanied with uncertainties, even if they are extremely variable according to the filling rate and the age of the aircraft, but also meteorological conditions among others.

We have also highlighted the weak scientific consensuson the non-CO_2 effects and the multiplier factors to be chosen, and the great uncertainty that this choice entails. Indeed, the formation of condensation trails is a complex physical phenomenon that depends not only on altitude, but also on temperature, humidity of the surrounding air, etc. Thus, there are areas where contrails are more likely to form, but for the sake of simplification, we have considered that this probability is higher above 9 km (as *Atmosfair*). This methodological choice can be refined if we want to consider the probability of formation of these trails in different environments. This would reduce the uncertainties for flights in the distance range where altitude approaches 9 km.

Finally, we have discussed most of the parameters involved in the calculation of GHG emissions from flights but have left out the production phase of aircraft and infrastructure. The latter requires a separate study to establish aircraft type specific data. This could be done, for example, on the basis of the average mass of each aircraft and assuming an average material content (e.g. percentage of aluminum, composites, plastics, etc.). It would also be necessary to find a way to categorize airports according to their size, for example.

V. CONCLUSION

In the end, each stakeholder will tend to defend the model in line with their interests. For example, carbon offsetting entities may tend to favor models that provide high values, while airlines may tend to pull down CO_2 emissions. For this reason, the scientific and practitioner community has been calling for standardization for several years. Thus, although our study does not establisha universal model, it does provide keys to understanding and analyzing it, enabling each actor to adapt the calculation protocol according to its needs and the data available. Our aim was to obtain less averaged and more specific values to compare different flights with the same origin-destination. But for any other use, it is relevant to ask whether this refining work is worth it in view of the final objective.

APPENDIX

ICAO Passenger load factors and passenger to freight factors

TABLE VIII: PLF AND PASSENGER TO FREIGHT FACTORS BY ROUTE GROUP

# Route Group	Origin	Destination	PLF	Pax to freightfactor
1	Africa	Asia &Pacific	73.70%	83.82%
2	Africa	Middle East	74.10%	82.92%
3	Africa	North America	77.10%	91.11%
4	Africa & MiddleEast	Central America & Caribbean	77.90%	84.03%
5	Africa & MiddleEast	South America	65.00%	83.97%
6	Central America & Caribbean	North America	80.70%	86. 57%
7	Central America & Caribbean	South America	79.70%	93,17%
8	Central America & Caribbean	Europe	81.70%	89.42%
9	Central & South West Asia	Europe	81.50%	63.43%
10	Central & South West Asia	Latin America & Caribbean	80.30%	84.45%
11	Central & South West Asia	Middle East	78.90%	81.18%
12	Central & South West Asia	North America	83.30%	62.38%
13	Central & South West Asia	North Asia	71.20%	79. 47%

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Nabila Iken collected and analyzed the data used in this article. She designed The Treep's calculation model and wrote the article. François-Xavier Aguessy supervised the design of the calculation protocol and proofread the article. He also implemented the computer programs to exploit the different data sources used.

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