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Research article

Features and evolution of civil aviation CO_2 emissions based on ADS-B data for the period between 2019–2024

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Abstract: Aviation, as a critical component of the global transportation infrastructure, has experienced substantial growth over the past few decades, facilitating the movement of people and goods. However, this sector is also a significant consumer of fossil fuels and contributor to global warming. In this study, we estimated the carbon dioxide (CO_2) emissions from global aviation for the period between 2019 to June 2024 using Automatic Dependent Surveillance-Broadcast (ADS-B) data. We estimate that a yearly total of 42 million of flights were responsible for 895 Mt of CO_2 emissions in 2019. Flight disruptions caused by the Covid-19 pandemic have decreased emissions during the years 2020–2023, but the recovery has been quick: the number of domestic flights in 2023 surpassed its pre-Covid level while international flights were slightly lagging behind. This results in CO_2 emissions in 2023 that were still 9% below their pre-Covid levels. However, traffic and emissions levels calculated for 2024 indicate a return to pre-Covid levels. Our analysis indicates that North America, Europe, and Asia account for almost 75% of the aviation CO_2 emissions. Flights shorter than 2600 km are responsible for 50% of the aviation CO_2 emissions worldwide. Flights longer than this distance account for the other half of emissions, although they represent less than 15% of the total number of flights. The most recent generation of aircraft represented 20% of the fleet at the start of 2024, resulting in an 8% gain in efficiency, equivalent to 144 Mt CO_2 avoided over the whole period. However, the ongoing growth in traffic delays the fleet renewal and hinders the reduction in emissions. Aviation does not appear to be on track to reach a 55% reduction in emissions by 2030. Additionally, if sustainable aviation fuels are to be used, this will require a substantial increase in biomass or low-carbon electricity use.

Keywords: air traffic; aviation; carbon dioxide emissions; Covid-19; fleet renewal

1. Introduction

Aviation emits carbon dioxide and other chemical species that contribute to global warming but also have an impact on air quality. However, aviation is an important economic sector and an essential element in today's globalized economy. Civil aviation was responsible for 2.5–2.6% of the total anthropogenic fossil-fuel CO_2 emissions with 2018 emissions estimated at 910 Mt CO_2 by Quadros et al. [1] and 918 Mt CO_2 by Graver et al. [2]. A more recent estimate by Teoh et al. [3] placed emissions at 893 Mt CO_2 in 2019. Aviation CO_2 emissions approximately doubled since 2000 but its share of total emissions has remained fairly constant as they increased in concert with CO_2 emissions from other economic sectors [4, 5, 6]. Fleet efficiency, measured in CO_2 per unit flown distance, has improved by 36% over the period between 2000–2019 but the growth in traffic of around 5% per year has more than offset that gain [7, 8].

Deriving emission inventories for aviation is difficult. On the one hand, top-down estimates rely on global kerosene fuel sales and usage, e.g., from the International Energy Agency [4]. Such data are thought to be comprehensive but they are not readily available, include military as well as a small non-aviation usage, and do not provide much granularity on how the fuel is used within the aviation sector. On the other hand, bottom-up estimates, based on actual aircraft movements, are becoming more common [1, 2, 3] as they provide more accurate information on the location of the emissions and non-CO_2 emissions than top-down estimates. However databases of flight movements are often incomplete, in a way that is not well documented. Bottom-up approaches necessitate the reconstruction of the global air traffic from available data sources. Quadros et al. [1] compared three different databases: FlightRadar24 (FR24) and OpenSky, both relying on networks of Automatic Dependent Surveillance-Broadcast (ADS-B) receivers, and OAG, consisting of scheduled passenger flights based on data provided by airlines. It should be noted that both the OAG and FR24 databases are proprietary and only available to the user at a cost. Quadros et al. [1] concluded that the ADS-B technology is more reliable than using scheduled flights to calculate global emissions from aviation and, therefore, can be used to monitor the climate impact of aviation, but it requires complete worldwide coverage. Teoh et al. [3] also chose to use the ADS-B technology to provide a high-resolution emissions inventory of aviation emissions but with a different provider than FR24 and their own fuel flow model, which can explain the few percent differences with the other estimates at the global scale.

Like any other sector, aviation needs to reduce its impact on climate and adopt a trajectory toward net-zero carbon emissions [5]. In that context, it is important to calculate CO_2 emissions accurately and know the details of their distribution. This knowledge is a prerequisite for taking action to reduce aviation CO_2 emissions effectively. In addition, reducing the non-CO_2 climate impacts of aviation often requires a trade-off between CO_2 and non-CO_2 effects and therefore an accurate characterization of the CO_2 emissions at flight, route, and fleet levels is needed.

In this study, we follow Quadros et al. [1] and also use the FlightRadar24 [9] database to monitor aircraft movements. FR24 relies on the ADS-B technology to track aircraft and provide a consolidated dataset of air traffic. The broadcast mode means the aircraft transmits unencrypted information (such as aircraft identification, position, ground speed, etc.) at regular intervals that can be received and decoded by any appropriately equipped ground facility, aircraft, or satellite. Modernization of air travel has led countries to make its usage widespread for commercial aircraft [10, 11]. ADS-B receivers are now widespread and are organized into networks providing both commercial and free online services to monitor air traffic. These networks provide the actual flown trajectories and have been used to develop flight and emission inventories, from simple approaches that consider constant emissions per kilometer flown based on previous bottom-up estimates [12] to more complex modeling [1, 2, 3].

This study presents a new bottom-up estimate of global civil aviation CO_2 emissions using flight movements from commercial services along with a thorough analysis of how these emissions are distributed and evolve. The ADS-B data used here were acquired between January 2019 and June 2024. Emissions were calculated for each individual flight from the knowledge of aircraft type and flight distance. Section 2 details the methodology of the emission estimate. We then discuss various characteristics of this emission inventory in Section 3: global estimates and distribution by aircraft type, the impact of and recovery from the Covid-19 pandemic, the regional distribution and the distribution by distance of these emissions and their annual and weekly cycles. Lastly, we estimate the evolution of the efficiency and its variation with the distance flown, available seats, and fleet renewal.

2. Methodology

2.1. Dataset

Aviation CO_2 emissions are calculated from a global reconstruction based on the FR24 flight database. The data were pre-processed by FR24 using their proprietary code. This pre-processing is required to assign the origin and destination airports of the flights as the raw ADS-B data do not contain this information. The dataset that we purchased from FR24 consists of a list of flights characterized by their departure and arrival airports, aircraft type, airline, and flight number, and the latitude-longitude-altitude coordinates of six points on their trajectory: the departure gate, the take-off, the start of the cruise, the end of the cruise, the landing, and the arrival gate. We have compared the FR24 database with a sample of the EuroControl database [13] for flights arriving and departing from CDG and ORY airports in Paris for selected days. All FR24 flights are included in the Eurocontrol database. However, we cannot guarantee the completeness of the Eurocontrol database nor can we estimate the completeness of the FR24 database worldwide.

2.2. Aircraft classification

To focus on civil aviation, we sort out all non-commercial planes. Aircraft technical data were extracted from the ICAO database [14] based on the aircraft type provided by the FR24 database. When required the aircraft were renamed with their proper ICAO code (section S5 of the Supplementary Materials (SM)). Small aircraft (mono-seater, two-seater, gliders, etc.), helicopters, and some fighter aircraft, were identified from the database. Specifically, helicopters were identified based on a wingspan of 0, small leisure aircraft based on a ceiling lower than 20,000 feet and a maximum take-off weight (MTOW) lower than 5 tonnes and fighter aircraft based on a ceiling higher than 51,000 feet and a passenger capacity of 1 or 2. It would have been useful to estimate CO_2 emissions from military aviation, but most military flights are missing from the FR24 database. Therefore this study considers civil aviation only. A flowchart of the aircraft classification is available in Figure S8.1 of the SM. Small aircraft and helicopters represent 12% of the flights in the database, corresponding to less than 2.5% of the distance flown. This category is later referred to as General Aviation.

For the analysis, we split commercial aircraft into two main categories: business and commercial aircraft. Business flights were separated from general aviation based on their number of passengers (lower than 25), their MTOW lower than 50 tonnes, and their ceiling between 20,000 and 50,000 feet. Commercial aircraft were divided into two categories, narrowbody and widebody, based on their passenger capacity below or above 250, respectively.

It is more difficult to distinguish cargo and passenger aircraft from ADS-B data alone because cargo aircraft are often converted from passenger aircraft so the aircraft type does not bring much information. However we can detect some cargo from their flight number, especially from pure cargo airlines such as FedEx or DHL. The complete list of cargo airlines is available in section S10. If an airline is not in Table S.10.1, the flight is considered to be a passenger flight. Therefore our statistics for the cargo share of commercial aviation should be seen as conservative estimates.

2.3. Database and consumption calculation

We compute the CO_2 emissions of each individual flight using the fuel estimation in air transportation (FEAT) model of Seymour et al. [15]. The FEAT model consists of a reduced order fuel consumption model, based on the Eurocontrol performance mode, the Base of Aircraft Data (BADA) [16], to compute the fuel consumption for a flight with only the origin-to-destination distance, and the aircraft type as input.

The fuel estimation model considers a small deviation from the orthodromic distance (also known as the great-circle distance) to account for the take-off and landing phases at the departure and destination airports, airspace restrictions, and other air-traffic management inefficiencies. The flight path distance d_{fp} is approximated as:

$$d_{fp} = 1.0387 \cdot d_{gc} \; + \; 40.5 \tag{1}$$

where d_{gc} is the great-circle distance between the origin and destination airports and all variables are expressed in km. A detailed model is then used to compute the fuel burned as a function of this corrected distance for a set of different aircraft using BADA for the climb, cruise, and descent and the ICAO database [17] for the landing and take-off (LTO) cycle. These calculations are then fitted by a polynomial function that expresses the fuel burned as a function of the distance d_{gc} where the coefficients α_i, β_i, and γ_i are estimated from least squares regression for each aircraft type i:

$$F_i = \alpha_i \cdot d_{gc}^2 + \beta_i \cdot d_{gc} + \gamma_i \tag{2}$$

It should be noted that Eq. 2 is a function of d_{gc} and already includes the effects of deviations. It does not consider how atmospheric winds may decrease or increase fuel consumption; thus it has to be understood as valid on average only. It does not describe either variations in fuel consumption due to differences in payload.

Fuel burned can then be converted to CO_2 emissions using the usual CO_2 emission factor for kerosene of 3.16 kg CO_2/kg fuel. In our study, we consider that all flights are powered with standard kerosene, Jet-A1. This method does not estimate how the emissions are distributed along the flight route. While the ADS-B technology makes it possible, in principle, to know accurately each trajectory, computing the CO_2 emissions along the trajectory would require a large amount of data that is not readily available given the approximately 100,000 flights per day across the world. Therefore, using a fuel estimation model with the geodesic trajectory and a scaling factor is an acceptable and computationally efficient solution to perform a bottom-up estimate of aviation emissions, provided that corresponding uncertainties are accounted for.

We map the actual aircraft types met in the FR24 database onto the 133 aircraft types available in the Seymour et al. [15] study. We have complemented the database by assigning an equivalent aircraft (available in Seymour et al.) to a range of aircraft based on BADA. The list of equivalent aircraft assigned to aircraft missing from the Seymour et al. database is available in section S6.

For aircraft with no equivalence in the Seymour et al. study, average coefficients were used for categories of commercial aircraft and business jets (see section S7). For flight data that do not contain any indication at all on the aircraft type, average coefficients from all aircraft considered in the Seymour et al. study have been used. These default values were applied to fewer than 0.6% of the flights. The flowchart of the aircraft fuel consumption calculation is available in section S9.

Our approach has several limitations that are sources of uncertainties. First, it should be noted that the fuel estimation model takes into account the aircraft types but not the specific engine mounted on the aircraft. Indeed a given aircraft can be equipped with different engine types but this information is not present in the FR24 database. Second, as the model is a quadratic regression of several flights, it cannot be considered as being accurate for a specific flight. Seymour et al. [15] estimated the error of fuel consumption to be below 5% for a given flight.

For the emissions analysis, we also distinguish domestic travel (i.e., flights within a country, including their overseas territories when relevant) from international travel. For this purpose, the European Union (currently composed of 27 countries, or EU27) is seen as one country, with flights within EU27 being counted as domestic and flights in and out being counted as international. Emissions for domestic flights are attributed to the corresponding country while emissions from international flights are split equally between the countries of origin and destination. Flights between the mainland of a country and its islands or overseas territories were counted as domestic flights of that particular country.

3. Results

We estimate global CO_2 emissions for 2019 at 895 Mt CO_2, which is close to the results of Teoh et al. [3] but 5% and 3% less than Quadros et al. [1] and the International Council on Clean Transportation (ICCT) [18], who estimated emissions of 893, 937 and 920 Mt CO_2, respectively. These estimates are for the same year and rely on similar bottom-up approaches. Differences are within the 5% uncertainty range expected from the use of the FEAT model. In contrast, Lee et al. [4] estimated that aviation emitted 1034 Mt CO_2 in 2018, using top-down International Energy Agency (IEA) data on usage of Jet-A and aviation fuel for 2016 and a linear scaling factor to consider the growth of the aviation sector. However it should be noted that the Lee et al. [4] estimate also includes emissions from military aviation. Possible reasons for the differences will be discussed in Section 4.

Some statistics for civil aviation traffic and CO_2 emissions for the period between 2019–2023 are presented in Table 1. For the year 2019, the FR24 database contained more than 42 million flights with a total distance flown of more than 57 billion km. The impact of flight disruptions in response to the Covid-19 pandemic is clearly seen in the decreased number of flights for the rest of the period studied. Despite having more flights and kilometers flown, the rolling average of October 2023 to September 2024 does not reach pre-Covid emissions levels. The fractions of flight, distance, and emissions are also highlighted for our four categories of aircraft. General aviation, excluding business jets, represents a significant number of aircraft and flights but accounts for about 1% of CO_2 emissions. Narrowbody, widebody, and business jets thus represent 99% of the emissions.

Table 1. Summary of statistics (number of flights, distance flown, and CO_2 emissions) of civil aviation for the period between 2019–2024. The last column represents the annual rolling average for the period between October 2023 to September 2024.

		2019	2020	2021	2022	2023	2023–24
Number of flights (millions)		43.7	27.4	34.1	37.4	43.0	45.5
	Domestic flights	28.2	20.1	24.9	25.2	28.4	29.7
	International flights	15.5	7.4	9.2	12.2	14.6	15.8
Total distance flown (10^9 km)		59.2	32.6	40.5	47.7	57.1	60.8
	Domestic distance	26.2	17.9	22.9	22.8	26.5	27.4
	International distance	33.1	14.7	17.6	24.9	30.5	33.4
Total emissions (Mt CO_2)		895	477	563	683	825	879
	Domestic emissions	312	210	262	267	315	323
	International emissions	583	267	300	416	510	556
Fraction of flights (%)	Widebody	9.3	8.8	8.0	8.3	8.6	8.6
	Narrowbody	74.2	62.9	62.2	69.6	71.7	71.1
	Business jets	7.0	9.9	11.8	7.4*	6.8*	6.7*
	General aviation	9.5	18.4	18.1	14.7	12.9	13.6
Fraction of distance (%)	Widebody	29.5	29.2	26.4	27.6	27.8	28.0
	Narrowbody	63.8	59.1	60.2	64.0	65.1	65.0
	Business jets	4.8	7.7	9.4	5.3*	4.4*	4.3*
	General aviation	1.9	4.0	4.1	3.1	2.6	2.6
Fraction of emissions (%)	Widebody	48.1	48.4	45.0	45.5	45.7	46.1
	Narrowbody	49.9	47.7	50.5	51.8	52.1	51.8
	Business jets	1.4	2.2	2.9	1.5*	1.3*	1.2*
	General aviation	0.7	1.7	1.7	1.1	0.9	0.9

∗ We have reasons to believe that the ADS-B dataset is incomplete in 2022, 2023, and 2024 for this category. See main text.

There is a large difference between the respective shares of widebody and narrowbody aircraft. In 2019, emissions from widebody aircraft represented 48% of total aviation emissions for only 10% of the flights. In contrast, narrowbody aircraft were responsible for 50% of the emissions but accounted for 76% of the flights. The rest of the flights were attributed to business jets and general aviation. Looking at average emission per flight, narrowbody aircraft emit 7 times less per flight but their missions are 3 times shorter. On a km basis, the average emission for a widebody aircraft is double that of a narrowbody aircraft, with 24.3 and 11.8 kg CO_2/km, respectively. Assuming an average passenger load of 82% [19] and a typical number of passenger seats per aircraft type [14], the average emissions on a km-passenger basis is found to be higher for narrowbody aircraft (~110 gCO_2/km/pax) than for widebody (~85 gCO_2/km/pax).

3.1. Evolution of aviation emissions since Covid-19

The aviation sector was strongly affected by the Covid-19 pandemic and subsequent travel restrictions that started in the first quarter of 2020. A large number of planes were grounded for several months and the traffic is still recovering. Figure 1 shows the time evolution of the monthly global CO_2 emissions over the period from January 2019 to September 2024.

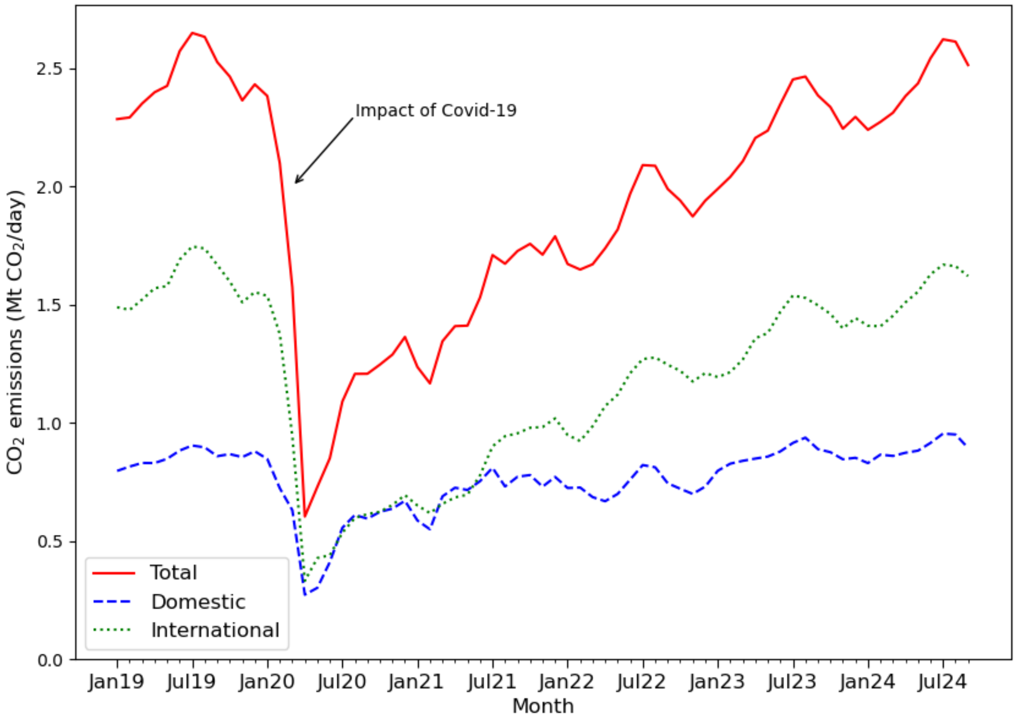

Figure 1. Evolution of aviation CO_2 emissions (in Mt CO_2 per day) worldwide for the period from Jan 2019 to Sept 2024. The dashed blue curve represents emissions from domestic flights, the dotted green curve represents emissions from international flights, and the solid red curve is the total. Data are daily averages per month with flight emissions assigned to the day of the flight departure.

Domestic flights were quicker to recover from the pandemic disruption than international flights. Table 2 highlights the impact of the Covid-19 pandemic on the number of flights and emissions during the peak period of lockdown from March to May 2020. Globally, traffic dropped by 57% during this period, with a greater effect for international flights than domestic ones. Our estimates show that emissions from commercial aviation between March to May 2024 are at 98% of their 2019 level, specifically 103% for domestic flights and 96% for international flights. Globally, after the drop observed in the Spring of 2020 and up to the Summer of 2024 (at the time of writing this study), aviation CO_2 emissions have been increasing at an average rate of 3% per month. Traffic in 2024 is higher, globally, for domestic and international traffic. However, international emissions are still lower than in 2019 and have not reached their 2019 level yet. The reason behind the higher number of flights and lower emissions will be seen in section 3.4.

Table 2. Number of flights (in thousands) and CO_2 emissions (in Mt CO_2) from aviation as estimated in this study. The computations are made for the period from March to May to highlight the peak period of the pandemic lockdowns in 2020. The percentage was computed relative to the same months in 2019.

	March–May					
	2019	2020	2021	2022	2023	2024
Total flights (10^3)	10,881	4,689	7,970	8,964	10,620	11,401
Domestic flights (10^3)	7,042	3,488	6,140	6,062	7,071	7,427
International flights (10^3)	3,839	1,201	1,831	2,902	3,549	3,974
Total flights relative to 2019	-	43%	73%	82%	98%	105%
Domestic flights relative to 2019	-	50%	87%	86%	100%	105%
International flights relative to 2019	-	31%	48%	76%	92%	104%
Total emissions	220	89	127	160	200	216
Domestic aviation emissions	77	37	65	63	78	79
International aviation emissions	143	52	62	97	123	137
Total relative to 2019	-	41%	58%	73%	91%	98%
Domestic emissions relative to 2019	-	48%	85%	82%	101%	103%
International emissions relative to 2019	-	37%	44%	68%	86%	96%

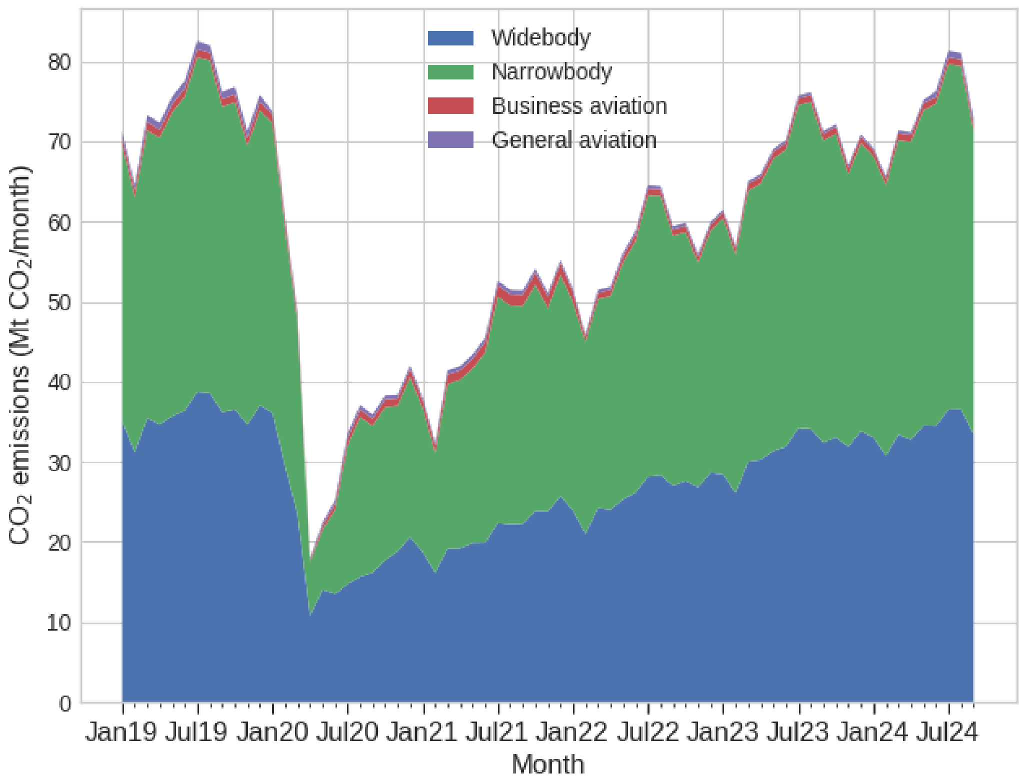

Figure 2. Monthly emissions per aircraft category, as defined in section 2.2, over the period from January 2019 to September 2024.

We also observe a shift of emissions as a function of the aircraft category before and during the pandemic. Figure 2 shows the evolution of monthly emissions for the four categories of aircraft (widebody, narrowbody, business jets, general aviation). In 2019, narrowbody aircraft accounted for a majority of emissions. However, during the 2020 lockdowns due to the Covid-19 pandemic, there was a temporary shift to a majority of widebody aircraft. This can be attributed to the fact that the decline in traffic was more pronounced for shorter flights (due to their high number of flights operated on a daily basis) than for longer ones and given that widebody aircraft burn more fuel per flight. Figure 2 indicates that narrowbody aircraft accounted for the majority of emissions again after July 2021.

The decline did not extend to cargo operations which continued and even increased during the lockdowns that occurred worldwide. Cargo flights represented 9% of the emissions for the period between March–May 2020, equivalent to 7.97 Mt CO_2, whereas they were responsible for only 3.3% of emissions in the equivalent period in 2019, equivalent to 7.12 Mt CO_2, which corresponds to a 12% increase. Cargo operations represented 6.2%, 4.7%, and 3.7% of the CO_2 emissions in 2021, 2022, and 2023, respectively.

The recovery of air traffic has not been uniform across destinations and countries. International routes were more impacted than domestic routes due to restrictions related to the pandemics in various countries. As noted above, narrowbody aircraft were more impacted during Covid-19, and therefore it is not accurate to identify domestic travel with narrowbody aircraft and international travel with widebody aircraft. Since the proportion of domestic flights is higher for large countries such as China, Russia, or the United States, air traffic in these countries recovered faster. The same is true for the European Union where domestic travel recovered quickly to the pre-Covid level but international flights are still below their pre-Covid level.

3.2. Spatial and temporal distribution

3.2.1. Emissions per region

To investigate the regional variations in air traffic emissions, the world was divided in different regions. The American continent was separated in three regions, namely North, Central, and South America. Europe forms one region. Belarus, Ukraine, Russia, and Central Asia are grouped together under Eastern Europe and Central Asia (EECA). Middle East represents one region. China and Eastern Asia are grouped under East Asia. Africa and Oceania form the rest of the regions. To better visualize emissions by countries, the United States (US), EU27, and China were also separated from their respective regions.

Aviation emissions from these regions for the year 2019 are shown in Figure 3. Three regions (North America, Europe, and Eastern Asia) account for about 75% of total emissions. The Middle East accounts for 10%. The other regions are responsible for about 3% each. Among the main three regions, the US is the largest emitter as a country as it represents most of the emission in North America. EU27 is the major emitter in Europe and China emits 35% of East Asian emissions. No significant changes in aviation emissions distribution across the world happened between 2019 and 2024.

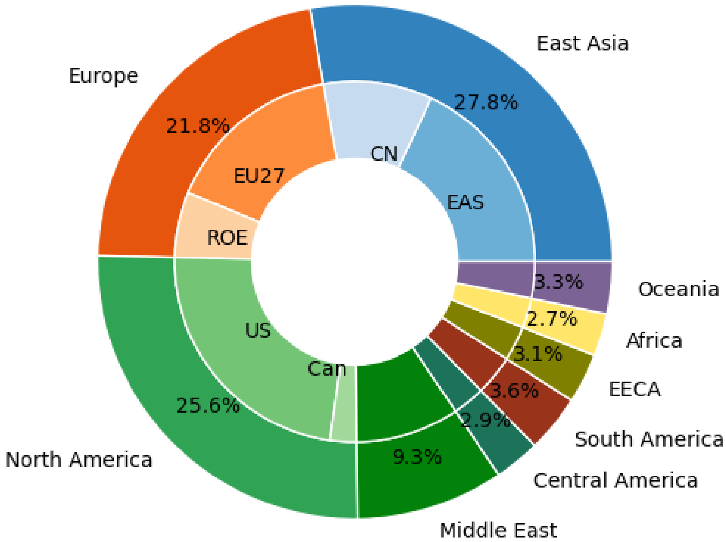

Figure 3. Distribution of aviation CO_2 emissions in 2019 across our defined regions. Emissions are further disaggregated in the inner circle. EAS represents East Asia without China, CN: China, EU27: European Union, ROE: Rest of Europe, US: United States, Can: Canada, EECA: Eastern Europe and Central Asia. A map representing the regions is available in section S12.

Table 3. Percentage of the flights and emissions for different routes in 2019 and the rolling average from October 2023 to September 2024, sorted in decreasing contribution to total emissions in 2019. Only the 10 most CO_2 emitting routes are shown.

Routes	2019		2023–2024	
	% flights	% of emissions	% flights	% of emissions
Intra Asia	23%	19%	24%	19%
Intra North America	34%	18%	32%	17%
Intra Europe	17%	9.2%	16%	9.5%
North America $\Longleftrightarrow$ Europe	1.0%	7.1%	1.1%	7.1%
North America $\Longleftrightarrow$ Asia	0.5%	5.9%	0.5%	5.5%
Europe $\Longleftrightarrow$ Asia	0.5%	5.5%	0.5%	4.9%
Middle East $\Longleftrightarrow$ Asia	1.1%	4.3%	1.3%	4.9%
Middle East $\Longleftrightarrow$ Europe	1.8%	4.3%	2.1%	4.6%
North America $\Longleftrightarrow$ Central America	2.2%	2.2%	2.4%	2.6%
Oceania $\Longleftrightarrow$ Asia	0.4%	2.1%	0.3%	2.0%

Emissions from different routes between regions are also unevenly distributed. Table 3 lists the most emitting routes in the world. Flights within individual regions represent the majority of the flights, with close to 73% of the flights, and are responsible for 46% of the emissions when combining North America, Europe, and Asia. The number of flights connecting regions between them is much smaller. No single connecting route represents more than 3% of the flights. However, inter-region flights can be responsible for a substantial portion of total emissions. With 7.7% of the total, the North America/Europe route is the most emitting international route. Between 2019 and the rolling average of 2023–24, we have seen an increase in flights connecting the different regions except for flights to Asia from North America, Europe, or Oceania (and vice-versa). More information on the localization of emissions is available in the SM, section S1.

3.2.2. Temporal cycles

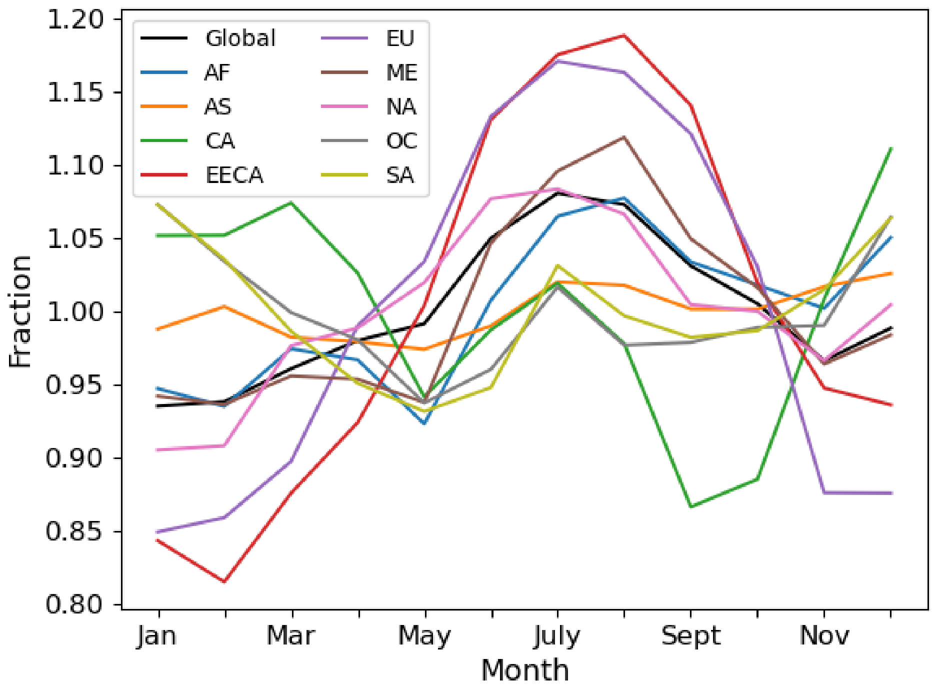

Figure 4. Annual cycle of CO_2 emissions in 2019 for different regions across the world. The annual cycle is normalized to the annual mean for each region. Global represents the whole world. AF: Africa, AS: Asia, EU: Europe, OC: Oceania, CA: Central America, EECA: Eastern Europe and Central Asia, ME: Middle East, SA: South America, NA: North America.

We now examine the annual and weekly cycle of CO_2 emissions for these regions for the year 2019 as it is more representative than the years 2020–2023 that were strongly impacted by the pandemic. Annual cycles are estimated from the ratios of the monthly to the annual average. Weekly cycles are estimated from the ratios of the daily to the weekly average. For the weekly cycle, emissions were attributed to the weekday of the departure as estimated from the local time.

It is important to highlight the differences between the Northern and Southern Hemispheres in the annual cycle. As seen in Figure 4, there is a peak of emissions in June–July–August (boreal summer) for most regions of the Northern Hemisphere. The opposite is true in regions of the Southern Hemisphere with the strongest traffic in December–January during the austral summer. The region with the least annual variation is Asia.

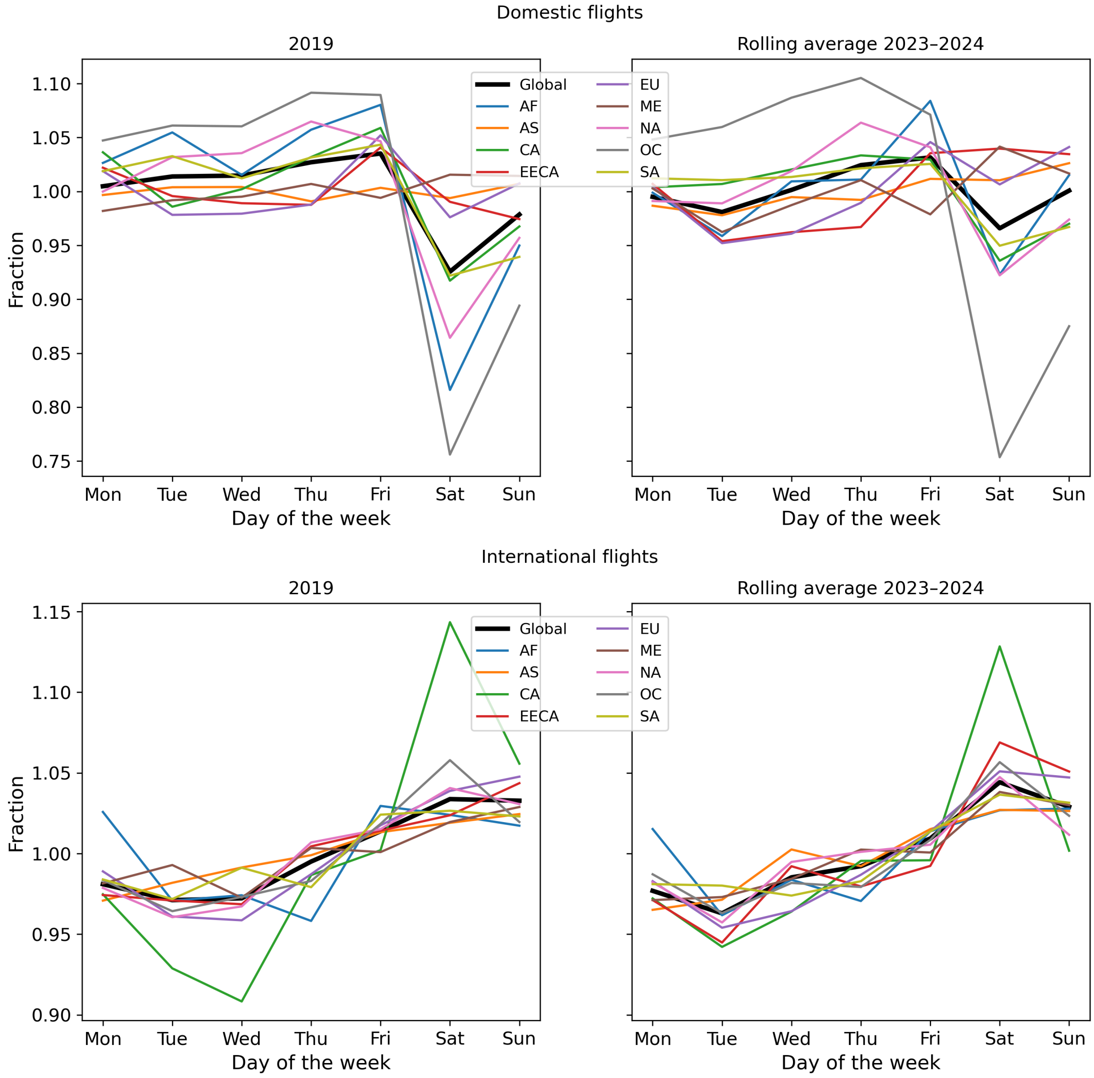

Figure 5. Weekly cycle of the CO_2 emissions for 2019 and the annual rolling average, October 2023–September 2024, on the left and on the right side, respectively, for different regions across the world. The top panel shows domestic flights, and the bottom panel shows international flights. Global represents the whole world. AF: Africa, AS: Asia, EU: Europe, OC: Oceania, CA: Central America, EECA: Eastern Europe and Central Asia, ME: Middle East, SA: South America, NA: North America.

The weekly cycle of CO_2 emissions also differs from one region to another. Domestic and international flights were separated in Figure 5 to highlight the potential differences in their weekly cycle. Regarding domestic flights, for most regions of the world, the busiest day is toward the end of the week (usually Thursday or Friday). The strength of the weekly cycle for domestic flights varies a lot across regions. International flights have a distinct and more uniform weekly cycle: all the regions have an increase in emissions from Wednesday to the weekend. The peak happens in all regions on Saturday.

There were no significant changes in the temporal and spatial distributions of global aviation between the years 2019 and 2023–2024. The regional distribution of emissions is similar between 2023–24 and 2019. The same is true for the annual and the weekly cycles of domestic and international flights, as shown in Figure 5. While slight differences can be observed, the overall variations remain consistent. Aviation traffic dropped drastically due to the Covid-19 pandemic in 2020, but since then, traffic bounced back, with traffic patterns remaining largely unchanged.

3.3. Distribution by flight distance

We now examine emissions by the class of flight distance (not considering general aviation). Flights were separated by their distance: regional flights below 800 km (typically a 1-hour flight or less), short-haul flights between 800 to 2400 km (between 1 and 3 hours), medium-haul flights between 2400 to 4800 km (3 to 6 hours), and long-haul flights above 4800 km (more than 6 hours). We calculated that flights below 3000 km represent almost half of the emissions from civil aviation, with medium-haul and long-haul flights representing 19% and 36%, respectively, of the total emissions as seen in Figure 6. The figure also provides a visual representation of emissions by flight distance (short-, medium-, and long-haul) for the three main regions. In Europe, more than 50% of the emissions come from long-haul flights. In Asia, this number is slightly lower, around 44%, whereas in North America, the distribution between the different distances is more homogeneous.

Figure 6 provides a comparison between two different periods, 2019 and the annual rolling average between October 2023 and September 2024. The inner circle represents traffic in 2019 while the outer circle represents traffic in 2023–24. Similarly, with regard to the spatial and temporal distributions, no significant changes can be identified for the two periods. The traffic remained consistent and unvaried.

Figure 6. Pie charts of aviation CO_2 emissions (in Mt CO2) in 2019 (inner circle) and for the period between October 2023–September 2024 (outer circle) for the world, Europe, Asia, and North America for different flight ranges. The percentages of emissions are also indicated. For international flights, emissions are attributed 50% to both the origin and destination countries.

Figure 7 gives a more detailed comparison of the emissions by distance with a step of 500 km. The cumulative fraction of flight numbers and CO_2 emissions for three main regions are analyzed along with the same quantities at the world level. Several elements are worth noting. First of all, regional and flights shorter than 1000 km account for a large fraction of the total flight number but a small fraction of total emissions: the 50% shortest flights are responsible for less than 20% of the emissions. Flights shorter than 2000 km represent 80% of flights and 40% of emissions. Second, the figure can be read the other way around. Long-haul flights represent a very small fraction of total flights, yet their contribution to emissions is very high. Flights longer than 4000 km represent around 6% of flights but 40% of emissions. Across the world, we estimate that 2% of flights (those longer than 8000 km) are responsible for 20% of aviation CO_2 emissions. The longer the flight, the more fuel has to be carried, which means additional consumption. For these long flights, the average emissions on a km-passenger basis is found to be higher than the average value for widebody aircraft calculated in section 3, at 96 g CO_2/km/pax, assuming the same average passenger load of 82%.

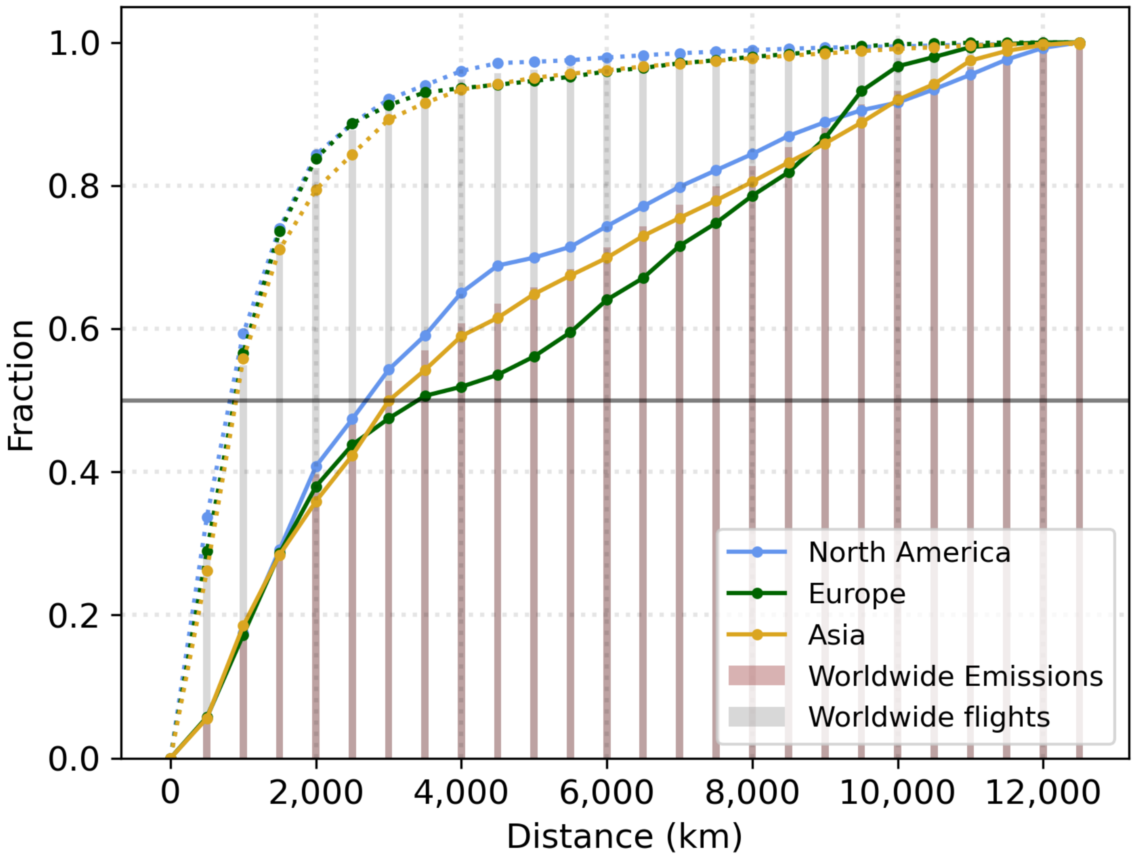

Figure 7. Cumulative fraction of flights (gray bars for the world and dashed colored lines for North America, Europe, and Asia) and CO_2 emissions (brown bars for the world and solid colored lines for North America, Europe, and Asia) for the year 2019. A step of 500 km has been used to categorize the flights by distance. For this graph, all emissions were attributed to the origin country.

Going beyond these global numbers, we can observe differences between different regions of the world. On the one hand, in terms of emissions, the median distance value is different for each of the three emitters studied, namely North America, Asia, and Europe. It is around 2600 km for North America, 3000 km for Asia, and 3500 km for Europe. The numbers are in alignment with the numbers in Figure 6. It should be noted that, for this analysis, emissions were attributed entirely to the origin country. The median distance globally is shorter in the annual rolling average of 2023–24, at ~2600 km, compared to 2019, when it was at ~3000 km due to fewer international flights following the Covid-19 pandemic in 2020. This is consistent with Table 1. Domestic emissions recovered faster and actually exceeded the number in 2019 whereas international flight emissions are still slightly behind. On the other hand, in terms of the number of flights, the median distance value is similar for the various regions, with a median distance of approximately 1000 km. This indicates that 50% of flights are less than 1000 km.

3.4. *Impact of fleet evolution*

It is important to study the evolution of the fleet and its emissions to understand the drivers and the barriers to the necessary decarbonation of aviation. Here, we focus on commercial aviation only and ignore business and general aviation that are responsible for 2–3% of the emissions as seen in Table 1. Furthermore, we consider only new generation aircraft with an MTOW larger than 20 tonnes and divide them into two mains categories: narrowbody and widebody. We also define new generation aircraft arriving into the fleet and old generation aircraft. We consider aircraft to be "new" when they include a new generation of engine and/or a newly designed frame. Therefore, not all aircraft currently being introduced on the market can be considered "new". The list of new generation aircraft is available in section S4, and is similar to the one Airbus [20] used for its calculation where it computed that 25% of the fleet were considered new generation aircraft in 2023. The distribution of the fleet in Figure 8 shows that 80% of total aircraft flying are narrowbodies, with two types of aircraft (the A320 and the B737 families) representing the majority. In 2019, only 5% of the fleet belonged to the new generation; that number climbed to 22% at the end of 2023. At this current pace, the total renewal of the fleet with new generation aircraft would take 20–25 years. A significant increase in the total number of aircraft can be seen (~21,500 at the beginning of 2019 and ~24,500 in 2023), which highlights the growth of the traffic.

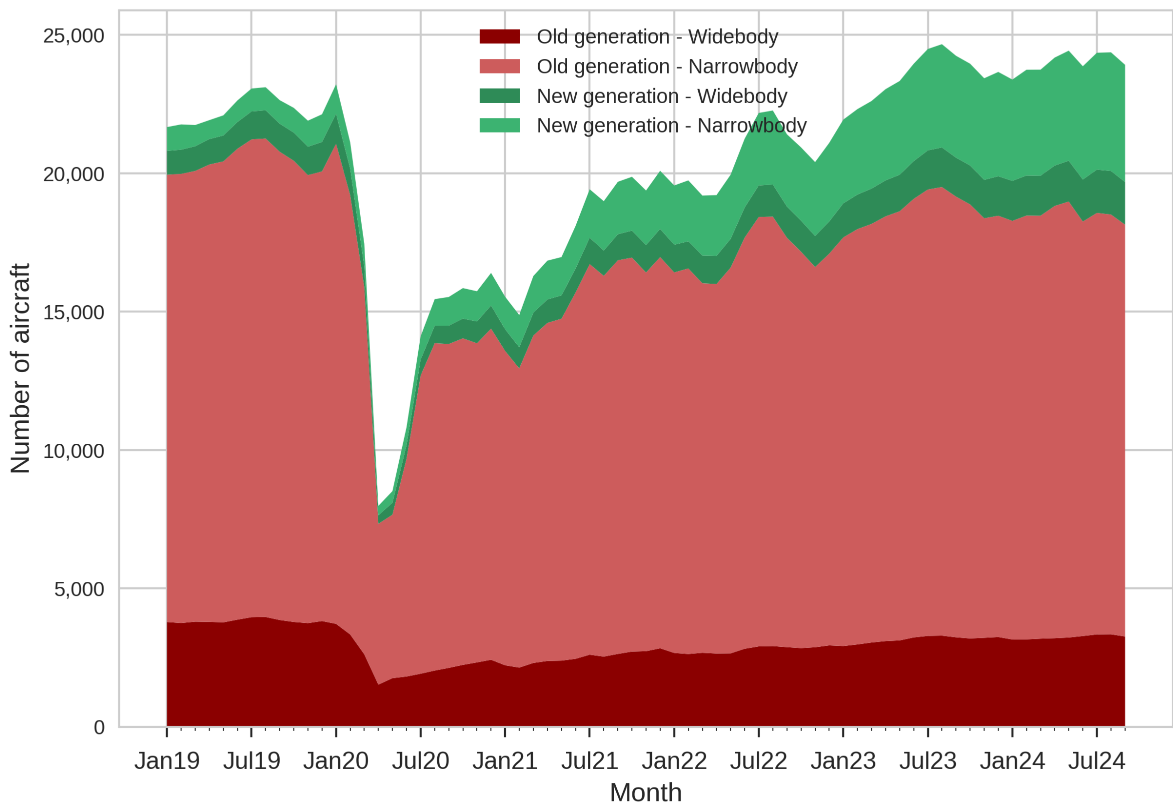

Figure 8. Evolution of the daily number of unique aircraft in operation averaged per month by generation (old and new) and by class type (narrowbody and widebody aircraft) for the period from January 2019 to September 2024.

The new generation of aircraft arriving on the market has a fuel consumption lowered by around 20%–25%, depending on the aircraft type, compared to the old generation [21, 22, 23]. More information is available on the efficiency of these aircraft in section S4 of the SM. As the number of aircraft in operation across the world continues to grow, new generation aircraft do not automatically replace old generation aircraft. This means that the renewal of the fleet could take longer and CO_2 emissions may not decrease immediately.

To gain further insight in this issue, we decompose the emissions as:

$$E = K \cdot < AS > \frac{E}{K \cdot < AS >} \tag{1}$$

where $< AS >$ stands for the average available seats (computed as the total number of available seats divided by the total number of flights) and K is the total kilometers flown. The overall emission per unit available seat per kilometer, ASK, denoted as $E/(AS \cdot K)$, is expressed in g CO_2/km/seat.

The evolution of aviation's carbon intensity is shown in Figure 9, along with the total numbers of flights, available seats, and kilometers flown. The emission per unit ASK (E/ASK) decreases throughout the 4-year period, as new generation aircraft join the fleet. However, we also see an impact of Covid-19 as the quantity depends both on the fleet being used through changes in the available seats and the distance flown. For example, during the Covid-19 pandemic, domestic flights were shorter and smaller aircraft were used, which have made air traffic less efficient. The opposite appears to be true for international flights, which were more efficient during this period. Our estimate should be considered conservative for this period for the reasons explained in Section 4. More information on the evolution of these quantities in different regions of the world can be found in section S1. Figure 9 also highlights the evolution of the fleet average flight distance and available seats. Throughout the whole period, there were no significant differences in the average figures between 2019 and latest data in 2024. However, in terms of overall figures, whether in flight numbers, seats available, or distance flown, there has been a notable increase between 2019 and the most recent data from 2024.

The emission per unit ASK of air travel has decreased by 8% in the 4 years between 2019 and 2024. Considering only commercial aircraft, the number of flights and available seats were slightly higher in 2023 compared to 2019 but the number of kilometers flown in 2023 was still slightly lower. The difference can be explained by the faster recovery of domestic flights than international ones after the Covid-19 pandemic. There were more short-haul flights than long-haul flights, which explains the differences in emissions. The decrease in emissions can be also attributed to the incorporation of new generation aircraft in the fleet as more narrowbody aircraft, which are used for short-haul flights, join the fleet. This is also true for widebody aircraft used for long-haul flights, although to a lesser extent due to the fast incorporation of new generation narrowbody aircraft in the fleet.

This disaggregation between old and new generation aircraft allows us to estimate what would have happened if the fleet had not been renewed. We first compute E/ASK for the old generation for narrowbody and widebody aircraft and different classes of flown distance. We denote i as the index for the distance classes by a step of 500 km [i.e., 0–500, $\cdots$, 15,000–15,500] and k the index for narrowbody or widebody aircraft. Projected emissions without fleet renewal were calculated as:

$$E_{projected} = \sum_k \sum_i \frac{AS_{i,k} \, K_{i,k}}{N_{i,k}} \left(\frac{E}{ASK} \right)_{2019,i,k} \tag{2}$$

where $(E/ASK)_{2019,i,k}$ is estimated as in Eq. 1 but considering only flights pertaining to class i and aircraft type k in year 2019.

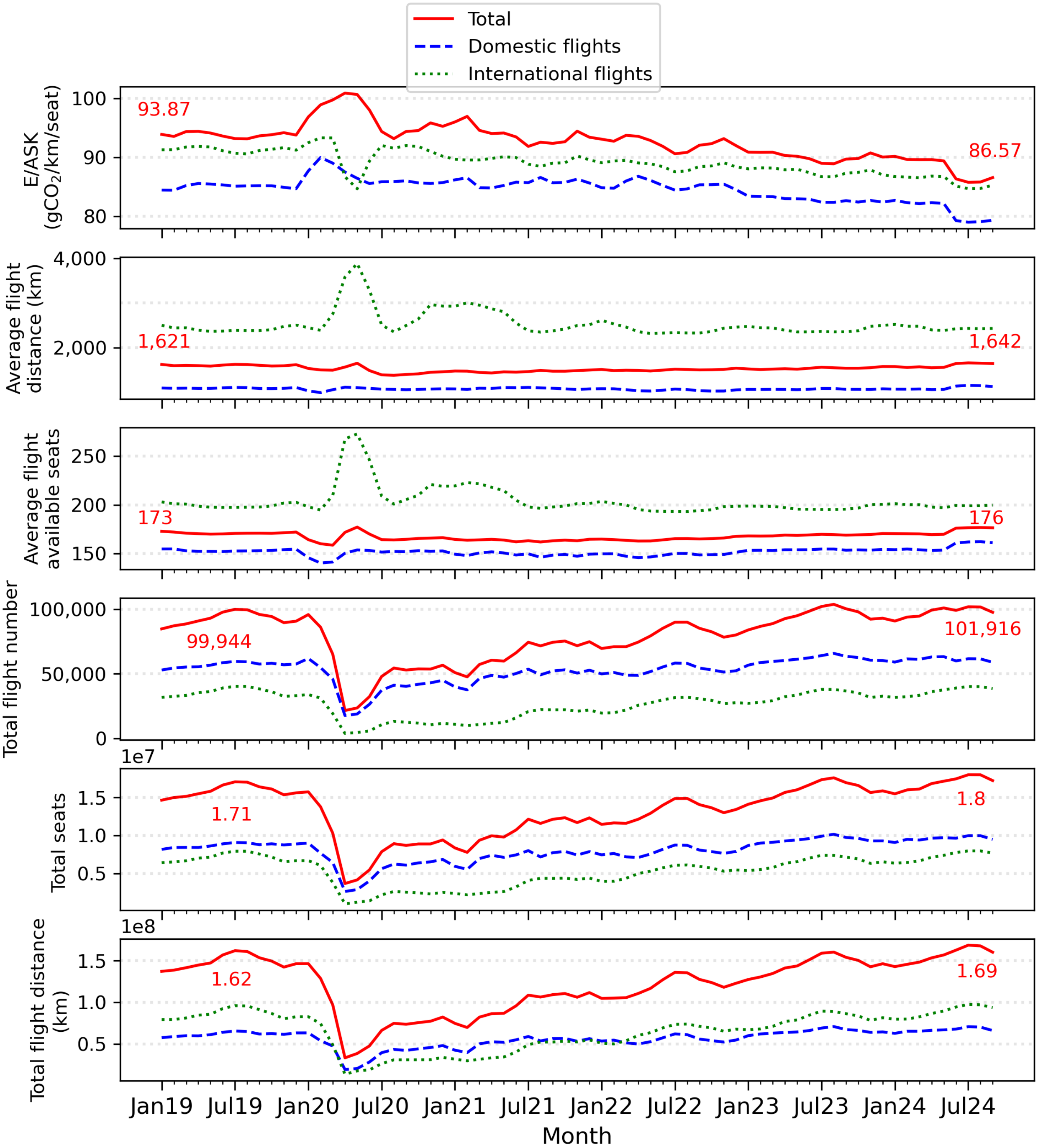

Figure 9. Evolution from top to bottom of the emission per unit ASK in g CO_2/ASK, the average flight distance (km), the average flight available seats, the total flight number per day, the total available seats per day, and the total kilometers flown per day (km) for the whole world, for the period from January 2019 to September 2024. The first and last values for the period for E/ASK, average flight distance and available seats are shown for the total flights, while maximum values in 2019 and 2024 are shown for the total numbers.

We estimate the cumulative emissions avoided by the incorporation of new generation aircraft in the fleet to be 144 $MtCO_2$ for the period between January 2019–September 2024, with the largest majority, 42 $MtCO_2$, occurring in 2023 as more new generation aircraft joined the fleet. The period between January–September 2024 account for 37 $MtCO_2$ saved.

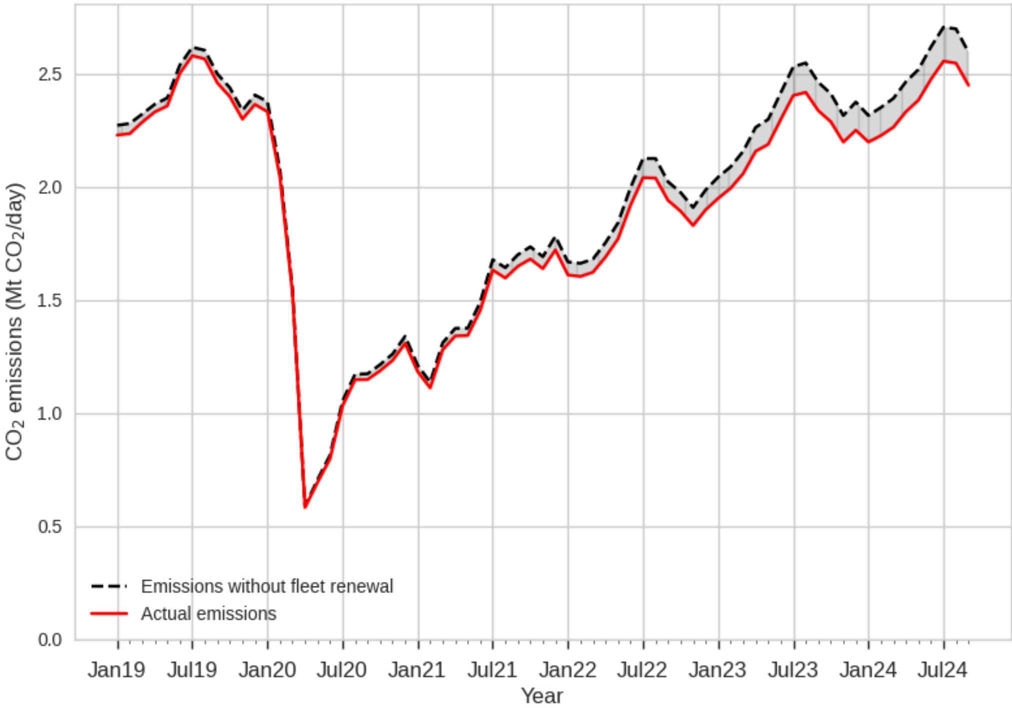

Figure 10. Daily aviation CO_2 emissions, in Mt CO_2/day, of the actual fleet (red line) and a hypothetical fleet with no aircraft renewal from the new generation (dashed black line).

Figure 10 shows that even without fleet renewal, emissions in 2023 would still have been lower than in 2019 even though the peak in flight numbers in 2023 was higher that in 2019 (Figure 9). This points to a different distribution between domestic and international flights between 2019 and 2023 with more domestic flights in 2023. The total distance flown was still slightly lower in 2023 compared to 2019, which explains the lower projected emissions in 2023. Table 1 indicates that the number of flights for the rolling average between October 2023–September 2024, either domestic or international, exceed the number in 2019. Emissions are still 2% lower due to the increase in new generation aircraft in the fleet, as is seen in Figure 10. However air traffic continues to grow so fleet renewal is not sufficient to halt the growth of CO_2 emissions and it is expected that 2024 emissions will reach or even exceed those of 2019.

4. Discussion

The discrepancy between top-down and bottom-up aviation emissions is well known and is around 10% [4]. Our study confirms this finding and does not reduce the gap. There are several reasons for it.

First, military flights are not included in flight databases, both for security reasons and also because it would be necessary to have access to many points of the trajectory, as some military flights take off and land at the same airport. According to the ICCT [18], military flights can account for around 10%

of aviation emissions, but uncertainties on that number are large.

Second, flights may be missing in ADS-B databases. Some peculiarities were found in the FR24 database, in particular regarding movements of business jets. Business aviation recovered more quickly than commercial aviation after Covid-19 and even surpassed its pre-Covid level in 2021 but dropped surprisingly beginning in January and February 2022. We speculate that a number of flights were withdrawn from the database for confidentiality reasons. More information on business aviation is available in the SM, section S3. Furthermore, limited comparisons between different databases (such as the OpenSky network, Eurocontrol database, or OAG) show that some flights are available in one database but not in others, and vice-versa. The completeness of air traffic databases appears difficult to establish because of differences in the format and reporting method. Yet, according to the comparison made by Quadros [1], FR24 provides the most complete coverage at the time of writing.

Third, a lower value of CO_2 emissions in bottom-up estimates may be caused by an underestimation of fuel consumption. For each specific aircraft, the fuel estimation model used is a linear regression of multiple flights and therefore cannot be as accurate as modeling a specific flight. However, considering that there are 100,000 flights every day, this method has the advantage of being computationally very fast. We also compared the fuel estimation with other models [1, 24, 25, 26, 27] for different aircraft types and distances. For the same aircraft type, the difference in consumption can be as large as 10% depending on the distance, with our estimate being generally lower than that from other models. Differences between our estimates and other models tend to increase with increasing flight distance. On average for a sample of the fleet representative of the whole database (considering the number of flights by distances and aircraft type), the average bias between our calculation and other models was around 8%. Results of such comparisons are available in section S11. An additional source of error comes from uncertainties in the take-off weight, which is a crucial parameter for accurately estimating the fuel burn. Consequently, the load factor coefficient is a significant parameter in a fuel consumption model. Seymour et al. [15] used a constant load factor of 82% in his model which, considering the period of the study during the Covid-19 pandemic, can overestimate the consumption as the load factor dropped during this period. Our study may also overestimate emissions for the period between March 2020 to May 2021. For the rest of the period when the load factor bounced back to its pre-Covid level [28], the assumption of a constant load factor could overestimate or underestimate emissions by no more than 1–2%. Seymour et al. [15] acknowledged an estimated error of fuel consumption of 5%, compared to fuel reports, which is the total difference calculated with the other studies [1, 18].

Ambitious targets have been set by the International Civil Aviation Organization (ICAO) and the United Nations (UN) for commercial aviation to reach net-zero emissions by 2050 [29, 30], and also by the European Union with a goal to reach a 55% net reduction in aviation greenhouse gas emissions by 2030 [31] compared to the 1990 level, before reaching net zero in 2050. This considers not only emissions reductions but also any carbon removal methods, such as reforestation or direct air capture. Without counting carbon offsetting, the aviation industry aims to achieve that target through a number of different solutions: 1) reduction of fuel consumption through technological progress, fleet renewal, and operation improvements and 2) decarbonizing energy through electrification, sustainable aviation fuels (SAF), and hydrogen [32, 33, 34, 35].

Considering the first aspect of a reduction in fuel consumption through fleet renewal, the reduction calculated over the 4-year period is estimated at 6% but occurred in the context of a strong rebound following the reduction in traffic caused by Covid-19. By extrapolation we estimate that fleet renewal could achieve a 15% reduction by 2030 compared to the 2019 level, but this assumes a small growth of the sector estimated at 2.2% (calculated from the peak number of flights in July 2019 compared to July 2023). The aviation sector estimates the growth to be around 3.6% per year [20]. The actual reduction through fleet renewal could thus be lower than 15% by 2030.

The second aspect in the mitigation of greenhouse gas emissions relies on the use of sustainable aviation fuels (SAF) and hydrogen. Replacing kerosene with hydrogen will be a difficult task. Hydrogen has a high energy content per mass but is difficult to store at ambient temperature and pressure and would need to be either pressurized or liquefied to be stored on an aircraft. Its use would require drastic infrastructure and design changes. Therefore, drop-in solutions such as SAF could be deployed more quickly. However, at the time of writing in 2024, the incorporation rate of alternative fuel is still low. It was less than 0.1% in 2018 [36] and around 0.2% in 2023 according to the IATA [37], which is far from the objective given by the EU to reach 2% of sustainable aviation fuel by 2025. That is the reason why we consider in our estimates that all the flights are powered with standard kerosene, Jet A-1. The production of synthetic fuel using the electrolysis of water and carbon capture storage with renewable electricity is seen as an alternative to overcome the availability of biofuel and to reduce land-use. However, given the efficiency of the electrolysis and the Fischer-Tropsch (FT) process (70% for the electrolysis and between 32–51% for FT depending of the carbon capture process) [38], the carbon intensity of the electricity should be below 60–90 gCO_2/kWh to decrease CO_2 emissions compared to kerosene. In 2021, the carbon intensity of electricity production was 260, 400, and 600 gCO_2/kWh in Europe, North America, and Asia, respectively, according to OurWorldInData [39]. Though this is expected to improve over time, the carbon intensity is far from the calculated threshold to have any benefit on the CO_2 emissions. Only a few countries with high electricity production (above 10 TWh/year) have a carbon intensity lower than 90 gCO_2/kWh, namely Costa Rica, France, Iceland, Norway, Sweden, Switzerland, and Zambia, where the majority of their electricity production is generated from either hydro or nuclear power. It is also important to consider the additional electricity required for the production of e-fuel. Converting all the current aviation fleet in North America or Europe to synthetic fuel would require 50% of the total electricity generated in those regions, while in East Asia, the number drops to 20% since the region produces around 3 times more electricity than North America and Europe according to the EIA [40].

5. Conclusions

Bottom-up estimates to quantify CO_2 emissions from aviation are being used more and more frequently. ADS-B networks and the completeness of the open-source databases are also expected to increase due to recent regulation on their use. These databases are needed to fully assess the total climate impact of aviation, taking into account both CO_2 emissions and non-CO_2 effects that depend on the trajectory of the aircraft.

Using the ADS-B database of FlightRadar24 and a fuel estimation model based on BADA, annual emissions from commercial aviation in 2019 were calculated at 895 Mt CO_2, of which 65% were from international commercial flights and 35% from domestic flights. Cargo accounted for 3.3% and business jets for 1.4% of the total emissions. CO_2 emissions as a function of flight distance was also estimated. For 2019, it was calculated that flights shorter than 3000 km account for half of the global CO_2 emissions, while representing 80% of the flights. In contrast, flights longer than 4000 km represent only 10% of the total but account for 40% of the emissions.

Global traffic plummeted due to flight restrictions following the Covid-19 pandemic. During the peak period from March to May 2020, the traffic was 60% below that of 2019, although the period also saw a partial increase in CO_2 emissions due to cargo operations. The traffic has recovered at different rates in different regions of the world. Domestic routes are recovering faster than international routes. In 2023, emissions from domestic flights were calculated to be higher than in 2019 but the total emissions were still lower due to lower international flights in 2023 compared to 2019. Emissions calculated at the beginning of 2024 indicate that the level of emissions has returned to its pre-crisis levels.

We also investigated the impact of technological progress through the introduction of new generation aircraft. The proportion of new generation aircraft was calculated to be 22% by the end of 2023. This represents a 6% reduction in CO_2 emissions for the current structure of air traffic. A 15% efficiency gain could be achievable by 2030 (compared to 2019) through technological progress and fleet renewal but it may be offset or even overcompensated by air traffic growth. The total number of active aircraft in 2023 is higher than in 2019 and is expected to double withing 20 years, thereby mitigating the reduction in emissions resulting from fleet renewal.

To meet the ambitious goal set by the Paris Agreement to limit global warming to well below 2°C, the aviation industry plans to use a range of decarbonized energies to replace kerosene. Electric aircraft would be a viable option, but only for short or regional flights. The concept of sustainable aviation fuels (SAF) is regarded as a prospective solution to the challenges posed by the aviation industry's carbon footprint. Nevertheless, it is worth noting that the incorporation rate of these sustainable aviation fuels (SAFs) remained minimal in 2018, accounting for less than 0.1% of the total fuel consumption, and has only marginally increased to approximately 0.2% in 2023. Such SAF also have drawbacks. Biofuels represent a viable option but their production at scale may compete with other land usage. The production of synthetic kerosene with electricity would, in every region of the world, result in an increase of CO_2 emissions given the current carbon intensity of the electricity mix. Thus, decarbonation of aviation, as currently envisaged in the roadmap of the industry, would necessitate both a decarbonation and a substantial increase in electricity production.

Author contributions

G.D: Computing, Investigating, Analysing, Writing. O.B: Investigating, Writing. NB: Writing. All authors contributed to the manuscript.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

O. Boucher receives consulting fees as a member of the Stakeholder Committee of Groupe ADP. All other authors have no competing interests to declare.

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Supplementary

For supplementary Information, refer to: SM.pdf.