

<https://doi.org/10.1038/s43247-024-01775-z>

Private aviation is making a growing contribution to climate change

Check for updates

Stefan Gössling ¹ ✉, Andreas Humpe ² & Jorge Cardoso Leitão³

Commercial aviation's contribution to climate change is growing, but the global role of private aviation is not well quantified. Here we calculate the sector's CO₂ emissions, using flight tracker data from the ADS-B Exchange platform for the period 2019 to 2023. Flight times for 25,993 private aircraft and 18,655,789 individual flights in 2019–2023 are linked to 72 aircraft models and their average fuel consumption. We find that private aviation contributed at least 15.6 Mt CO₂ in direct emissions in 2023, or about 3.6 t CO₂ per flight. Almost half of all flights (47.4%) are shorter than 500 km. Private aviation is concentrated in the USA, where 68.7% of the aircraft are registered. Flight pattern analysis confirms extensive travel for leisure purposes, and for cultural and political events. Emissions increased by 46% between 2019–2023, with industry expectations of continued strong growth. Regulation is needed to address the sector's growing climate impact.

Global commercial aviation is estimated to have emitted 892–936 Mt carbon dioxide (CO₂) in 2019^{1–3} and is responsible for about 4% of global net anthropogenic effective radiative forcing^{4,5}. Industry estimates suggest continued strong growth over the next two decades^{6,7}. As demand growth has outpaced efficiency gains in the past, emissions from the sector will continue to rise unless sustainable aviation fuels can be made available at scale^{8–10}. Technical and cost challenges are transition barriers to net-zero aviation^{8,11–13}.

Air transport is an energy-intensive activity, in which only a small share of the world population is involved¹⁴. Within the population of commercial air travelers, the percentile of the most frequent fliers accounts for approximately half of all emissions. Premium class flights are known to be five to nine times more carbon intense than those in economy class¹⁵. To be effective, policies designed to reduce the environmental impacts of aviation need to consider such complexities of growth, geographical distribution, and energy intensity.

Private aviation (PA) is the most energy-intensive form of air transport, but its global scale, distribution, and energy intensity remain insufficiently understood. Sun et al.¹⁶ evaluated “250 private jets” for the period 2019–2022, concluding that emissions amounted to between 0.45 and 0.5 Mt CO₂. Sobieralski and Mumbower¹⁷ assessed US private aviation during the COVID-19 pandemic (January 2019 to October 2021), finding that private air travel accounted for 6.3% of the ‘total commercial plus private aviation emissions’ in the USA in 2019, and 7.9% in 2021.

PA has received attention because of its interlinkages with climate change and emission distributions¹⁸. Users of PA have been described by industry as the “ultra-high net worth”, including about 256,000 individuals, or 0.003% of the global adult population, owning an average of US\$123

million and a combined wealth of US\$31 trillion¹⁹. Private aircraft can be owned, or accessed through demand chartering, membership programs, or fractional ownership. The sector has relevance for climate politics, as international aviation is not covered by efficient climate policies²⁰. While the scale and distribution of PA remain insufficiently understood, industry expectations point to continued growth^{21,22}.

Global climate change mitigation efforts are hampered by growth in individual economic sectors, and the energy intensity of consumption patterns of affluent population groups²³. Wealth determines per capita emissions^{23,24}, with evidence that differences in individual emissions between low and high emitters within a country are high, and up to several orders of magnitude between individuals^{18,25}. Analyses show that global emissions continue to grow^{26–28}, and that this growth is driven by the wealthiest^{23,29}.

There are two important implications: emission reductions are particularly difficult to achieve under scenarios of continued growth in economic output or wealth³⁰; and policies focused on CO₂ will disproportionately affect less affluent population groups^{31,32}. Given difficulties in reducing emissions in line with the Paris Agreement that are evident in most countries³³, a central question is how further growth in emissions can be limited. Private air transport illustrates the policy conundrum of addressing the role of the affluent, as policymakers are reluctant to focus on the wealthy and powerful³⁴. Against this background, the paper investigates the energy intensity of private aviation, its global scale and distribution, the role of events in attracting private aviation, patterns of individual aircraft use, as well as travel motives and growth trends.

¹School of Business and Economics Linnaeus University, Kalmar, Sweden. ²Munich University of Applied Sciences, München, Germany. ³Jorge Leitão ApS, Dieselvej 20 ST TV, Copenhagen, Denmark. ✉e-

Results

Energy intensity and distribution

Private aviation is energy-intensive. Our analysis identified 72 PA models marketed as business jets, with fuel consumption values ranging between 48 to 576 gph (equivalent to 182–2180 L per hour). For some aircraft models, this implies more CO₂ per hour than emitted by an average human per year (4.5 t CO₂e in 2020³⁵) (Fig. 1). Private aircraft spend 45.4% of the total flight time at >30,000 and 21.4% at >40,000 feet, suggesting that a share of emissions enters sensitive layers of the atmosphere with relevance for non-CO₂ radiative forcing^{5,36}.

The total number of private aircraft in service at the end of December 2023 was 25,993. A total of 4,301,561 individual flights (legs) were made in 2023, with a total flight time—not including taxiing—of 6,474,710 hours, or 249 h per aircraft. Weighted for aircraft models, this generated 15.62 Mt CO₂ (3.6 t CO₂ per flight) in direct emissions. The average great circle distance flown was 865.7 km, with an average speed of 575 km/h, and an average flight time of 90 min. Almost half of all flights (47.4%) cover distances below 500 km, and 4.7% of flights are shorter than 50 km (Table 1). Less than one-third of flights (29.1%) are longer than 1000 km.

The spatial distribution of private aviation is shown in Fig. 2. Most of the air traffic is taking place within the USA, followed by Europe. Central American capitals (Mexico City, Guatemala City, San José, and Panama City), as well as the Caribbean (Turks and Caicos, Anguilla, Barbados, Cancun) are highly frequented, as is the Middle East. Private air transport is less common in China and Southeast Asia, Oceania, Central and South America, except Brazil and individual capital cities (Caracas, Bogota, Montevideo, Buenos Aires). There appears to be limited private air transport in all of Africa, with the exception of South Africa and Nigeria. Some islands attract much air transport, including the Hawaiian Islands, Caribbean, Canary Islands, Cape Verde, as well as some remote destinations, including Maldives, Seychelles, Mauritius, or French Polynesia. There are also notable concentrations of air transport in specific areas: for example, the Miami area alone accounts for 6% of all PA departures.

PA use is concentrated, with six countries accounting for more than 80% of aircraft. The USA are home to about 4% of the world population, but 68.7% of all PA are registered in the country (Table 2). Brazil has the second highest number (3.5%, 927 private aircraft), followed by Canada (2.9%, 770), Germany (2.4%, 630), Mexico (2.0%; 534), and the UK (2.0%; 522). Per capita, Malta has by far the highest density of PA (46.5 per 100,000

residents), followed by the USA (5.5), Switzerland (3.8), and Austria (2.9) (Supplementary Material, Table 2).

Air transport patterns

Further insights can be derived from the analysis of spatial patterns, such as the importance of global events. Figure 3 depicts various global events and conferences taking place in 2023, including the World Economic Forum in Davos, Switzerland (16–20 January), the Super Bowl in Arizona, USA (12 February), the Conference of Parties (COP28) in Dubai (30 November–12 December), and the Cannes Film Festival in France (16–27 May). The maps illustrate that events attract considerable air transport activity, including international (WEF, COP28), national (Super Bowl), and regional (Cannes) air traffic.

One of the most relevant global events is the FIFA World Cup (Fig. 4). In 2022, the event took place in Qatar, attracting visitors from all over the world. This may have included affluent spectators, but also functionaries, or football stars owning PA³⁷.

Events can attract hundreds of individual flights, and generate considerable emissions, ranging from 1.5 kt CO₂ (Super Bowl) to 14.7 kt CO₂ (FIFA Qatar) (Fig. 5, Table 4). Total emissions from events are higher, as affluent attendees may also use helicopters, or arrive by yacht (Cannes).

The analysis of the spatial movement patterns of individual air travelers reveals considerable differences in flight numbers, emissions, min-max, and average distances (Figs. 6 and 7). These require further investigation, as very short flights (13–72 km) suggest that aircraft are moved for parking and used for pickup/delivery (for both business and leisure; Supplementary Material, Fig. 2). An indeterminable share of flights is made empty. For example, in on-demand chartering, the nearest available jet will be sent to pick up a client¹⁹.

Travel motives

The use of PA for leisure purposes is investigated for Ibiza, Spain, and Nice, France (Fig. 8), showing a clear seasonal trend of visitation peaking in summer. Arrivals are also concentrated on weekends (arrivals on Fridays, departures on Sundays), suggesting that travel motives are leisure-dominated. In Ibiza, visitation is highest in the summer (June to August).

Data also reveal that private aircraft serve the same events. The events studied (Figs. 3–5) have political, economic, cultural, and sports foci, yet are frequented by the same aircraft (Fig. 9). For example, 172 of the 595 aircraft

Fig. 1 | Private aircraft emission intensity*.

*Highlighted models are the most popular in the global fleet of PA; see also “Methods” and Table 1.

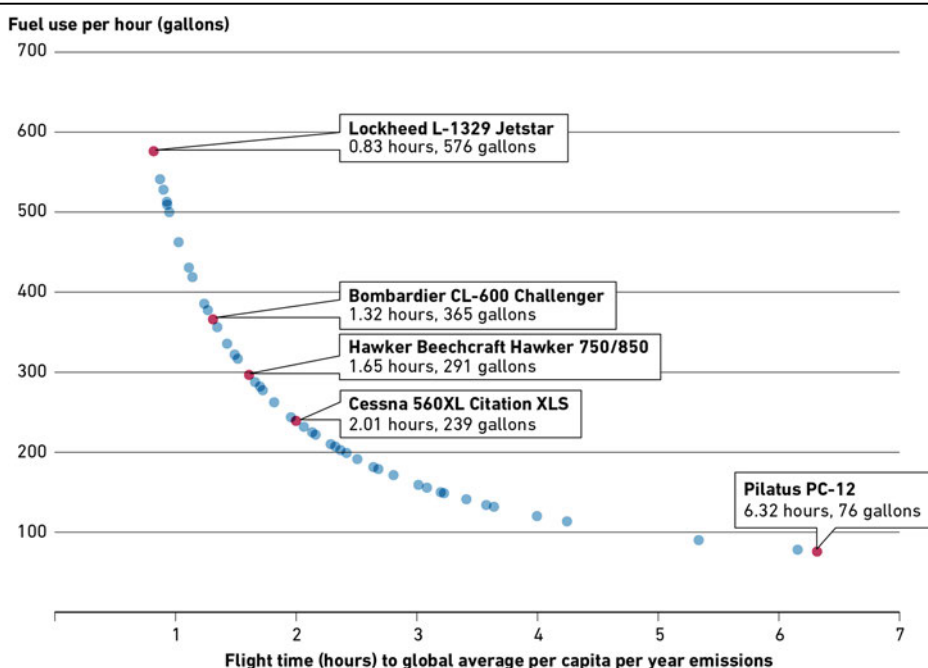


Table 1 | Trip length* distribution

Trip length (km)	# of flights	% of total	Cumulative %
<50	204,300	4.7	4.7
50–100	190,925	4.4	9.2
101–200	415,867	9.7	18.9
201–500	1,226,123	28.5	47.4
501–1000	1,012,051	23.5	70.9
>1000	1,252,295	29.1	100.0

*Great circle distances. Real distances are on average 10.1% longer.

Table 2 | National private aircraft densities

Country	Number of aircraft	% of global total	Aircraft per 100,000 residents
United States	18,163	68.7%	5.45
Brazil	927	3.5%	0.43
Canada	770	2.9%	1.98
Germany	630	2.4%	0.75
Mexico	534	2.0%	0.42
United Kingdom	522	2.0%	0.78
Switzerland	330	1.2%	3.76
Australia	317	1.2%	1.22
Austria	266	1.0%	2.94
France	248	0.9%	0.36
Malta	247	0.9%	46.51
China	213	0.8%	0.02
Argentina	167	0.6%	0.36
Portugal	160	0.6%	1.54
South Africa	160	0.6%	0.27
India	147	0.6%	0.01
Russia	139	0.5%	0.10
Turkey	137	0.5%	0.16
Venezuela	129	0.5%	0.46
Netherlands	114	0.4%	0.64

tail numbers appearing at the World Economic Forum (WEF) in Davos also served the Cannes Film Festival, and 65 identical tail numbers were identified at both the WEF and COP28. Of the 404 aircraft at COP28, 96 also appeared at the FIFA World Cup. It is not possible to say whether this means that events are attended by the same individuals, as aircraft are often chartered, though it would be of interest to further investigate travel motivations across political, economic, and cultural dimensions.

Growth trends

Data for 2019–2023 confirms PA growth trends for jet numbers (6.45% per year), distances traveled (11.31% per year) and emissions (9.93% per year) (Fig. 10). In total numbers, PA numbers grew by 28.4%, distances flown by 53.5%, and emissions by 46.0%. Growth trends are distorted by the COVID-19 pandemic, as 2020 saw a reduction in flight distances and emissions, even though aircraft numbers increased consistently (from 25,993 aircraft in December 2023 to 26,454 in February 2024 alone; see Supplementary Material, Table 1), as did the average distances flown. Emissions per km stagnated. It is less clear why the total distance flown stagnated between 2022 and 2023. One explanation may be the growing use of Privacy ICAO Addresses (PIA): according to the FAA (personal information, 19 April 2024), 283 aircraft in US airspace temporarily used PIAs in 2023.

Conclusions

The study provides a first understanding of global private aviation’s role in climate change. Total direct emissions of 15.6 Mt CO₂ in 2023 amount to 1.7% to 1.8% of commercial aviation’s CO₂ emissions. As this research only assesses direct emissions from fuel use in flight, the full impact of private aviation on climate change would have to consider the time aircraft spend taxiing, or support services such as helicopters used to reach final destinations. Non-CO₂ effects from PA require further investigation^{5,38}.

In the future, PA will become more relevant, as efficiency gains for the period 2019–2023 at around 1.25% per year (fuel use per km) are likely lower than growth rates in this market: for the period 2019–2023, our data points to a 46% increase in emissions. Industry expectations are that another 8500 business jet deliveries will be made in the period 2024–2033²². PA will thus likely become increasingly important as a source of emissions in relative (share of global emissions) and absolute terms (sector’s total emissions). As sustainable aviation fuel use remains limited, and a majority of private aircraft owners do not plan to use it in the near future²², it will be necessary to regulate the sector. There are similarities to commercial aviation, where demand and supply side management have become a focus of discussions³⁹, including reductions in air traffic¹³.

Findings also have relevance for distributional perspectives^{11,23–25}. There is a social cost of carbon (SCC)⁴⁰ that constitutes a subsidy to emitters under current policy regimes, which have only internalized a small share of the SCC³⁵. This should also be seen in light of energy use patterns. As the analysis of travel patterns shows, 18.9% of flights are short (<200 km), and many are empty, delivery, or pickup flights. Findings also confirm that PA are used routinely, and in many instances appear to replace cars for time gains or convenience, as evident from the 4.7% share of very short flights below 50 km. As seasonal and weekly arrival peaks in popular holiday destinations show, many flights are made for leisure purposes.

The analysis shows that individuals using PA emit disproportionately more than an average human. This illustrates the sector’s relevance from distributional per capita viewpoints, and its relevance for climate policy. As many flights are made for leisure, findings thus also have relevance for tax authorities, as private aircraft expenses, including fuel, maintenance, and management costs, can be tax-deductible when the aircraft is used for business purposes (for the USA)⁴¹. To monitor PA is fundamental to understanding and managing the sector. This may become more difficult in the future, as the use of PIA is growing and will potentially lead to a declining quality of ADS-B data for emission assessments.

Methods

Inclusion of aircraft models

Private aircraft are defined as aircraft models primarily intended for transporting individuals. To identify the range of private aircraft models, marketing materials were manually analyzed. In total, 72 aircraft models were identified, based on the definition of being marketed as ‘business jets’ by manufacturers or brokers.

ADS-B data

For air traffic control and monitoring, aircrafts are required to switch on the Automatic Dependent Surveillance–Broadcast (ADS-B) transponder during flight^{42,43}. ADS-B enhances airspace safety by offering a precise tracking of aircraft in real time. There are only very few exceptions to this rule, such as military operations. The ADS-B data was retrieved from ADS-B Exchange (<https://www.adsbexchange.com>), a platform that offers comprehensive and unfiltered traffic data for every aircraft on a 60 s basis. For each aircraft, the dataset contains timestamp, latitude, longitude, barometric altitude, and an indicator of whether the aircraft is grounded. For this project, the entire database for private aircraft was retrieved for the period 2019 and 2023, totaling 1.8 TB of data related to a total of 18,655,789 legs (individual flights).

ADS-B Exchange is a flight-tracking website and supplier of ADS-B data. Earlier studies have pointed to FlightRadar24 as the provider of the most comprehensive data, in comparison to OAG (Official Airline Guide) and OpenSky², but ADS-B Exchange is the only supplier that does not filter

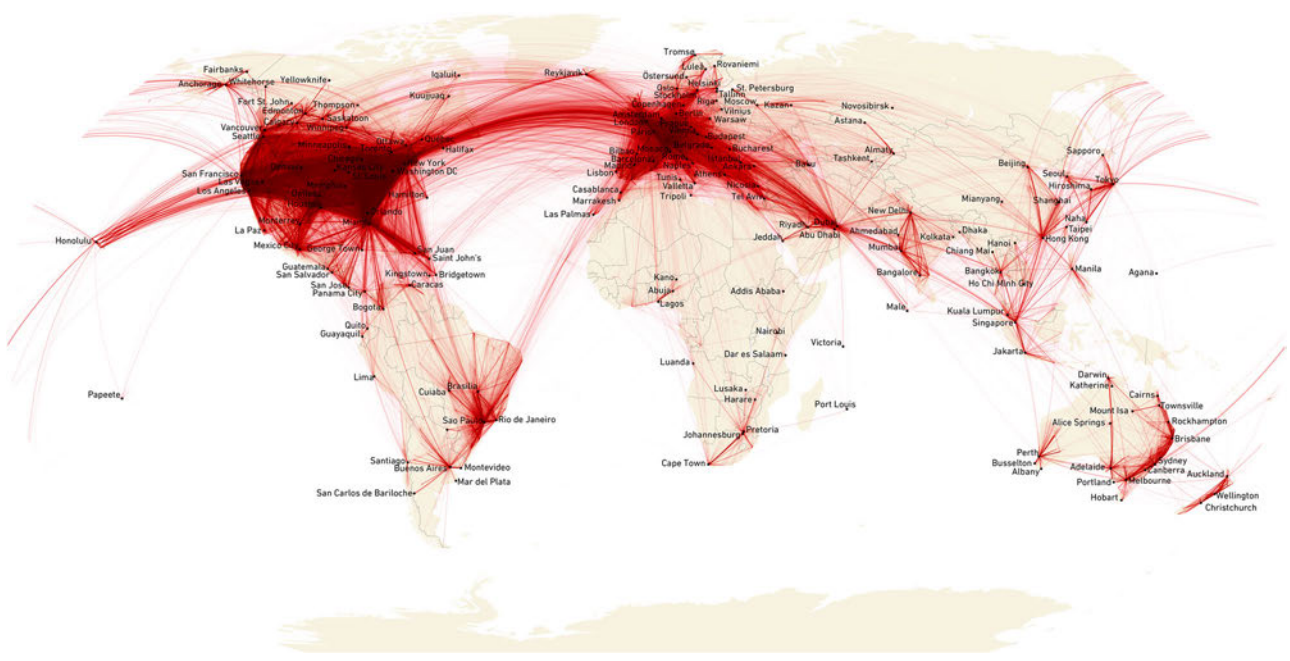


Fig. 2 | Geospatial pattern of private aviation, 2023*. *Lines depict direct connections between city pairs, considering 4.3 million flights.

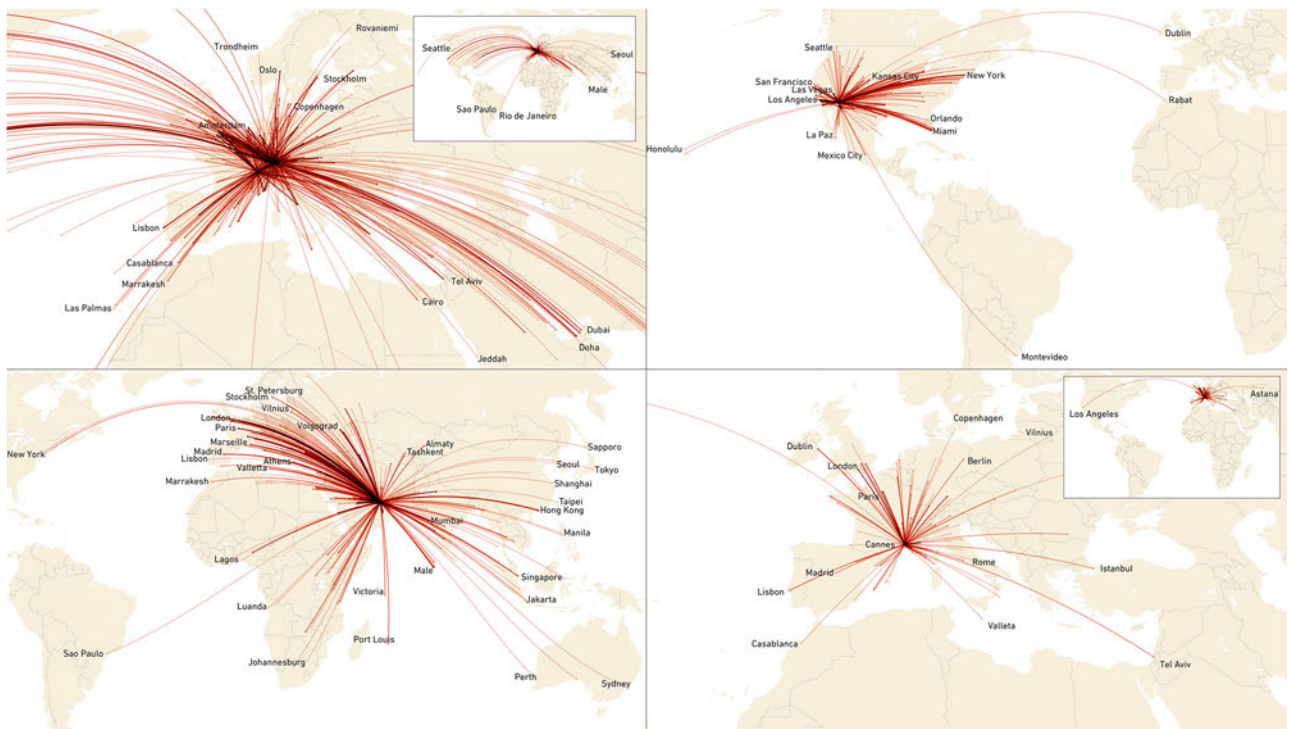


Fig. 3 | Global events attracting private air transport in 2023*. *From top left to bottom right: World Economic Forum, Super Bowl, Conference of Parties, Cannes; includes all air travel at dates of the event.

signals under the USA’s Federal Aviation Administration’s⁴⁴ Limiting Aircraft Data Displayed (LADD). To understand the scale of LADD, we examined a sample of 10% of all private flights in 2023, finding that 30% had requested LADD. ADS-B Exchange thus appears to be a more reliable provider for private aviation data than FlightRadar24. As data are continuously updated, marginal changes can occur.

There are limitations even to the use of ADS-B Exchange data. Flights are not tracked when they are using a third-party flight ID. Under

the Federal Aviation Administration’s ADS-B Privacy program, aircraft registered in the US and flying in US-managed flight information regions can apply for Privacy ICAO Addresses (PIA). These are temporary ICAO aircraft addresses not assigned to the owner in the Civil Aircraft Registry (CAR)⁴⁵. Legs under these ICAO numbers are not considered in the analysis, because the ADS-B exchange database relies on the original ICAO aircraft address to link it to the model that we use to determine if it is a private aircraft. According to information provided by the FAA



Fig. 4 | FIFA World Cup*. *Includes all air travel at dates of the event.

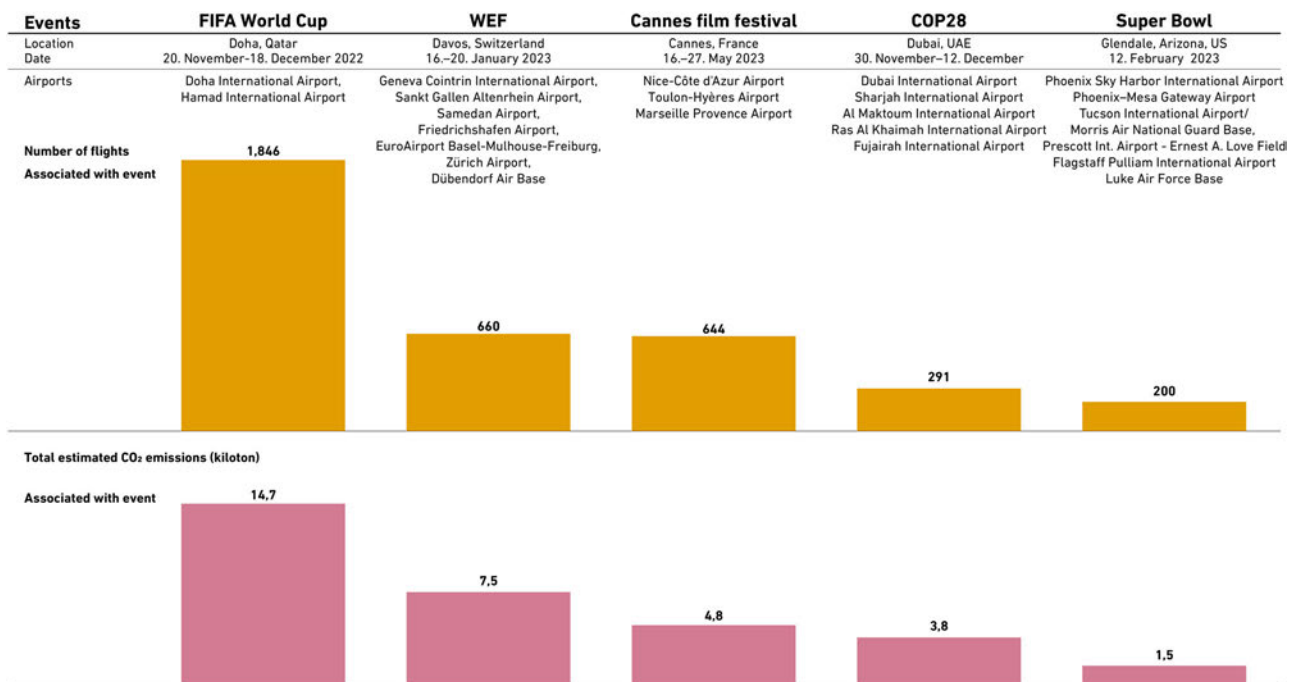


Fig. 5 | Carbon-intensity of events*. *Includes only flights associated with the event.

(personal communication, 19 April 2024), 283 PIA are currently issued, indicating that around 1% of aircraft may not be covered by ADS-B Exchange temporarily. It is possible that these are used primarily by owners of larger aircraft and lead to a larger underestimate in fuel consumption. We generally find earlier ADS-B Exchange data to be noisier, potentially because of changes to the open-source software distributed by volunteers of the ADS-B Exchange network. In more recent years, PIAs affect the data, as the FAA (Personal Communication, April 19, 2024) outlines that the number of PIA applications has risen considerably since 2020.

ADS-B Exchange data is used to calculate fuel use and emissions based on flight time, as well as great circle distances based on the identification of departure/arrival airports for each leg. To assess the difference between great circle and real distance, we calculate real distances based on georeferenced flight tracks (60 s intervals). Flown distances are on average 10.1% larger than great circle distances.

Aircraft fuel use

ADS-B Exchange provides data of all aircraft with a ICAO 24-bit code, the tail number and model. A manual inspection and comparison of $n = 23$

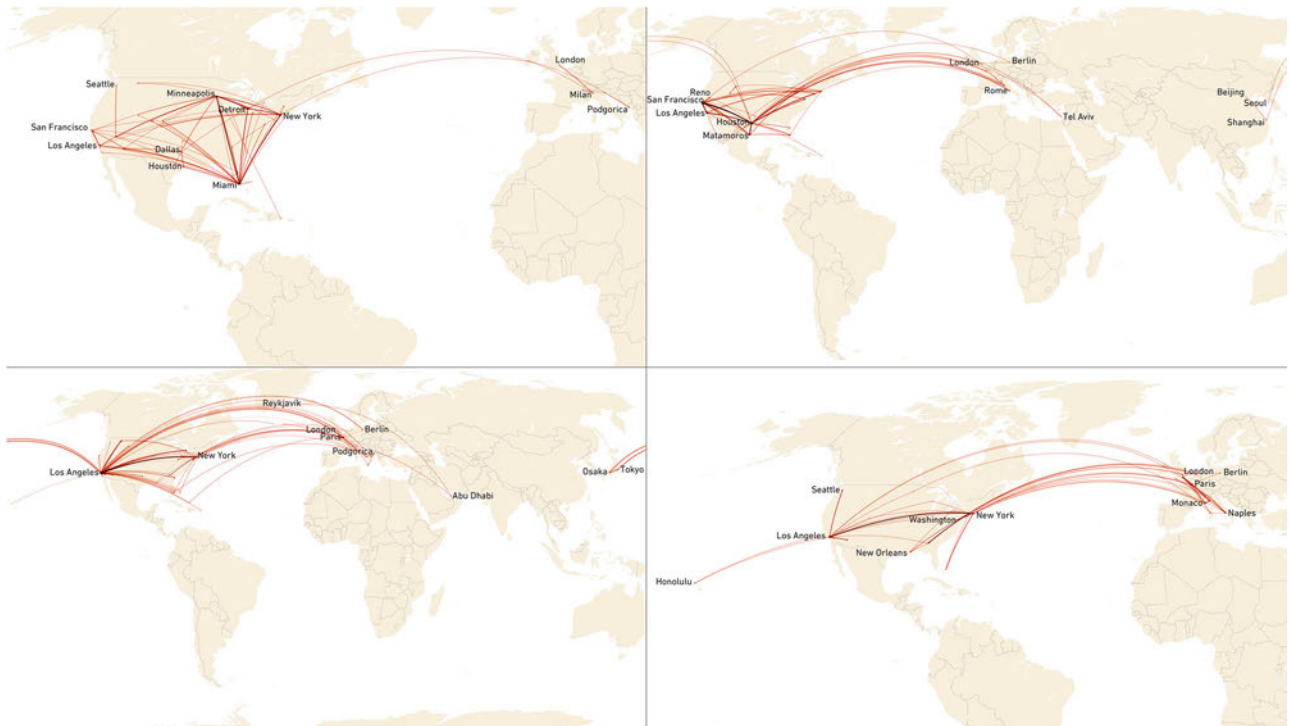


Fig. 6 | Individuals' air travel, 2023*. *Global public figures, anonymized.

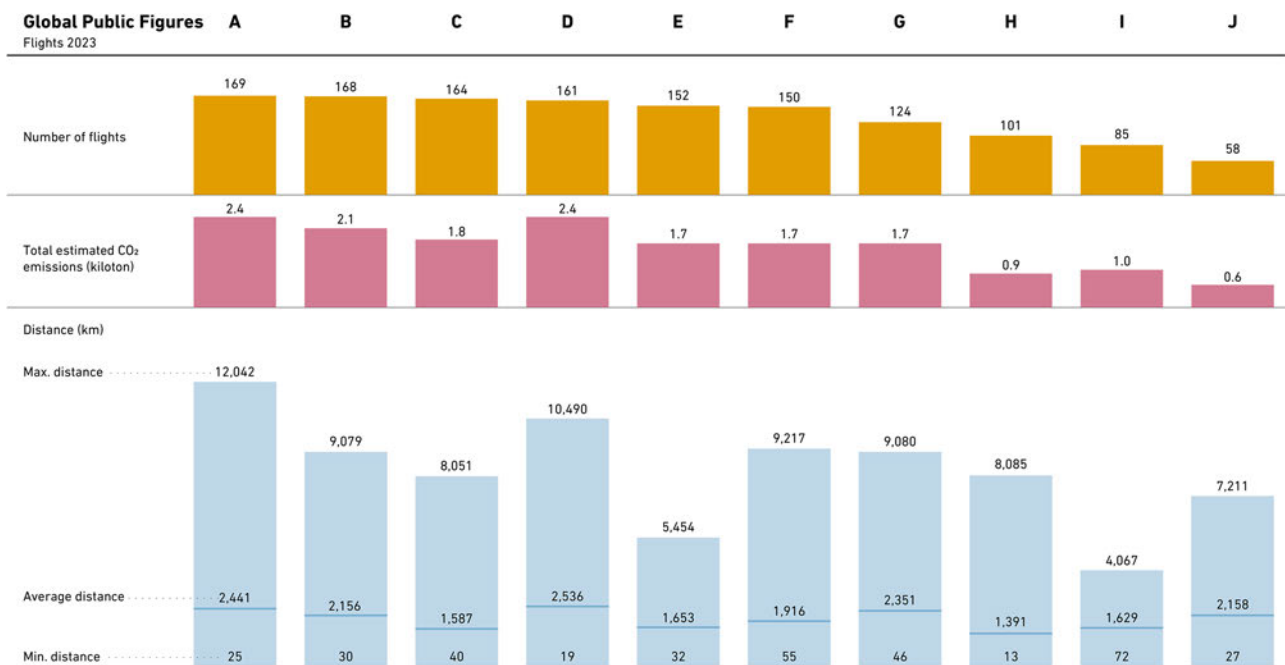


Fig. 7 | Global public figures and their private air travel, 2023*. *List based on Yard⁵⁰, includes renowned actors, singers, and directors.

aircraft with FAA, FlightAware, and FlightRadar24 was performed to assess the quality of ADS-B Exchange, but no differences were found. The country of registration was obtained from the ICAO 24-bit code based on [ICAO working paper NACC/DCA/3 – WP/05]. This dataset is available at https://private-jets.fra1.digitaloceanspaces.com/private_jets/all.csv.

Based on ADS-B Exchange data and unique hex codes, it was determined that there were 25,993 aircraft in December 2023. This compares to industry figures pointing to 23,369 business jets in 2023⁴⁶, 2.1% more than our number that includes 22,878 business jets, as well as 3115 turboprops. The difference can potentially be explained with the use of PIA or aircraft

that are offered for sale and not in use. Table 1 shows the number of private aircraft by model, including fuel consumption in gph, as provided by aircraft brokers for these models. The 10 most popular models represent about 40% of the total fleet. The most common is the Pilatus PC-12 with an 8% market share, followed by the Bombardier CL-600 Challenger and the Piper PA-46-500TP.

For the analysis of private aircraft traffic between 2019 and 2023, all data was retrieved and stored to minimize operational impact to ADS-B exchange. The data includes the ICAO code, aircraft, timestamp, coordinates, altitude of the aircraft, and an indicator variable whether the plane is

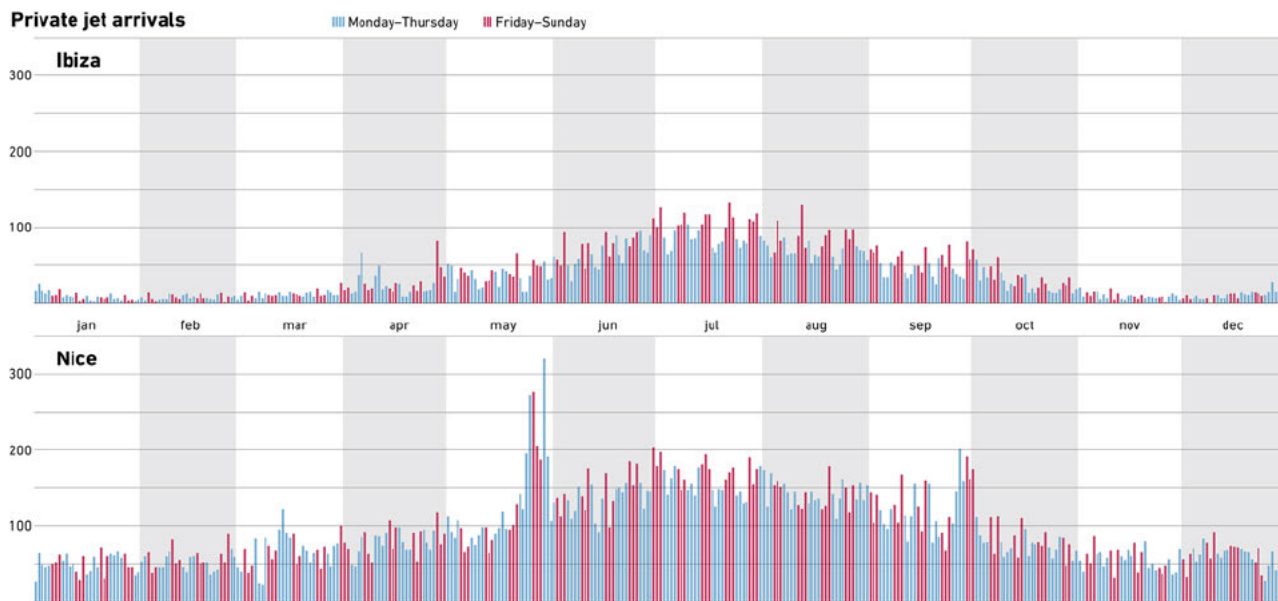


Fig. 8 | Seasonality of arrivals in Ibiza and Nice*. *Peaks in arrivals in Nice: 24 May, during the Cannes Film Festival.

Table 3 | Uncertainties

Issue	Potential error	Relevance for assessment
1. The actual number of aircraft is higher than the number tracked	Industry sources suggest 2.1% more aircraft, but this is potentially explained by PIA use and aircraft for sale/not in use.	Not considered in analysis, potentially leads to underestimate.
2. Aircraft using PIA	PIA are temporarily used by 1.0% of aircraft.	Not considered in analysis, potentially leads to underestimate.
3. LADD	ADS-B providers may not offer comprehensive tracking data.	Not an issue with ADS-B Exchange data.
4. ADS-B Signal losses	Signals may be lost and flights not tracked properly.	Addressed through methodology (Supplementary Fig. 1).
5. ADS-B Coverage	Flights within regions that do not track aircraft. The error is likely small, as the number of aircraft tracked is within 2% of industry aircraft number estimates (issue 1).	Not considered in the analysis.
6. Fuel use averages	Average fuel use values used do not consider thrust-specific flight stage energy use. Calculation of SD suggests error within 10%.	Not considered in the analysis.
7. Taxiing, lifecycle emissions	Consumption of fuel use for taxiing, lifecycle emissions (aircraft production, etc.) not considered.	Results of this study focus on direct emissions from flight.
8. Ambulance and government services	Operations not serving affluent individuals.	Not considered in the analysis, but leading to overestimate.
9. Use of biofuels	The share of fuels with lower lifecycle emissions used.	Not considered in analysis, but likely <1%.

grounded at around 60 s intervals. By tracking the position of each aircraft over time, flight legs, distances, and flight times can be calculated. To calculate fuel use, we use averaged fuel economy values provided for the 72 models, in gallons per hour (gph), as retrieved from marketing materials (see <https://private-jets.fra1.digitaloceanspaces.com/model/db/data.csv>).

Fuel consumption is calculated for aircraft in flight, i.e., this excludes time spent taxiing or other on-the-ground emissions, and results thus need to be considered lower boundary values for fuel use. Whether an aircraft is in flight is determined based on transponder data that signals a touch-down/takeoff. Emissions of CO₂ were computed based on leg duration for each flight:

$$\text{leg emission kg CO}_2 = \text{consumption gallon/h} * \text{liters per gallon/Lgallon} * \text{kg per liter of jet fuel kg/L} * \text{CO}_2\text{emissions per kgCO}_2\text{kg} * \text{leg time[h]}$$

Where:

Liters per gallon = 3.78541 [L/gallon], kg per liter of jet fuel = 0.8 [kg/L], CO₂ emissions per kg = 3.16 [kg CO₂/kg jet fuel], leg time [h] computed duration of flight, and average consumption [gallon/h] obtained from the manufacturer.

The focus is on CO₂, and does not consider non-CO₂ warming. To assess this contribution, we use ADS-B Exchange data^{47,48} for an analysis of the flight time spent at altitudes >30,000 and >40,000 feet, finding that 21.4% of flight hours are spent at >40,000 feet, and 45.4% at >30,000 feet. This is not proportional to emissions at these altitudes, as larger aircraft models are more likely to fly at these altitudes. The data are available at⁴⁹.

A limitation of our approach is that we use averaged LTO fuel economy values that are applied to flight times. Various earlier studies have sought to assess aviation fuel use through complex models^{1,2,16,17}. These consider the different flight cycle elements and assign specific fuel use values to each of these; some models also consider aircraft mass and payload, and weather conditions¹². While these models may be more accurate than the LTO fuel economy values used in this paper, discussions with pilots have pointed us to the fact that PA is characterized by specific flight styles that lead to considerable differences in fuel burn.

To assess the potential range of fuel consumption values, we consider the ranges specified by brokers for *n* = 18 aircraft. Average fuel consumption values are calculated for standard operating profiles, i.e., the Landing and Take-Off (LTO) cycle that considers taxiing, takeoff, climb, cruise, descent,

Table 4 | Calculation of flights related to events

Event	Airports	Flights during event	Flights before	Flights after	Associated with event	Emissions associated with event (kt)
FIFA World Cup 2022	Doha, Hamad	2090	290	199	1846	14.7
World Economic Forum 2023	Zurich, Geneva, Altenrhein, Dübendorf, Samedan, Friedrichshafen, Basel	1559	834	965	660	7.5
COP28, 2023	Dubai, Sharjah, Al Maktoum, Ras Al Khaimah, Fujairah	1012	738	704	291	3.8
Super Bowl, 2023	Phoenix Sky Harbor, Phoenix-Mesa, Tucson, Morris, Prescott, Flagstaff, Luke	505	321	289	200	1.5
Cannes Film Festival, 2023	Nice, Toulon, Marseille	2337	1341	2046	644	4.8

and landing. Brokers use these values so that customers—often charter companies—can compare the fuel efficiency of different aircraft models. As fuel is one of the major operational cost factors, reliable fuel economy values have relevance for purchase decisions. Ranges provide an indication of the relevance of other factors. Over the sample of the 18 aircraft models, we find a variation in fuel consumption values of 10.1%, calculated as the standard deviation from the average consumption values available at <https://privatejets.fra1.digitaloceanspaces.com/model/db/data.csv>.

Signals

ADS-B data relies on responder signals to determine flight altitude and location. Coverage is generally good. Signals may however be lost in specific situations, which could lead to an incorrect allocation of airports. Calculations thus follow a set of rules (for illustration, see Supplementary Material, Fig. 1):

1. When the signal is “on the ground”, the location is marked as the end of the leg.
2. When the signal is lost for more than 5 minutes at an altitude above 10,000 feet, the last known location is considered to be the end of the leg.
3. When the signal is lost for more than ten hours, the last known location is marked as the end of the leg.

Uncertainties

There are various uncertainties that affect the accuracy of the calculations. Some of these have been discussed in preceding sections, this section provides a summary (Table 3), showing that there is a risk of a small error.

Patterns

Distance and time-based flight patterns have been analyzed to determine their robustness, particularly concerning emissions. To quantify the uncertainty associated with our mean distance and emission estimates, we applied a bootstrapping methodology. We drew 10,000 bootstrap samples, each comprising 100,000 legs, from the original dataset of more than four million flights in 2023. For each bootstrap sample, the mean was calculated, and the distribution of all bootstrapped means was computed. From this distribution, we derived the empirical 95% confidence interval by taking the 2.5th and 97.5th percentiles. To report the accuracy of our estimates, we present the mean and the associated errors as indicated by the 95% confidence interval. Results show a 95% confidence interval (CI) for the average distance of 865.8 km (859.5–872.1 km), with an error of the mean that varies between a lower 6.3 km and an upper 6.4 km. For average emissions of 3632 kg, the CI is 3598–3666 kg, with a lower error of 33.88 kg and an upper error of 33.95 kg. This suggests robustness in determined flight patterns (distance) as well as emissions.

Geospatial patterns have been derived by focusing on events, individuals, and a family-owned company. For all events, the closest airports are included in the analysis, or those airports referred to by event organizers (Table 4). For example, the WEF in Davos includes Zurich, Geneva, Altenrhein, Dübendorf, Samedan, Friedrichshafen, and EuroAirport Basel. The exact dates of the event are used to determine private aviation arrivals. This can underestimate attendance, as participants may have arrived/departed on days preceding/following the event. Calculations are based on the following procedure:

1. Definition of all relevant airports for event
2. Definition of start and end date for event
3. Inclusion of all flights arriving at relevant airports in event period.

To derive the net emissions associated with an event, arrivals are compared with a corresponding period prior to and after the event. For short events, this includes flights a week before/after the event, for an identical number of days (a three-day event is compared with a three-day period). For longer events, the period for comparison is chosen with a greater distance to the event (two weeks). Results for the before/after periods are added and divided by two to derive an average. Estimates of the “net” number of flights arriving for the event are then derived by subtracting the

Fig. 9 | Cross-visitation of global events*. *Event bubbles show the total number of aircraft, with satellites referring to identical tail numbers appearing at other events.

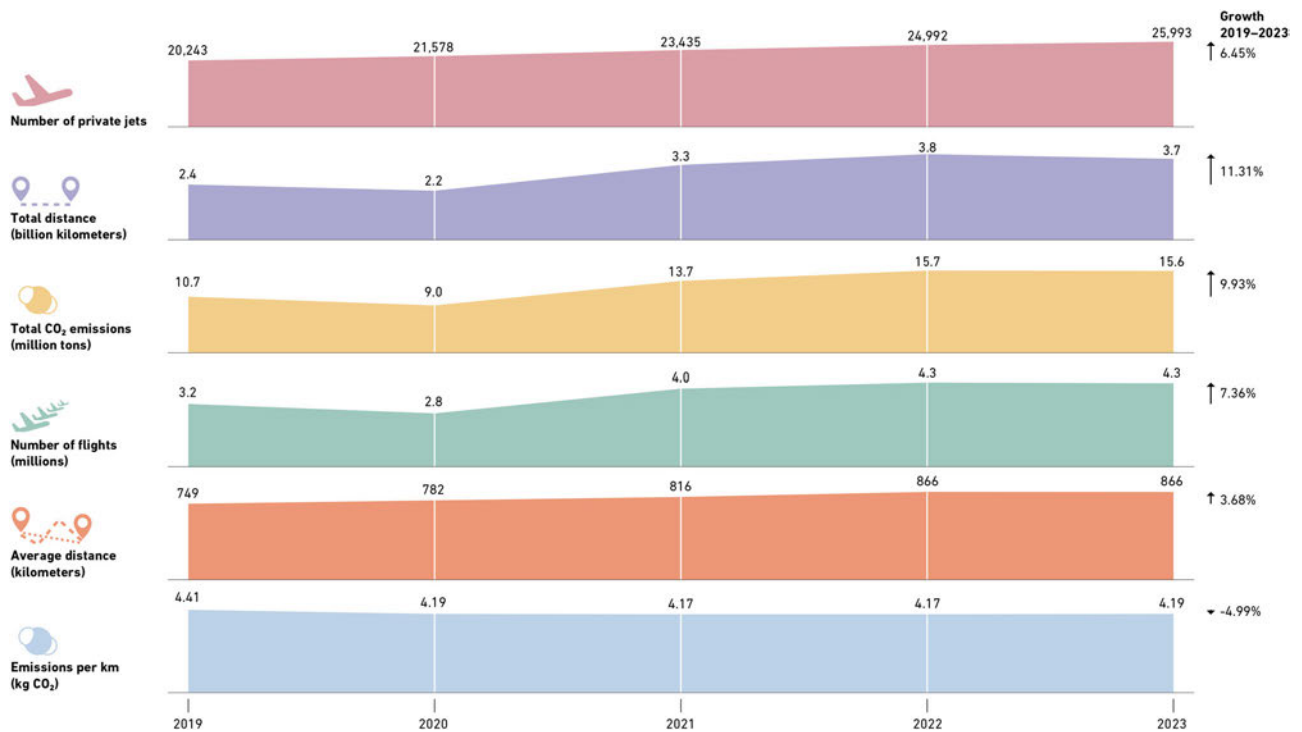
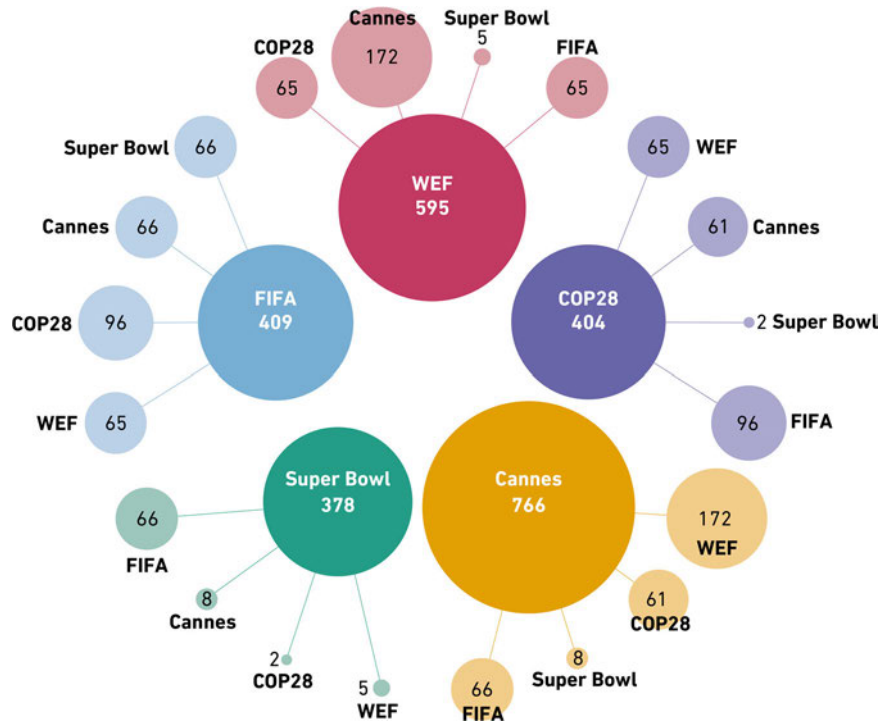


Fig. 10 | Growth in private aviation and key performance indicators*. *Does not include distances flown under PIA use.

average from the total number of flights arriving during the event. This data is then used to estimate emissions associated with the event by calculating total emissions associated with all flights during the event, and subtracting the average of all flights before and after the event period.

Data for the flight patterns of public figures is derived from the database through the compilation of all flights associated with the publicly available tail number. This may underestimate flights in cases where an individual owns several aircraft, or where PIAs have been assigned. It may

overestimate emissions where aircraft are made available to friends or family.

Company patterns are exemplified on the basis of a family-owned company in Denmark for which tail numbers for three aircraft are publicly known. As the company is family-owned, it is possible to explain flight patterns as partially related to publicly known second homes, and flights that appear to serve holiday destinations (for illustration see Supplementary Material, Fig. 2). Flight patterns are illustrated for a five-year period to show

overlap. It is unknown who used the aircraft, which may also have been made available to non-family members within or outside the company.

Development of maps

Maps visualize air transport based on the geographic coordinate system World Geodetic System 1984 that defines latitude, longitude, and altitude. Maps are generated based on ADS-B transponder data for departure and arrival points. The projection distorts distance by increasingly stretching distances between points as they move away from the equator towards the poles, leading to visual distance exaggeration of high-latitude regions.

Data availability

All data are available through the following link⁴⁹: (enter the year 2019, 2020, 2021, 2022 or 2023 in {year}: <https://private-jets.fra1.digitaloceanspaces.com/leg/v2/all/year=2023/data.csv>). There are no restrictions to data access.

Code availability

The code is available via Github, <https://github.com/jorgecardleita0/private-jets>.

Received: 7 May 2024; Accepted: 10 October 2024;

Published online: 07 November 2024

References

- Teoh, R., Engberg, Z., Shapiro, M., Dray, L. & Stettler, M. E. The high-resolution Global Aviation Emissions Inventory based on ADS-B (GAIA) for 2019–2021. *Atmos. Chem. Phys.* **24**, 725–744 (2024).
- Quadros, F. D., Snellen, M., Sun, J. & Dedoussi, I. C. Global civil aviation emissions estimates for 2017–2020 using ADS-B data. *J. Aircr.* **59**, 1394–1405 (2022).
- Graver, B., Rutherford, D. & Zheng, S. CO₂ Emissions from commercial aviation. <https://theicct.org/wp-content/uploads/2021/06/CO2-commercial-aviation-oct2020.pdf> (2020).
- Klöwer, M. et al. Quantifying aviation's contribution to global warming. *Environ. Res. Lett.* **16**, 104027 (2021).
- Lee, D. S. et al. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmos. Environ.* **244**, 117834 (2021).
- Airbus. Global Market Forecast 2023. <https://www.airbus.com/sites/g/files/jcbta136/files/2023-06/Airbus%20Global%20Market%20Forecast%202023-2042%20Presentation.pdf> (2024).
- Boeing. Commercial Market Outlook 2023-2042. <https://www.boeing.com/commercial/market/commercial-market-outlook> (2024).
- Bergero, C. et al. Pathways to net-zero emissions from aviation. *Nat. Sustain.* **6**, 404–414 (2023).
- Dray, L. et al. Cost and emissions pathways towards net-zero climate impacts in aviation. *Nat. Clim. Change* **12**, 956–962 (2022).
- Grewe, V. et al. Evaluating the climate impact of aviation emission scenarios towards the Paris agreement including COVID-19 effects. *Nat. Commun.* **12**, 3841 (2021).
- Delbecq, S., Fontane, J., Gourdain, N., Planès, T. & Simatos, F. Sustainable aviation in the context of the Paris Agreement: a review of prospective scenarios and their technological mitigation levers. *Prog. Aerosp. Sci.* **141**, 100920 (2023).
- Gössling, S. & Humpe, A. Net-zero aviation: transition barriers and radical climate policy design implications. *Sci. Total Environ.* **912**, 169107 (2024).
- Sacchi, R. et al. How to make climate-neutral aviation fly. *Nat. Commun.* **14**, 3989 (2023).
- Gössling, S. & Humpe, A. The global scale, distribution and growth of aviation: Implications for climate change. *Glob. Environ. Change* **65**, 102194 (2020).
- World Bank. Calculating the carbon footprint from different classes of air travel. Policy Research Working Paper 6471. [worldbank.org/curated/en/141851468168853188/pdf/WPS6471.pdf](https://documents1.worldbank.org/curated/en/141851468168853188/pdf/WPS6471.pdf) (2023).
- Sun, J., Olive, X. & Strohmeier, M. Environmental footprint of private and business jets. *Eng. Proc.* **28**, 13 (2022).
- Sobieralski, J. B. & Mumbower, S. Jet-setting during COVID-19: environmental implications of the pandemic induced private aviation boom. *Transp. Res. Interdiscip. Perspect.* **13**, 100575 (2022).
- Barros, B. & Wilk, R. The outsized carbon footprints of the super-rich. *Sustain.: Sci. Pract. Policy* **17**, 316–322 (2021).
- Vista Jet. The Jet Traveler Report 2018. <https://www.vistajet.com/globalassets/documents/jettravelerreport.pdf> (2018).
- Lyle, C. Beyond the ICAO's CORSIA: towards a more climatically effective strategy for mitigation of civil-aviation emissions. *Clim. Law* **8**, 104–127 (2018).
- Astute Analytics. Business Jet Market. <https://www.astuteanalytics.com/industry-report/business-jet-market> (2024).
- Honeywell. 2023 Global Business Aviation Outlook. https://aerospace.honeywell.com/content/dam/aerobt/en/documents/landing-pages/brochures/2023_BusinessAviationReport.pdf (2023).
- Chancel, L. Global carbon inequality over 1990–2019. *Nat. Sustain.* **5**, 931–938 (2022).
- Wiedmann, T., Lenzen, M., Keyßer, L. T. & Steinberger, J. K. Scientists' warning on affluence. *Nat. Commun.* **11**, 3107 (2020).
- Ivanova, D. & Wood, R. The unequal distribution of household carbon footprints in Europe and its link to sustainability. *Glob. Sustain.* **3**, e18 (2020).
- Lamboll, R. D. et al. Assessing the size and uncertainty of remaining carbon budgets. *Nat. Clim. Change* **13**, 1360–1367 (2023).
- Li, S. et al. Revisiting Copenhagen climate mitigation targets. *Nat. Clim. Change* **14**, 468–475 (2024).
- Liu, Z., Deng, Z., Davis, S. J., Giron, C. & Ciais, P. Monitoring global carbon emissions in 2021. *Nat. Rev. Earth Environ.* **3**, 217–219 (2022).
- Oswald, Y., Owen, A. & Steinberger, J. K. Large inequality in international and intranational energy footprints between income groups and across consumption categories. *Nat. Energy* **5**, 231–239 (2020).
- Haberl, H. et al. A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights. *Environ. Res. Lett.* **15**, 065003 (2020).
- Fremstad, A. & Paul, M. The impact of a carbon tax on inequality. *Ecol. Econ.* **163**, 88–97 (2019).
- Moz-Christofolletti, M. A. & Pereda, P. C. Winners and losers: the distributional impacts of a carbon tax in Brazil. *Ecol. Econ.* **183**, 106945 (2021).
- Climate Action Tracker. Home. <https://climateactiontracker.org> (2024).
- Kenner, D. *Carbon Inequality: The Role of the Richest in Climate Change* (Routledge, 2019).
- World Bank. CO₂ equivalent emissions. [https://urldefense.com/v3/https://data.worldbank.org/indicator/EN.GHG.CO2.PC.CE.AR5_::!NLFGqXoFfo8MMQ!trwF0JujLwmQ5yc1b8UzjmMQh5HAgNbU8WdmT4hbd-A12TENZJA_1nWcn0_XYiQ408r2rFqRunalAWwISg6CiPR865lu6_mk-VJP\\$](https://urldefense.com/v3/https://data.worldbank.org/indicator/EN.GHG.CO2.PC.CE.AR5_::!NLFGqXoFfo8MMQ!trwF0JujLwmQ5yc1b8UzjmMQh5HAgNbU8WdmT4hbd-A12TENZJA_1nWcn0_XYiQ408r2rFqRunalAWwISg6CiPR865lu6_mk-VJP$) (2023).
- Lee, D. S. et al. Uncertainties in mitigating aviation non-CO₂ emissions for climate and air quality using hydrocarbon fuels. *Environ. Sci. Atmos.* **3**, 1693–1740 (2023).
- Menkor Aviation. World footballers who own luxurious and expensive private jets. <https://www.menkoraviation.com/en/lifestyle/world-footballers-who-own-private-jets/> (2024).
- Teoh, R. et al. Global aviation contrail climate effects from 2019 to 2021. *Atmos. Chem. Phys.* **24**, 6071–6093 (2024).
- Planès, T., Delbecq, S., Pommier-Budinger, V. & Bénard, E. Simulation and evaluation of sustainable climate trajectories for aviation. *J. Environ. Manag.* **295**, 113079 (2021).

40. Tol, R. S. Social cost of carbon estimates have increased over time. *Nat. Clim. Change* **13**, 532–536 (2023).
41. IRS. IRS begins audits of private jet usage. <https://www.irs.gov/newsroom/irs-begins-audits-of-corporate-jet-usage-part-of-larger-effort-to-ensure-high-income-groups-dont-fly-under-the-radar-on-tax-responsibilities> (2024).
42. FAA (Federal Aviation Administration). Automatic Dependent Surveillance—Broadcast (ADS-B). https://www.faa.gov/about/office_org/headquarters_offices/avs/offices/afx/afs/afs400/afs410/ads-b (2023).
43. ICAO (International Civil Aviation Organization). ADS-B implementation and operations guidance document. https://www.icao.int/APAC/Documents/edocs/cns/ADSB_AIGD7.pdf (2014).
44. FAA (Federal Aviation Administration). Limiting Aircraft Data Displayed (LADD). <https://www.faa.gov/pilots/ladd> (2024).
45. FAA (Federal Aviation Administration). ADS-B Privacy. https://www.faa.gov/air_traffic/technology/equipadsb/privacy (2024).
46. Aviation Week. The global business jet fleet by age & region. <https://aviationweek.com/business-aviation/global-business-jet-fleet-age-region> (2024).
47. ADS-B Exchange. ADSB Exchange. <https://www.adsbexchange.com> (2024).
48. IEA (International Energy Agency). Aviation. <https://www.iea.org/energy-system/transport/aviation#tracking> (2024).
49. Data repository. Aviation data. <https://private-jets.fra1.digitaloceanspaces.com/leg/v2/all/year=2023/data.csv> (2024).
50. Yard. Just plane wrong. <https://weareyard.com/insights/worst-celebrity-private-jet-co2-emission-offenders> (2022).

Author contributions

S.G., A.H. and J.C.L. conceived and designed the study. A.H. and J.C.L. performed the analysis. S.G. wrote the paper.

Funding

Open access funding provided by Linnaeus University.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s43247-024-01775-z>.

Correspondence and requests for materials should be addressed to Stefan Gössling.

Peer review information *Communications Earth & Environment* thanks Zarah Zengerling and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editor: Alice Drinkwater. A peer review file is available.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2024