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communications earth & environment

Article

https://doi.org/10.1038/s43247-024-01956-w

Airspace restrictions due to conflicts increased global aviation's carbon dioxide emissions in 2023

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As air traffic rebounds from its large drop during the Covid-19 crisis, civil aviation needs to continue addressing its climate impact. Knowledge of aircraft trajectories is essential for an accurate assessment of the CO_2 (and non-CO_2) climate impact of aviation. Here we combine an aircraft trajectory optimization algorithm and a global database of aircraft movements to quantify the impact of airspace restrictions due to conflict zones on CO_2 emissions. Among current restrictions, we show that the Russian ban of its airspace to Western airlines following the invasion of Ukraine has the largest impact. Our analysis reveals an initial reduction of flights to and from East Asia that would have crossed the Russian territory. Routes then gradually reopened by making a detour, which led to an average increase in fuel consumption of 13% on the affected routes, with a greater impact for flights to and from Europe (14.8%) compared to flights to and from North America (9.8%). Although these flights represent only a small fraction of the daily flights, the large detours have increased global aviation CO_2 emissions by 1% in 2023, equivalent to a quarter of the yet-to-be-achieved efficiency gain potential from improved air traffic management.

Airlines optimise their flight trajectories a few days to a few hours before departure to minimise the operating cost of the flight. Fuel consumption is one of the important factors considered and can be minimised by making the best use of wind patterns. However airlines also have to take into account a range of operational constraints such as weather conditions (e.g., to avoid thunderstorms), safety regulations (e.g. keeping a minimum distance to diversion airports), airspace crossing charges, staff costs and available air routes, in particular in the case of partial or total airspace closures. Flight optimisation thus seeks to balance fuel efficiency with other operational costs and constraints.

Trajectory inefficiencies represent an important challenge but also an opportunity to reduce CO_2 emissions[1]. Indeed, tackling trajectory inefficiencies is explicitly outlined in the strategic plans of the International Air Transport Association[2] and the International Civil Aviation Organisation[3]. They estimate that improving air traffic management operations has the potential worldwide to achieve a substantial reduction of 3–5% in CO_2 emissions by the aviation industry. However, geopolitical considerations often stand against that objective. Indeed airlines may be obliged by their regulators or may decide unilaterally to avoid certain airspaces because of safety concerns. Countries may also decide to close their airspace to all aircraft from certain airlines or from certain countries. In this context, armed conflicts and international sanctions are two main sources of airspace restrictions. For instance, many airlines started to avoid Eastern Ukrainian airspace after Malaysia Airlines Flight 17 was shot down by Russia-controlled forces on 17 July 2014. Following the Russian invasion of Ukraine in February 2022 and the ongoing war between Ukraine and Russia, Western countries have banned Russian airlines from their airspace. Russian authorities have reciprocated by banning Western airlines from their own airspace, which resulted in longer flights[4] between Europe and Asia and between North America and Asia.

Measuring and monitoring aviation emissions is complex. A growing number of studies have investigated different methods to accurately estimate CO_2 emissions from the aviation sector. Top-down estimates rely on global kerosene fuel sales and usage, e.g. from the International Energy Agency[5]. Such estimates have the advantage of being comprehensive but they take several months to years to become available and include military as well as some non-aviation usage. They also do not provide much information on how fuel is used and on the geographical distribution of CO_2 emissions. Bottom-up estimates, based on actual flight movements, are increasingly preferred[6–8] as they provide more accurate information on the location of the emissions and non-CO_2 impacts than top-down estimates. However bottom-up approaches require an accurate knowledge of the global air traffic, which is a challenge because databases of flight movements are incomplete in ways that are not well documented.

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The most common method to reconstruct trajectories, knowing the departure and arrival airports of each flight, is to assume a geodesic trajectory (also called great circle) between airport pairs. As there are, on average, 90,000 flights per day, this method has the advantage of being computationally efficient. Some studies use a correction factor to account for the extra distance flown during the landing and takeoff phases and for other air traffic inefficiencies[9]. However, this factor is based on distance flown alone and does not account for the positive impact of tailwinds and the negative impact of headwinds on flight time. Thus it can only be correct on average as it does not take into account flight-specific adjustments made by airlines to best exploit the wind patterns. The correction factor is also not adjusted for the case of large airspace restrictions, which leaves CO_2 emissions underestimated. Boucher et al.[10] introduced a simple method to compute time-optimised trajectories that proved to provide a reasonably good estimate of flight times and trajectories when compared with actual trajectories recorded from more than 1000 flights participating in the In-service Aircraft for a Global Observing System (IAGOS) programme[11]. In this study, we have extended the optimisation algorithm by Boucher et al.[10] to take into account airspace restrictions and applied this algorithm to a global database of flight movements in order to estimate the impact of major airspace restrictions on flight trajectories and the associated increase in CO_2 emissions. We focus on major, country-wide airspace closures related to international conflicts and sanctions because they are long-lasting and well-documented. Specifically, we identify the flights that are potentially affected by an airspace restriction. Then, we quantify the impact of the airspace restriction by comparing the CO_2 emissions of the time-optimised trajectories with and without the airspace restriction. Finally, we compute the additional CO_2 emissions that are attributable to airspace restrictions and present the results in the context of global air traffic.

Results

Table 1 summarises the impacts of several airspace restrictions considered in this study. The avoidance of the airspace of Libya, Syria, and Yemen affects of the order of 60–100 flights per day each and leads to average consumption increases of 2.7, 2.9, and 4.3%, respectively. As this represents a relatively small fraction of daily flights, we focus the rest of this study on the consequences of the Russo-Ukrainian war because the associated airspace restrictions have been affecting a large number of flights for a long period of time. In addition, the average distance of the affected flights is large and consequently, the increase in fuel consumption is expected to be large as well since fuel consumption is a quadratic function of the distance flown.

Approximately 1000 and 800 flights are affected daily by the avoidance of the Ukrainian and Russian airspaces, respectively, on average during the period March 2022 to December 2023. Over that period, we analysed 750,000 flights, representing a total of 1100 flights per day because a large fraction of long-haul flights are affected by both airspace restrictions. Figure 1 shows the time series from 2019 to 2023 of the number of Western Airlines routes whose shortest trajectory crosses the Ukrainian or Russian airspace, alongside the Russian Airlines routes whose shortest trajectory crosses the European Union airspace. Western flights began to avoid Russian airspace shortly before the restriction was introduced. Air traffic then gradually recovered as airlines (and their passengers) adapted to the new

Table 1 | Statistics of the impact of the five airspace restrictions considered in this study, over the period March 2022 to December 2023 on average, in terms of numbers of flights impacted per day, average flight distance without restriction, average increase in flown distance and consumption per flight caused by the airspace restriction

Airspace Restriction	Average number of flights impacted per day	Average flight distance (km)	Average distance increase (%)	Average consumption increase (%)
Ukraine	984	7885	5.3	7.9
Russia	809	8336	5.5	8.0
Libya	103	6800	2.0	2.7
Syria	100	5000	2.5	2.9
Yemen	60	4970	5.5	4.3

The comparison was made between two optimised flights, one affected by the restriction and the other not affected by the restriction. The impact of airspace restrictions over Ukraine and Russia are shown on two different lines but include a large number of flights affected by both.

Fig. 1 | Monthly average of total daily international flights and daily international flights affected by airspace restrictions for Western and Russian airlines. Average daily total international flights (red lines, right axis) of **a** Western airlines and **b** Russian airlines over the period 2019–2023. The black lines show the corresponding average daily number of flights whose shortest trajectory crosses **a** the Ukrainian and Russian airspaces and **b** the European Union airspace.

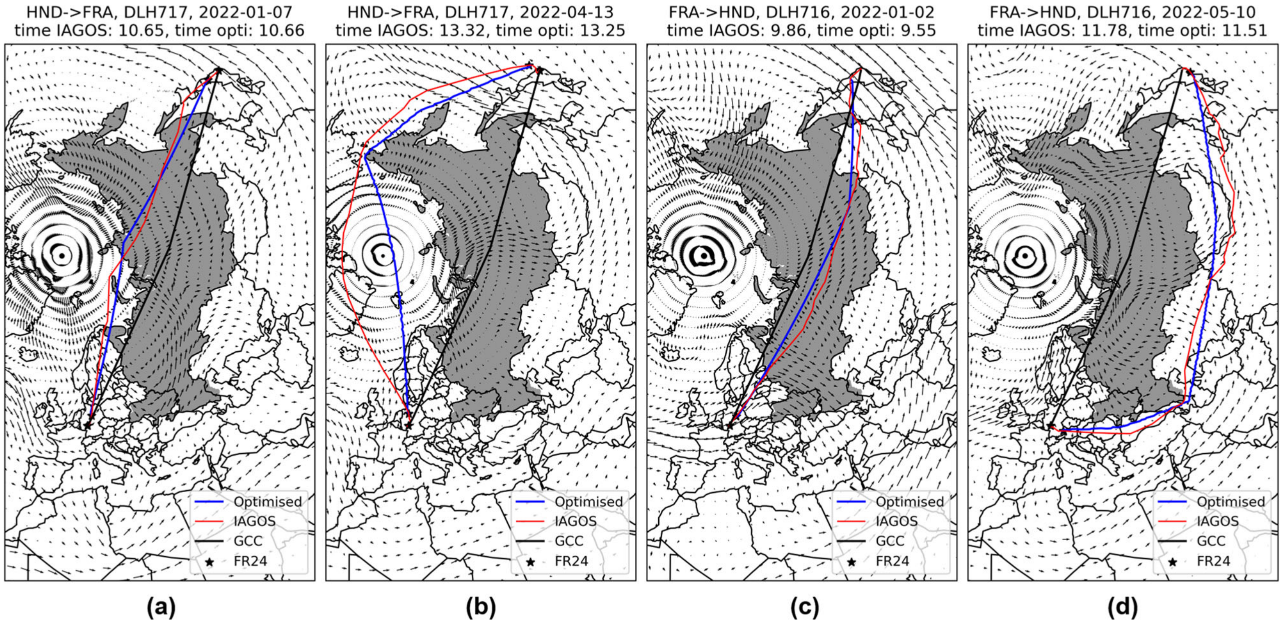

Fig. 2 | Flights trajectories between Tokyo and Frankfurt-am-Main, before and after the airspace restriction. Flight from Tokyo (HND) to Frankfurt-am-Main (FRA) **a** on 7 January 2022 (i.e., before the airspace restriction) and **b** on 13 April 2022 (i.e., after the airspace restriction) and flight from Frankfurt-am-Main (FRA) to Tokyo (HND) on **c** 2 January 2022 and **d** on 10 May 2022. The geodesic path (or great circle) between the two airports is shown in black. The computed optimised trajectory is in blue, and the actual trajectory from IAGOS in red. The wind pattern at 250 hPa is shown with the black arrows. The restricted airspace is shaded in grey. The optimised and actual cruising times (in decimal hours) are also displayed in the headers.

situation. This was not the case for the number of Russian international flights, which plummeted as a result of the restrictions and never recovered the following year. Figure 1 also shows the number of all international flights for Western and Russian airlines (red lines). A small decrease in international flights is visible for Western airlines and can be attributed to the airspace restriction, but this did not last, and overall, air traffic continues to recover from the Covid-19 crisis in 2020. Russian international flights have been more affected as the total number of international flights decreased and never returned to pre-war levels. Most of the remaining Russian flights are to destinations that do not have to fly through these airspace restrictions. Russian airlines also swapped their European destinations for destinations in the Middle East and Asia (see Supplementary Fig. S3).

Figure 2 shows optimised and actual IAGOS trajectories for a European-Japanese city pair in 2022, without the restriction (i.e., before March 2022) and with the restriction (i.e., after March 2022). For both cases and directions, the optimised flight trajectories and flight times are in reasonable agreement with actual IAGOS data. In particular, the selected Lufthansa flight bypassed Russia on its southern side for the outbound flight from Frankfurt-am-Main to Tokyo and over the Arctic for the inbound flight. On average for the 294 IAGOS flights affected in 2022 and 2023, our optimised trajectories (for the cruising phase) are 0.24% faster than actual flight times (see Supplementary Fig. S5). It is conceivable that airlines have adjusted the airspeed, the altitude or the payload of their aircraft for the longer routes, with possible impacts on the fuel consumption. We have compared the average airspeed and altitude of IAGOS flights from the years 2021 and 2022 before and after the Russo-Ukrainian airspace restriction, but have observed only small differences for these parameters (see the supplementary Section S5 for more details). This is expected as aircraft are designed and optimised to fly at a predefined Mach number and altitude range[12]. It is possible that the airlines have decreased the aircraft payload to offset some of the additional fuel consumption due to the longer routes, but we do not have the necessary data to confirm this hypothesis. It should be noted, however, that the impact of the additional fuel carried on the fuel consumption itself is already included in our calculation through the quadratic equation from Seymour et al[9]. As the sub-optimality of the IAGOS flights is similar in the absence of airspace restriction[10], we are confident that our method provides a very good estimate of the flight time and, therefore, the fuel overconsumption. The additional flight time and fuel consumption of the affected flights vary greatly depending on the extent to which they would have crossed the restricted airspace. We illustrate this by showing the spatial distribution of the emissions in Fig. 3. The restriction forced all flights of Western airlines to follow similar trajectories on the Europe-Asia and North America-Asia routes. The densest areas are in the corridor south of Ukraine and north of Japan.

We used the K-means clustering method to categorise the affected flights into different classes. The elbow method of this K-mean clustering suggests that splitting the flights into four classes is optimal, highlighting outbound and inbound routes between Europe and Asia and between Asia and North America (see Supplementary Fig. S7). Over the period March 2022 and December 2023, on average, 67% of the affected flights were on the Europe-Asia route, while the remaining 33% were on the Asia-North America route. The histograms of the relative changes in flown distance, flown time and fuel consumption with and without airspace restriction are shown in Fig. 4. Flights for which the difference in flown time with and without the airspace restriction was lower than 1% were considered as non-impacted and removed for our analysis (they accounted for around 11% of the pre-selected flights as we made sure to select all flights that could be impacted). The large majority of affected flights experience an increase in flown distance ranging from 1% to 20%. However, a small subset of flights shows a decrease indicating that certain flights had shorter distances due to the imposed restriction. This is expected as our algorithm optimises the flight duration and not the flight distance. For those flights, the trajectory that crossed the restricted airspace had a longer distance but was better optimised in terms of flight time than the trajectory that avoided the restricted airspace. The histogram of the flight time fractional increase is similar to that of the flight distance increase except for its lack of negative values. In comparison, the histogram of the fuel consumption fractional increase is shifted towards larger values, with most increases ranging from 0 to 30%. Even larger increases are possible, corresponding to flights having to cope with both a large increase in flown distance and an unfavourable wind pattern on their new route.

The distinction between the European and the North American routes is worth noting (Fig. 4), with a smaller impact on the North American routes

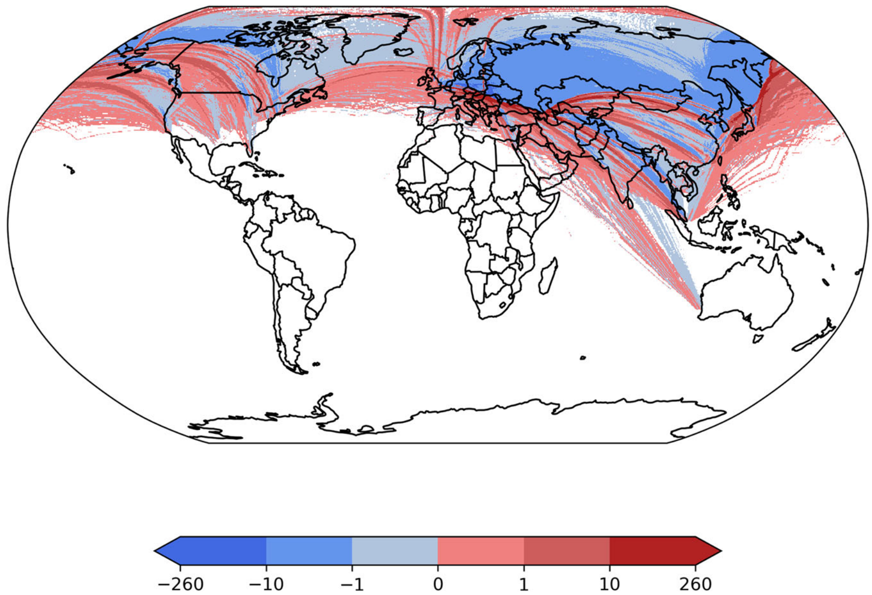

Fig. 3 | Change in-flight track density for flights affected by the Russo-Ukrainian airspace restriction. Change in-flight track density (km km^{-2}) for the flights affected by the Russo-Ukrainian airspace restriction in April 2023, computed as the difference between flight trajectories with restrictions minus those without restrictions.

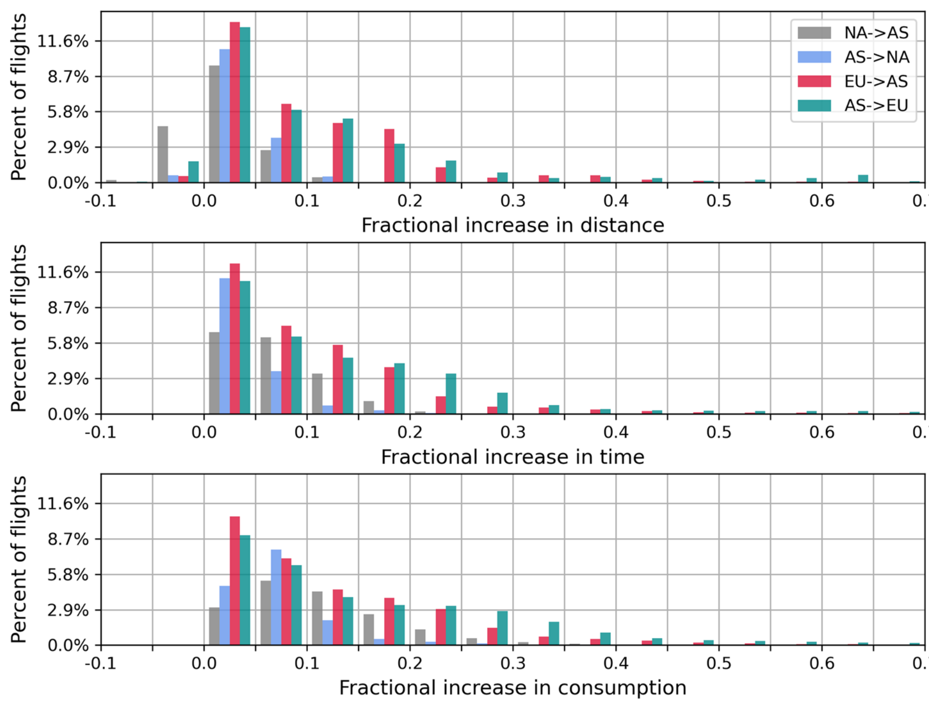

Fig. 4 | Distance, time and consumption variations for flights affected by the Russo-Ukrainian airspace restriction. Histograms of the fractional increases in the flight distance, flight time, and fuel consumption for trajectories with airspace restriction compared to those without. Only flights affected (considered if a flight crosses the Ukrainian and Russian airspace restrictions) are considered. The histograms are shown separately for the four clusters of routes: North America to Asia (NA → AS, grey), Asia to North America (AS → NA, blue), Europe to Asia (EU → AS, red) and Asia to Europe (AS → EU, green). The bins range from −0.1 to 0.7 with a step of 0.05 (i.e., the [0,0.05] bin is located on the right-hand side of label 0).

compared to the European ones. The average increase in consumption is calculated at 13% for all the flights but is 14.8% for the European flights and 9.8% for the North American ones on average. The direction of the route also has a substantial impact on the fuel consumption. The Ukrainian and Russian restrictions lead to an average increase of 11.8% of CO_2 emissions for North American routes to Asia, in comparison to an increase of 7.5% for routes from Asia to North America. The average increase reaches 16.8% for flights from Asia to Europe compared with 12.7% in the reverse direction. Flights from North America to Asia and flights from Asia to Europe are being forced to take trajectories with strong headwinds more often, increasing their flying time and, therefore, consumption.

Finally, we put the impacts of airspace restrictions into the context of the broader framework of global aviation CO_2 emissions. For the sake of computational efficiency, we follow the standard practice[6,7,9,13] for trajectories not affected by airspace restriction and estimate fuel consumption based on the geodesic distance between airport pairs rather than considering actual or optimised trajectories. We compute an increase in global aviation CO_2 emissions of less than 0.2% for the Libyan, Syrian and Yemen restrictions in Table 1. The Russo-Ukrainian restrictions led to an increase of 0.5% in 2022, rising to 1% in 2023, which corresponds to additional emissions of 8.2 $MtCO_2$ per year. The increase in 2023 can be attributed to the fact that restrictions were in place throughout the entire year, and routes had gradually reopened compared to 2022. Such an increase is remarkable given that only 1100 flights are impacted daily on average. This is because these flights are among the longest flights worldwide, and even though they account for a small percentage of the flights, they account for a disproportionally large fraction of the emissions. On average, a deviated flight emits 18 extra tons of CO_2, roughly equivalent to the emissions of one single short-haul flight. Non-CO_2 emissions have almost certainly increased as well.

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 type but not the specific engines mounted on the aircraft, as this information is not present in the database. As the model is a linear regression of several flights, it cannot be considered as being accurate for a specific flight. Seymour et al.[9] estimated the error in fuel consumption to be below 5%. Secondly, Boucher et al.[10] acknowledge that some routes are better optimised than others. Some flights may have operational constraints that are not considered in the optimisation. Consequently, the optimised flight time will be smaller than the actual flight time in these cases, which in turn will lead to a minimisation in fuel consumption and CO_2 emissions. Thirdly, the flight database of FR24 is one of the most complete databases of aircraft movements according to Quadros et al.[7]. However, the completeness of the database cannot be ascertained, and lack of operator information in the database can also lead to missing some flights in the study. Less than 2% of the flights considered are missing operator data, which makes it impossible to know the restriction that applies to these flights. Our study may be missing affected flights by these restrictions. For all these reasons, we can safely say that our study provides a lower bound of the impact of airspace restrictions on CO_2 emissions. Lastly, air traffic in 2022 and 2023 was still recovering from the COVID-19 pandemic. The longer the restriction remains in place, the more the traffic will rebound, and the greater the impact will be on CO_2 emissions.

In conclusion, the Russo-Ukrainian war has undoubtedly affected flight efficiency and contributed to an increase in CO_2 emissions by Western airlines in a sizeable manner. However, this is not the only impact on global aviation. There is also an apparent reduction in Russian international flights, which may have led to some avoided emissions. There is also a likely impact on the seat offer for direct flights between Europe and Asia and a transfer of air traffic to other routes. In fact, non-stop flights gradually resumed after the airspace restrictions but have not reached their pre-COVID-19 levels. Since layover flights between Europe and Asia have become even more economical compared to direct flights, it is likely that more passengers choose to fly through one of the Middle East hubs. If more efficient air traffic management can indeed contribute to the reduction of aviation CO_2 emissions, the current geopolitical situation presents a major obstacle to the achievement of such a reduction.

Methods

Dataset

Aviation CO_2 emissions are calculated from a global reconstruction of air traffic based on the FR24 flight database. The dataset that we purchase from FR24 consists of a list of flights characterised by their departure and arrival airports, aircraft type, airline and flight number, and the latitude-longitude-altitude coordinates of up to six datapoints of their trajectory: departure gate, take-off, start of the cruise, end of the cruise, landing and arrival gate. 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. We further process a flight if the aircraft has been detected to be in flight at some point, i.e. if at least one of the take-off, the start of the cruise, end of the cruise or landing points is available. This is done to avoid processing non-existent flights for which an ADS-B signal could have been received at the airport, but the aircraft did not actually fly. We have compared the FR24 database with a sample of the EuroControl database for flights arriving and departing from CDG and ORY airports in Paris for selected days and found a very good agreement on the number of flights. However we cannot ascertain the completeness of the FR24 database at the global scale.

Identification of restrictions

Since FlightRadar24 does not provide us with sufficient data points to reconstruct the flight trajectories and because we also need to estimate the trajectories that the aircraft would have taken in the absence of airspace restrictions, we reconstruct the flight trajectories using the trajectory optimisation algorithm by Boucher et al.[10] and the actual wind field from ERA5[14]. The Boucher et al. algorithm is too computationally expensive to be run for all flights in our database. Instead, we first seek to identify the subset of flights that are potentially affected by the different airspace restrictions in the years 2022 and 2023. We focus on major country-wide airspace restrictions around the world rather than small or partial restrictions (e.g., military space within a country or restrictions below a certain flight level). Table 2 provides a list of airspace restrictions considered in this study on the basis of information from airspace safety websites[15–17], news websites[18–20], and Wikipedia[21], which we corroborated by analysing live air traffic web sites[22].

Boucher et al.[10] showed that flights might deviate significantly from a great circle to benefit from favourable winds, which increases the flown distance relative to the ground but reduces fuel consumption. Thus it would be incorrect to simply consider flights whose great circle between departure and arrival crosses a restricted airspace. In this study, a flight was considered to be potentially impacted if the geodesic trajectory between the departure and arrival airports crosses either the restricted airspace itself or a 1° band defined around it by a dilation morphological operation on the country mask at 1° resolution. This identifies potential flights whose geodesic trajectory does not cross the restricted airspace but whose time-optimised trajectory might. A sensitivity test showed that increasing the size of the restricted airspace further did not result in additional potentially affected flights. Finally, the flight number was further used to identify the airline and determine whether a particular airspace restriction applies or not to that airline.

Aircraft classification

To focus on civil aviation, we screen out all non-commercial planes. Aircraft technical data were extracted from the ICAO documentation[23] using the aircraft type provided by the FR24 database. We renamed the aircraft codes to their respective ICAO codes as described in Supplementary Table S1. Supplementary tables are available in Supplementary Data. 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, military aircraft based on a ceiling higher

Table 2 | Airspace restrictions considered in this study

Airspace restrictions	Period	Airlines affected	Sources
Ukraine	24/02/2022-to date	All airlines	15,17–19,21
Russia	01/03/2022-to date	Western airlines	16,18–20,22
Western countries	01/03/2022-to date	Russian airlines	15,19,22
Libya	2014-to date	All airlines	15,21,22
Syria	2014-to date	All airlines	15,21,22
Sudan	15/04/2023-to date	All airlines	15,21,22
Yemen	10/07/2023-to date	All airlines	15,21,22

The list of Western and Russian airlines affected by the restrictions is given in the supplementary Table S5 and Table S6, respectively.

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 so we prefer to ignore them and focus on civil aviation only. A flowchart of the aircraft classification is available in Supplementary Fig. S1. Small aircraft and helicopters represent 12% of the flights in the database but correspond to less than 2.5% of the distance flown. This category is later referred to as General Aviation.

For the analysis, we differentiated business jets from commercial aircraft. Business flights were separated from commercial flights based on their number of passengers (lower than 25), their MTOW lower than 50 tons, 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.

Fuel consumption calculation

We compute the CO_2 emissions of each individual flight using the Fuel Estimation in Air Transportation (FEAT) of Seymour et al.[9] for the flights that are not affected by the airspace restrictions and a variant of that method for the flights that are affected. The FEAT model consists of a reduced order fuel consumption model, based on the Eurocontrol performance model, to compute the fuel consumption of 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 geodesic distance (also known as the great-circle distance) to account for the take-off and landing phases at the departure and destination airports, minor airspace restrictions and other air traffic management inefficiencies. The flight path distance d_{fp} is approximated as:

$$d_{fp} = 1.0387 \cdot d_{gc} + 40.5 \quad (1)$$

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 the Base of Aircraft Data (BADA[24]) for the climb, cruise and descent and the ICAO database[25] 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:

$$F_i = \alpha_i \cdot d_{gc}^2 + \beta_i \cdot d_{gc} + \gamma_i \quad (2)$$

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 and on the basis of a return flight, since inbound and outbound flights are treated similarly although they may experience different average wind patterns. 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. 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 90,000–100,000 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 aircraft types onto the 133 aircraft types available in the Seymour et al.[9] 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 the supplementary Table S2. For aircraft with no equivalent in the Seymour et al. study, average coefficients have been computed for categories of commercial aircraft and business jets, knowing the different categories of each aircraft in the Seymour et al. database (see supplementary Table S3 and Table S4). For flight data that do not contain any indication of 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. A flowchart of the aircraft fuel consumption calculation is available in Supplementary Fig. S2.

For the consumption calculation of flights affected by restricted airspace, the algorithm by Boucher et al. was modified to include a large penalty for flight segments that would cross a restricted airspace, which pushes the optimal trajectory outside the restricted airspace. Initial conditions for the trajectory optimisations were also modified to exclude the restricted airspace.

For each flight potentially affected by an airspace restriction, we compute two time-optimised trajectories that both account for the wind patterns, one that takes into account the airspace restriction and one that does not. Fuel consumption and the associated CO_2 emissions are computed with the fuel consumption model of Seymour et al. which we slightly modified to account for detours and the wind pattern. The correction consists of feeding the Seymour et al. model with a flight distance corrected in proportion to the ratio of the optimised flight time to that of the geodesic trajectory:

$$d_{\text{corrected}} = d_{\text{geodesic}} \cdot \frac{t_{\text{optimised}}}{t_{\text{geodesic}}} \quad (3)$$

In this way the fuel consumption for the trajectory with airspace restriction is always equal or greater than without restriction, which would not have been the case had we simply used the geodesic distance as a comparison point. Emissions are then calculated as previously using the factor of 3.16 kg of CO_2 emitted per kg of kerosene burnt[26].

Data availability

The flight database cannot be openly shared due to the terms of the licence agreement with FlightRadar24. The IAGOS data can be downloaded from the IAGOS data portal (10.25326/20).

Code availability

The fuel estimation model is a straightforward implementation of https://doi.org/10.1016/j.trd.2020.102528. The trajectory optimisation algorithm is described in 10.3390/aerospace10090744 and available from https://github.com/OB-IPSL/FlightTrajectories. The Python codes used to perform the analysis are available on request from the corresponding author.

Received: 10 May 2024; Accepted: 6 December 2024;
Published online: 12 February 2025

References

1. European aviation environmental report. Tech. Rep. European Union Aviation Safety Agency, EASA. https://www.easa.europa.eu/eco/sites/default/files/2023-02/230217_EASA%20EAER%202022.pdf (2022).
2. Resolution on the industry's commitment to reach net zero carbon emissions by 2050. Tech. Rep. International Air Transport Association. https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/iata-agm-resolution-on-net-zero-carbon-emissions.pdf (2021).
3. Report on the feasibility of a long-term aspirational goal (LTAG) for international civil aviation CO_2 emission reductions. Tech. Rep., International Civial Aviation Organisation, ICAO. https://www.icao.int/environmental-protection/LTAG/Documents/REPORT%20ON%20THE%20FEASIBILITY%20OF%20A%20LONG-TERM%20ASPIRATIONAL%20GOAL_en.pdf (2022).
4. Chu, C., Zhang, H., Zhang, J., Cong, L. & Lu, F. Assessing impacts of the Russia-Ukraine conflict on global air transportation: From the view of mass flight trajectories. *J. Air Transp. Manag.* **115**, 102522 (2024).

5. Lee, D. et al. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmos. Environ.* **244**, 117834 (2021).
6. Graver, B., Zhang, K. & Rutherford, D. Emissions from commercial aviation, 2018. Tech. Rep. The International Council on Clean Transportation (2019).
7. Quadros, F. D. A., 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).
8. Teoh, R., Engberg, Z., Shapiro, M., Dray, L. & Stettler, M. E. J. The high-resolution global aviation emissions inventory based on ADS-B (GAIA) for 2019-2021. *Atmos. Chem. Phys.* **24**, 725–744 (2024).
9. Seymour, K., Held, M., Georges, G. & Boulouchos, K. Fuel estimation in air transportation: modeling global fuel consumption for commercial aviation. *Transp. Res. Part D* **88**, 102528 (2020).
10. Boucher, O., Bellouin, N., Clark, H., Gryspeerdt, E. & Karadayi, J. Comparison of actual and time-optimized flight trajectories in the context of the in-service aircraft for a global observing system (IAGOS) programme. *Aerospace* https://doi.org/10.3390/aerospace10090744 (2023).
11. In-service aircraft for a global observing system, IAGOS. https://www.iagos.org/.
12. Cavcar, A. & Cavcar, M. Impact of aircraft performance differences on fuel consumption of aircraft in air traffic management environment. *Aircr. Eng. Aerosp. Technol.* **76**, 502–515 (2004).
13. Liu, Z. et al. Near-real-time monitoring of global CO_2 emissions reveals the effects of the COVID-19 pandemic. *Nat. Commun.* **11**, 5172 (2020).
14. Hersbach, H. et al. The ERA5 global reanalysis. *Q. J. R. Meteorol. Soc.* **146**, 1999–2049 (2020).
15. Safe airspace. https://safeairspace.net/. Accessed on 19/12/2023.
16. Scarr, S., Kawoosa, V. M., Chowdhury, J., Sharma, M. & Katakam, A. Unfriendly skies. https://www.reuters.com/graphics/UKRAINE-CRISIS/AIRLINES/klpykbmropg/ (2022). Accessed on 20/02/2024.
17. Asian city pairs: changes in distance flown pre/post-Ukraine invasion. https://www.eurocontrol.int/sites/default/files/2022-04/eurocontrol-data-snapshot-29.pdf (2022).
18. Japanese airlines cancel, reroute flights scheduled to fly over Russia. https://www.travelpulse.com/news/airlines-airports/japanese-airlines-cancel-reroute-flights-scheduled-to-fly-over-russia (Accessed on 20/03/2024).
19. Russia's war on Ukraine redrew the map of the sky—but not for Chinese airlines. https://edition.cnn.com/travel/article/china-europe-airlines-russia-ukraine-airspace/index.html (Accessed on 20/03/2024).
20. Timmins, B. Ukraine airspace closed to civilian flights. https://www.bbc.com/news/business-60505415 (2022). Accessed on 05/10/2023.
21. Prohibited airspace. https://en.wikipedia.org/wiki/Prohibited_airspace. Accessed on 20/12/2023.
22. Flightradar24. https://www.flightradar24.com/. Accessed on 21/01/2024.
23. ICAO. Doc 8643, aircraft type designators. https://www.icao.int/publications/DOC8643/Pages/default.aspx (2022).
24. Vincent, M. User manual for the base of aircraft data BADA. Tech. Rep., Eurocontrol (2019).
25. EASA. ICAO Aircraft Engine Emissions Databank. Tech. Rep. European Union Aviation Safety Agency. https://www.easa.europa.eu/en/domains/environment/icao-aircraft-engine-emissions-databank (2019).
26. ICAO. ICAO Carbon Emissions Calculator Methodology. Tech. Rep. International Civil Aviation Organization. https://www.icao.int/environmental-protection/CarbonOffset/Documents/Methodology%20ICAO%20Carbon%20Calculator_v10-2017.pdf (2018).

Acknowledgements
This research has been supported by the French Ministère de la Transition Ecologique et Solidaire (grant No. DGAC N2021-39), with support from France's Plan National de Relance et de Résilience (PNRR) and the European Union's NextGenerationEU.

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

Competing interests
O. Boucher receives consulting fees as a member of the Stakeholder Committee of Groupe ADP. The remaining authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-024-01956-w.

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Peer review information *Communications Earth & Environment* thanks Arturo Benito, Liudmyla Malytska and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Pallav Purohit and Martina Grecequet. A peer review file is available.