Impact of airspace restrictions due to conflict zones on air traffic CO_2 emissions in 2022 and 2023

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Supplementary Information

Contents

S1 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 characterized 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, 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 datapoints 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.[1] and the actual wind field from ERA5[2]. 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 restriction below a certain flight level). Table S1 provides a list of airspace restrictions considered in this study on the basis of information from airspace safety websites[3–5], news websites[6–8], and Wikipedia[9], which we corroborated by analysing live air traffic web sites[10].

Table S1. Airspace restrictions considered in this study. The list of Western and Russian airlines affected by the restrictions are given in Table S6 and Table S7, respectively.

Airspace restrictions	Period	Airlines affected	Sources
Ukraine	24/02/2022-to date	All airlines	3, 5–7, 9
Russia	01/03/2022-to date	Western airlines	4, 6–8, 10
Western countries	01/03/2022-to date	Russian airlines	3, 7, 10
Libya	2014-to date	All airlines	3, 9, 10
Syria	2014-to date	All airlines	3, 9, 10
Sudan	15/04/2023-to date	All airlines	3, 9, 10
Yemen	10/07/2023-to date	All airlines	3, 9, 10

Boucher et al.[1] 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 the 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-degree 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[11] using the aircraft type provided by the FR24 database. We renamed the aircraft codes to their respective ICAO codes as described in Table S2. 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 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 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.

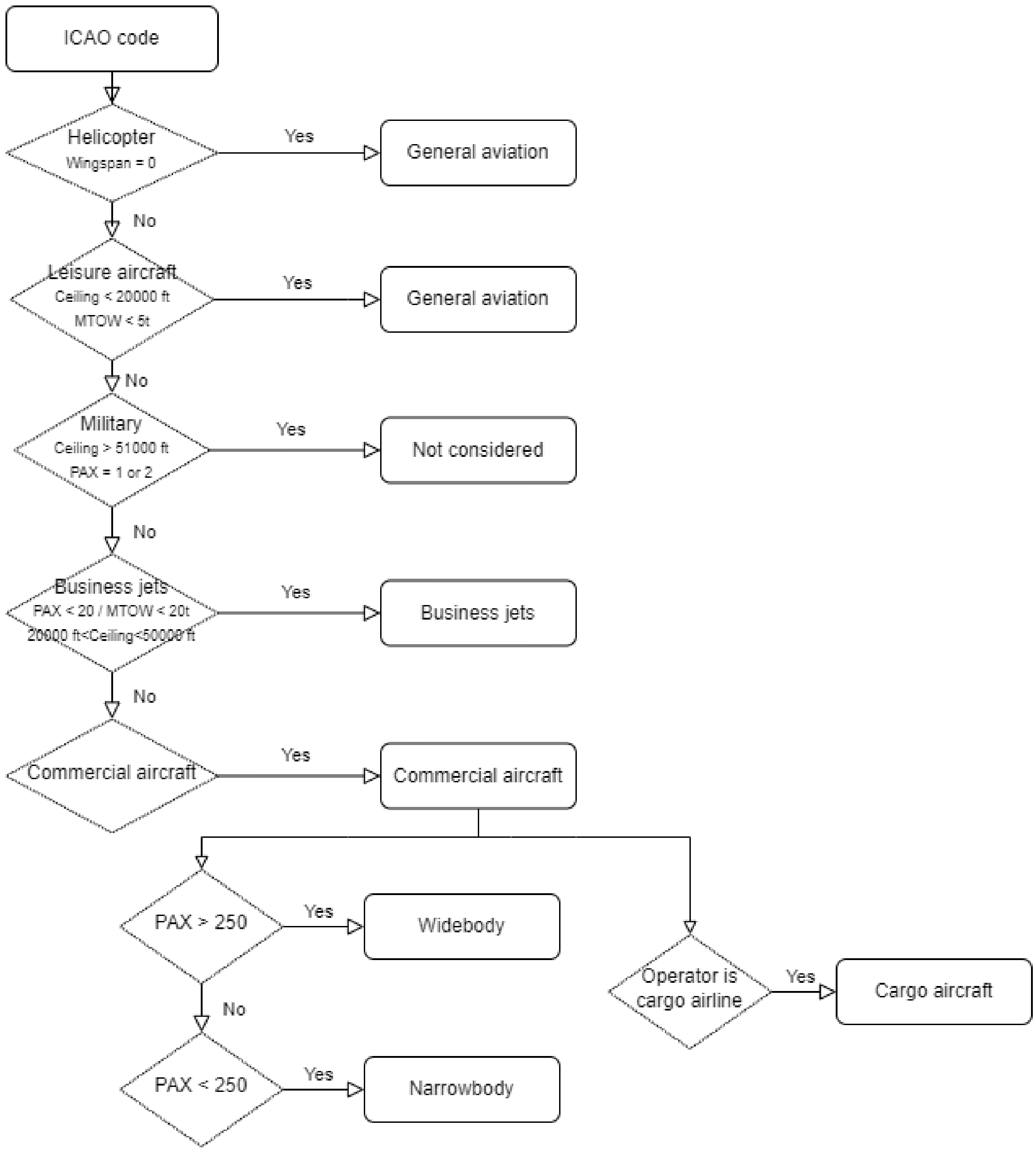


Figure S1. Flowchart for classifying the different aircraft into the respective categories.

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.[12] for the flights that are not affected by the airspace restrictions and a variant of that method for the flights that are affected (see main Text and below). 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:

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

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 the Base of Aircraft Data (BADA[13]) for the climb, cruise and descent and the ICAO database[14] 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 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 to 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.[12] 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 Table S3. 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 Table S4 and Table S5). For flight data that do not contain any indication on 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 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-optimized trajectories that both account for the wind patterns, one that take 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 in 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:

$$d_{corrected} = d_{geodesic} \cdot \frac{t_{optimised}}{t_{geodesic}} \tag{3}$$

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[15].

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. Second, as the model is a linear regression of several flights, it cannot be considered as being accurate for a specific flight. Seymour et al.[12] estimated the error on fuel consumption to be below 5%.

Table S2. List of “equipments” in the FR24 database that needed to be renamed onto aircraft ICAO codes.

Equipment given by FR24	ICAO code assigned	Equipment given by FR24	ICAO code assigned
100	F100	73R	B738
146	B462	73W	B737
310	A310	73Y	B733
318	A318	743	B744
319	A319	744	B744
31Y	A310	747	B744
320	A320	74E	B744
321	A321	74F	B748
322	A321	74H	B748
32A	A320	74N	B748
32B	A321	74Y	B744
32F	A320	752	B752
32N	A20N	753	B753
32Q	A321	757	B752
32S	A320	75F	B752
32V	A320	75T	B753
32X	A321	75W	B752
330	A332	762	B762
332	A332	763	B763
333	A333	764	B764
33X	A332	767	B763
340	A342	76C	B763
343	A343	76E	B763
346	A346	76F	B763
350	A359	76G	B763
351	A35K	76L	B763
359	A359	76P	B763
380	A388	76V	B763
388	A388	76W	B763
717	B712	76Y	B763
722	B722	772	B772
727	B722	773	B773
732	B732	777	B773
733	B733	77F	B77L
734	B734	77L	B77L
735	B735	77W	B77W
736	B736	77X	B77L
737	B737	787	B788
738	B738	788	B788
739	B739	789	B789
73C	B733	78P	B789
73E	B735	7M8	B38M
73F	B737	7M9	B39M
73G	B737	7S8	B738
73H	B738	A26	AN24
73J	B739	A35	A359
73M	B732	A4F	A124
73N	B734	A81	A148
73P	B737	AB3	A306

Equipment given by FR24	ICAO code assigned
AB6	A306
ABF	A30B
ABY	A306
AR1	RJ1H
AR8	RJ85
AT45	AT43
AT46	AT43
AT4	AT43
AT5	AT45
AT7	AT72
AT75	AT72
AT76	AT72
ATF	AT75
ATR	AT43
ATZ	AT43
B727	B722
B73M	B37M
B747	B744
B777	B772
B787	B788
BE2	BE65
BE9	BE20
BEH	B190
BES	BE1
BET	BE1
C12	PC12
CCX	GLEX
CJ2	C550
CJ8	C680
CJL	C560
CL3	CL30
CN1	C120
CN2	C210
CN7	C750
CNA	C402
CNF	C208
CR1	CRJ1
CR2	CRJ2
CR7	CRJ7
CR9	CRJ9
CRJ	CRJ7
CRK	CRJX
CS1	BCS1
CS3	BCS3
CV5	CVLT
D28	D228
D38	D328
D40	DA40
D93	DC94
DC9	DC94
DH1	DH8A
DH2	DH8B
DH4	DH8D

Equipment given by FR24	ICAO code assigned
DH8	DH8B
DHC	DHC4
DHT	DHC6
DR20	DR22
E175	E170
E45	E145
E70	E170
E75	E170
E7W	E75S
E95	E195
EC5	EC35
EM2	E120
EM55	E55P
EMB	E110
EMJ	E190
EP1	E50P
EP3	E55P
ER3	E135
ERJ	E145
F7X	FA7X
FRJ	J328
G36	GLF5
G6	GLEX
GJ4	GLF4
GR3	G280
H25	H25A
H25X	H25A
IL9	IL96
J300	J328
J31	JS32
J41	JS32
J532	JS32
LJ3	LJ31
LJ4	LJ40
LJ6	LJ60
LJ7	LJ70
M11	MD11
M1F	MD11
M80	MD81
M82	MD82
M83	MD83
M87	MD87
M88	MD88
MC10	MD11
MC21	MD11
PA28	P28A
S20	SB20
SF3	SF34
SH6	SH36
T20	T204
T214	T214
T45	T154

Table S3. List of aircraft ICAO codes that have been replaced by equivalent aircraft available in Seymour et al.[12] in order to compute the fuel consumption according to the BADA[13] model.

Aircraft	Equivalent aircraft
A1	SW4
A178	E190
A19N	A20N
A338	A339
A358	A359
A743	A158
A748	F27
AN22	A339
AN72	F100
ARVA	C208
AT6T	C208
AT7	AT72
B23	E120
B25	AT43
B26	SF34
B37M	B38M
B701	B752
B720	B752
B721	B752
B731	T134
B778	B77W
B779	B77W
BE1	B190
BE10	F406
BE4W	BE40
BLCF	B77W
C119	F27
C141	A310
C15	T154
C17	B764
C212	JS32
C295	F27
C46	F27
C68A	C680
C919	A20N
CN35	AT43
DC3	F27
DC3S	F27
DC3T	F27
DC4	F27
DC91	B712
DC92	DC94
DC95	DC94

Aircraft	Equivalent aircraft
DHC4	F27
DHC5	SW4
E275	E75L
E295	B736
E737	B738
ER4	E145
F60	F50
G159	D328
G21T	BE20
G222	F27
G73T	C208
IL62	A30B
JS1	D228
JS20	D228
JS3	D228
L37	JS41
LANC	F27
M28	JS32
MA60	F27
MA6H	F27
MC23	A20N
MRJ7	A148
MRJ9	A148
MU30	BE40
N262	JS41
NIM	B738
P2	F27
P61	D328
R721	MD83
R722	B722
RJ70	RJ85
S2T	JS41
SC7	D228
TBM	JS32
U21	F406
V22	A140
VF14	YK40
Y12F	JS32
YS11	ATP

Table S4. List of aircraft ICAO codes in the Seymour et al.[12] database that correspond to leisure aircraft and business jets. The other aircraft are all considered to be commercial aircraft.

Aircraft	Type
AN38	Leisure aircraft
BE40	Business jet
BE55	Leisure aircraft
BN2P	Leisure aircraft
C172	Leisure aircraft
C208	Leisure aircraft
C25A	Business jet
C310	Leisure aircraft
C680	Business jet
DHC2	Leisure aircraft
DHC3	Leisure aircraft
DOVE	Leisure aircraft
E55P	Business jet
F406	Leisure aircraft
GLF4	Business jet
GLF5	Business jet
L410	Leisure aircraft
P28B	Leisure aircraft
PA31	Leisure aircraft
PA46	Leisure aircraft
PC12	Leisure aircraft

Table S5. List of aircraft ICAO codes for which average coefficients have been used based on the classification in Table S4.

Aircraft	Type
A124	Commercial aircraft
A225	Commercial aircraft
A337	Commercial aircraft
A3ST	Commercial aircraft
A50	Commercial aircraft
AC72	Commercial aircraft
AC80	Business jet
AN12	Commercial aircraft
AN70	Commercial aircraft
ASTR	Business jet
AT44	Commercial aircraft
AT45	Commercial aircraft
AT46	Commercial aircraft
AT73	Commercial aircraft
AT75	Commercial aircraft
AT76	Commercial aircraft
ATLA	Business jet
B350	Business jet
B3XM	Commercial aircraft
B703	Commercial aircraft
B741	Commercial aircraft
B742	Commercial aircraft
B743	Commercial aircraft
B74D	Commercial aircraft
B74R	Commercial aircraft
B74S	Commercial aircraft
BA11	Commercial aircraft
BE12	Business jet
BELF	Commercial aircraft
C123	Commercial aircraft
C125	Commercial aircraft
C160	Commercial aircraft
C25B	Business jet
C25C	Business jet
C500	Business jet
C501	Business jet
C510	Business jet
C525	Business jet
C526	Business jet
C550	Business jet
C551	Business jet
C55B	Business jet
C560	Business jet
C56X	Business jet
C650	Business jet
C700	Business jet
C750	Business jet
C82	Commercial aircraft
C97	Commercial aircraft
CCJ	Business jet
CL30	Business jet
CL35	Business jet
CL44	Commercial aircraft
CL60	Business jet
CONI	Commercial aircraft
CVLP	Commercial aircraft
D28G	Commercial aircraft
DC10	Commercial aircraft
DC6	Commercial aircraft
DC7	Commercial aircraft
DC85	Commercial aircraft
DC86	Commercial aircraft
DC87	Commercial aircraft
DC93	Commercial aircraft
DH3	Commercial aircraft
E2	Business jet
E290	Commercial aircraft
E35L	Business jet
E390	Commercial aircraft
E45X	Commercial aircraft
E50P	Business jet
E545	Business jet
E550	Business jet
E6	Commercial aircraft
E90	Commercial aircraft
EVOT	Business jet
F2TH	Business jet
F900	Business jet
FA10	Business jet
FA20	Business jet
FA50	Business jet
FA5X	Business jet
FA7X	Business jet
FA8X	Business jet
FGTH	Commercial aircraft
G150	Business jet
G250	Business jet
G280	Business jet
GA5C	Business jet
GA6C	Business jet
GA7C	Business jet
GAC7	Business jet
GALX	Business jet
GL5T	Business jet
GL7T	Business jet
GLEX	Business jet
GLF2	Business jet
GLF3	Business jet
GLF6	Business jet
GSPN	Business jet
H25A	Business jet
H25B	Business jet
H25C	Business jet
HA4T	Business jet
HF20	Business jet
IL18	Commercial aircraft
IL86	Commercial aircraft
JCOM	Business jet
L101	Commercial aircraft
L188	Commercial aircraft
L29A	Business jet
L29B	Business jet
LJ23	Business jet
LJ24	Business jet
LJ25	Business jet
LJ28	Business jet
LJ31	Business jet
LJ35	Business jet
LJ36	Business jet
LJ40	Business jet
LJ45	Business jet
LJ55	Business jet
LJ60	Business jet
LJ70	Business jet
LJ75	Business jet
LJ85	Business jet
MD11	Commercial aircraft
P180	Business jet
P1HH	Commercial aircraft
PA47	Business jet
PAY1	Business jet
PAY3	Business jet
PAY4	Business jet
PC24	Business jet
PRM1	Business jet
S210	Commercial aircraft
S601	Business jet
SBR1	Business jet
SBR2	Business jet
SJ30	Business jet
SK70	Business jet
STAR	Business jet
TRIN	Commercial aircraft
TU95	Commercial aircraft
V280	Business jet
VC10	Commercial aircraft
WW23	Business jet
WW24	Business jet

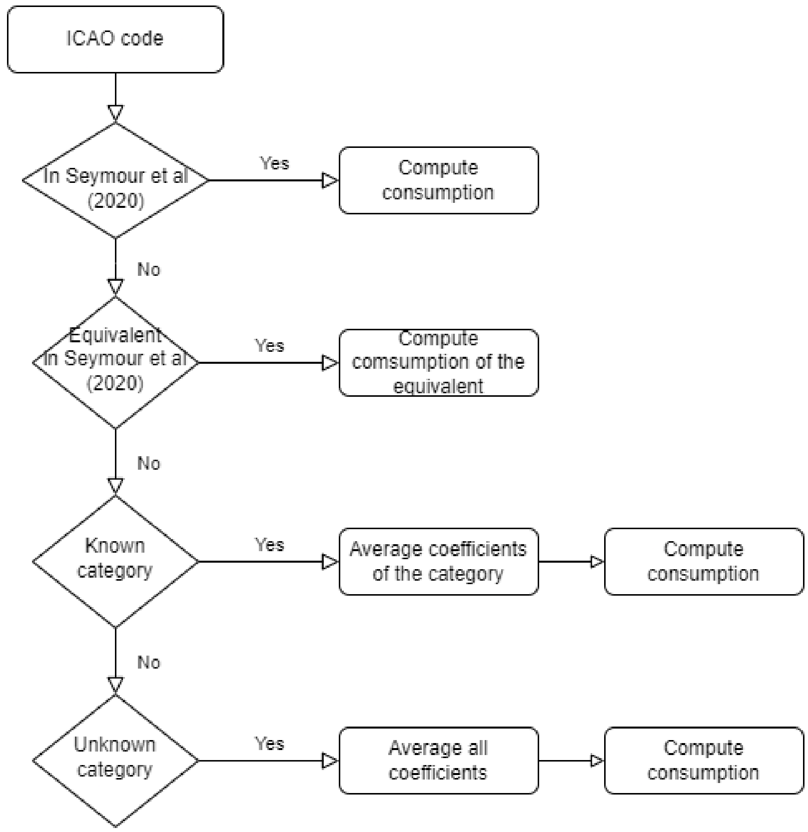


Figure S2. Flowchart for computing the fuel consumption of the different aircraft categories.

S2 ICAO airlines affected by the airspace restrictions

Table S6 lists the Western airlines affected by the Russian airspace restriction and Table S7 lists the Russian airlines affected by the Western airspace restrictions.

Table S6. List of Western airlines affected by the Russian airspace restriction.

ICAO code	Airline name	Country
AAL	American Airlines	United States
AAR	Asiana Airlines	South Korea
AAY	Allegiant Air	United States
ABD	Air Atlanta Icelandic	Iceland
ABL	Air Busan	South Korea
ACA	Air Canada	Canada
AEA	Air Europa	Spain
AEE	Aegean Airlines	Greece
AFR	Air France	France
AHO	Air Hamburg (AHO)	Germany
AJX	Air Japan	Japan
AMC	Air Malta	Malta
ANA	All Nippon Airways	Japan
ANK	Air Nippon	Japan
ASL	Air Serbia	Serbia
AUA	Austrian Airlines	Austria
BAW	British Airways	United Kingdom
BLX	TUIfly Nordic	Sweden
BPS	Budapest Aircraft Services	Hungary
BRG	Bering Air	United States
BTI	Air Baltic	Latvia
CAL	China Airlines	Taiwan
CFG	Condor Flugdienst	Germany
CLH	Lufthansa CityLine	Germany
CPA	Cathay Pacific	Hong Kong SAR of China
CTN	Croatia Airlines	Croatia
CYP	Cyprus Airways	Cyprus
DAL	Delta Air Lines	United States
DLA	Air Dolomiti	Italy
DLH	Lufthansa	Germany
EDW	Edelweiss Air	Switzerland
EJA	NetJets	United States
EVA	EVA Air	Taiwan
EWG	Eurowings	Germany
EXS	Jet2.com	United Kingdom
FCA	First Choice Airways	United Kingdom
FCM	Flybe Finland Oy	Finland
FIN	Finnair	Finland
FWI	Air Caraïbes	France
GEC	Lufthansa Cargo	Germany
GTI	Atlas Air	United States
HAL	Hawaiian Airlines	United States
HLF	Hapagfly	Germany
IAM	Aeronautica Militare	Italy
ICE	Icelandair	Iceland
ICL	CAL Cargo Air Lines	Israel
JAF	Jetairfly	Belgium
JAL	Japan Airlines Domestic	Japan

Table S6. List of Western airlines affected by the Russian airspace restriction.

ICAO code	Airline name	Country
JAL	Japan Airlines	Japan
JNA	Jin Air	South Korea
KAL	Korean Air	South Korea
KLM	KLM Royal Dutch Airlines	Netherlands
KRP	Carpatair	Romania
LAV	AlbaStar	Spain
LDA	Lauda Air	Austria
LOT	LOT Polish Airlines	Poland
LTC	LatCharter	Latvia
LZB	Bulgaria Air	Bulgaria
NCR	National Air Cargo	United States
NVR	Novair	Sweden
QFA	Qantas	Australia
ROT	Tarom	Romania
RYA	Ryan Air Services	United States
RYR	Ryanair	Ireland
SAS	Scandinavian Airlines System	Sweden
SDR	City Airline	Sweden
SEH	Sky Express	Greece
SEU	XL Airways France	France
SIA	Singapore Airlines	Singapore
SJO	Spring Airlines Japan	Japan
SVR	Ural Airlines	Russia
SWR	Swissair	Switzerland
SWR	Swiss International Air Lines	Switzerland
TGW	Tiger Airways Australia	Australia
TGW	Tiger Airways	Singapore
TOM	Thomsonfly	United Kingdom
TRA	Transavia Holland	Netherlands
TUI	Tuninter	Tunisia
TVF	Transavia France	France
TVS	Travel Service	Czech Republic
UAL	United Airlines	United States
VIR	Virgin Atlantic Airways	United Kingdom
WIF	Widerøe	Norway
WZZ	Wizz Air	Hungary

Table S7. List of Russian airlines affected by the Western airspace restrictions.

ICAO code	Airline name	Country
AFL	Aeroflot Russian Airlines	Russia
GZP	Gazpromavia	Russia
LLM	Yamal Airlines	Russia
NWS	Nordwind Airlines	Russia
SBI	S7 Airlines	Russia
SDM	Rossiya	Russia
VDA	Volga-Dnepr Airlines	Russia

S3 Impact of the European Union airspace restriction on Russian flights

Western countries banned Russian airlines from flying through their airspace. Russian airlines therefore adjusted their destinations by cancelling some destinations, opening new destinations and rerouting some of the flights. It is noteworthy that Russian flights had a much more diverse set of destinations in 2019. Overall there is a total reduction in the number of destinations to Europe, partly compensated by the addition of new destinations in Turkey, Egypt, other Middle East countries, and former Soviet republics.

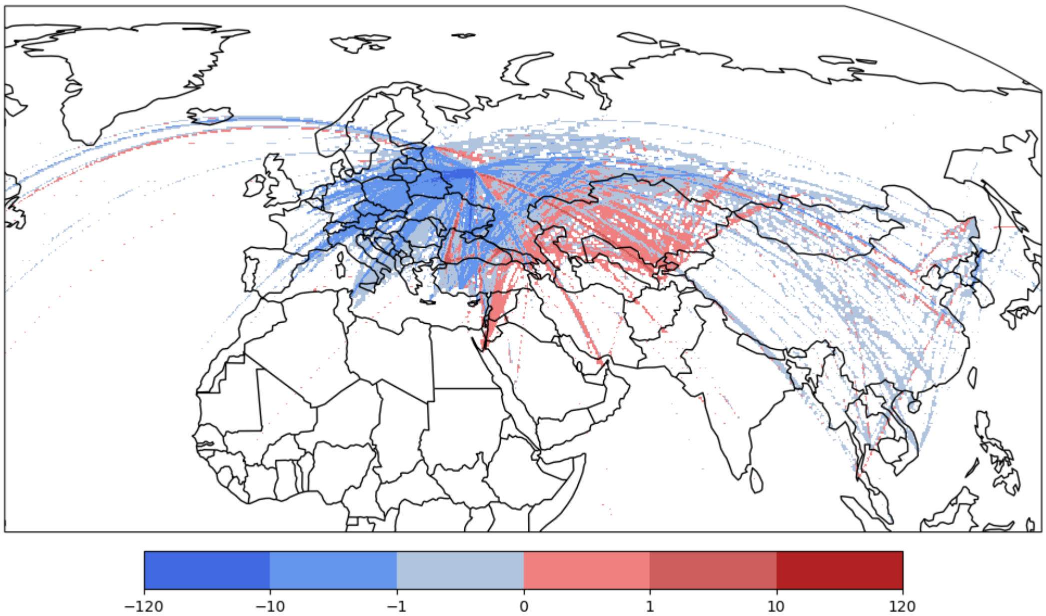


Figure S3. Change in flight track density (km.km^{-2}) for all international Russian flights between June 2019 and June 2023 assuming great circle approximation for the flight paths.

The Russian enclave of Kaliningrad, which is located on the Baltic Sea between Poland and Lithuania, did not appear to have experienced a significant decrease in the number of flights (counting both arrivals and departures), as shown on Fig S4. Instead a larger peak is observed in summer 2023 compared to previous years. Because of the airspace restriction, flights have to divert north of Estonia to avoid European Union airspace.

Figure S4. Evolution of traffic to and from the Russian Kaliningrad enclave.

S4 Comparison of optimised flight times against IAGOS-trajectory flight times

We identified 294 flights in the IAGOS database that were affected by the Ukrainian and Russian restrictions between March 2022 and December 2023. For each of these flights, we estimated the flight time of the cruising phase using our optimisation method and compare it against the recomputed flight time of the actual IAGOS trajectory (note that this differs from the actual IAGOS flight time because of potential small differences in the air speed). Fig. S5 shows the histogram of this difference. On average the optimised flight times are 2.6% smaller than the recomputed IAGOS-trajectory flight times, illustrating the fact the IAGOS trajectories are not perfectly optimised[1]. Only 13% of the optimised flights were slower than the actual flights, which can be explained by occasional imperfection in our optimisation method.

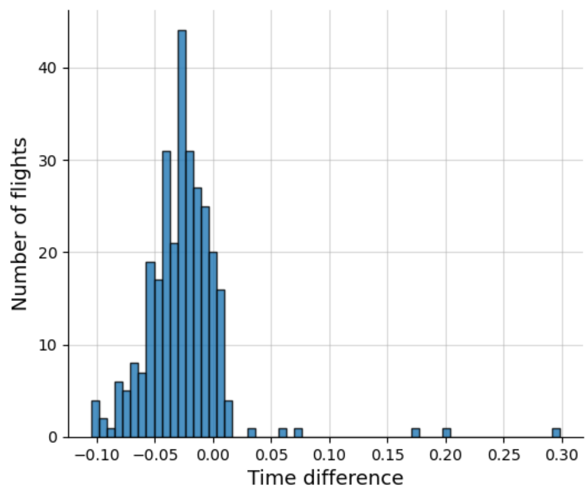


Figure S5. Distribution of the flight time difference (in decimal hours) between the optimised trajectory and the recomputed IAGOS-trajectory flight time. The bins range from –0.1 to 0.3 with a step of 0.006.

S5 Clustering of flights for the restriction of the Ukrainian and Russian airspace

Fig. S6 represents the four clusters obtained using the K-means clustering method to categorize the affected flights into different classes. On average, 67% of the affected flights were on the Europe-Asia route, while the remaining 33% were on the Asia-North America route.

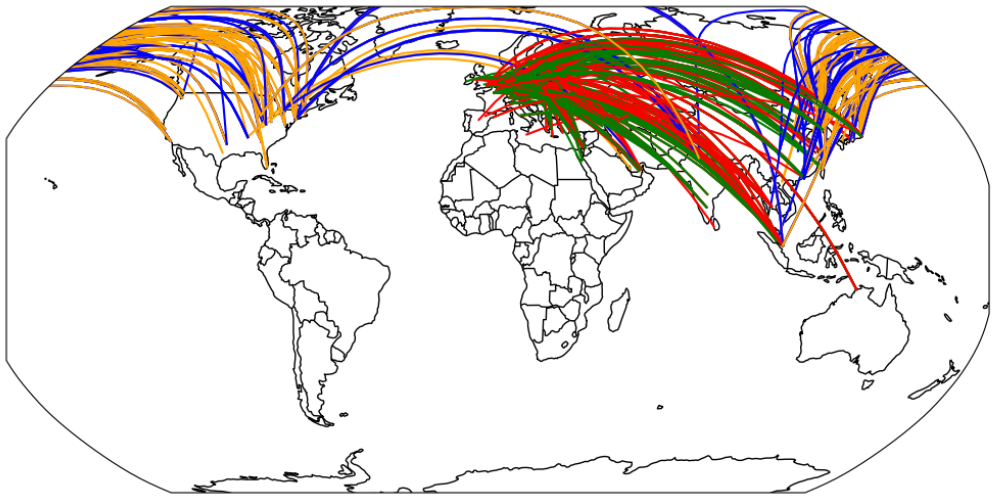
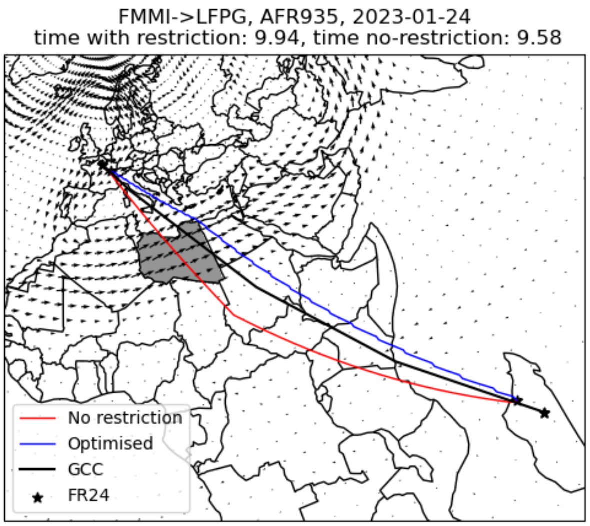


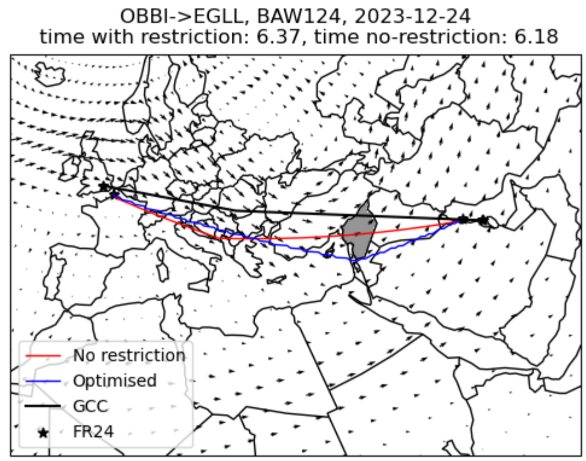
Figure S6. Clusters of flights affected by the airspace restriction over Ukraine and Russia for a given day (10 April 2023). The red and blue categories represent flights from Europe to Asia and Asia to North America, respectively, while the orange and green categories represent the reverse routes. The flight trajectories were mapped on the basis on great circles between the departure and arrival airports.

S6 Example of flights affected by the different restrictions

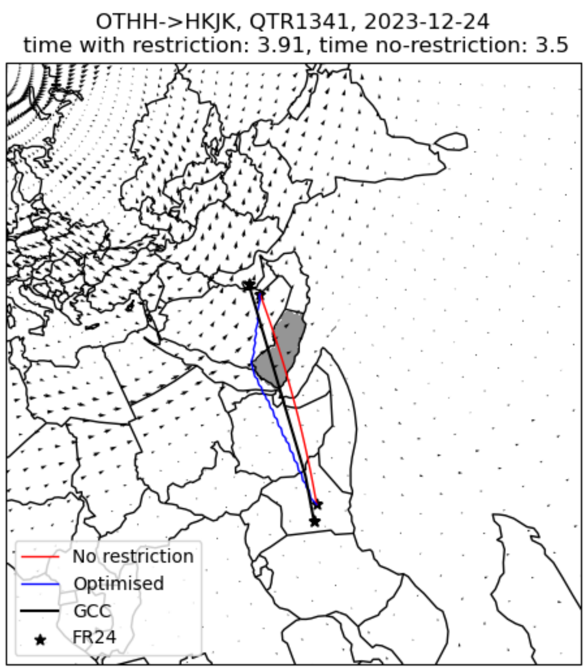
Fig. S7 and Fig. S8 show different examples of flights affected by the restriction considered in the study. Fig. S8 illustrates that flights from North America to Asia can be more affected by the airspace restriction due to strong headwinds on the North Pacific trajectory with detour (compare the differences in flight times with and without the airspace restriction).



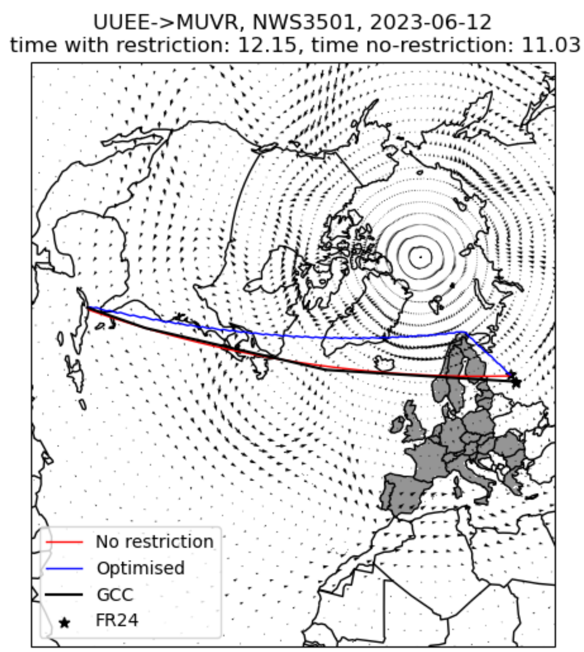
(a) Flight from Antananarivo to Paris Charles de Gaulle.



(b) Flight from Bahrain to London Heathrow.

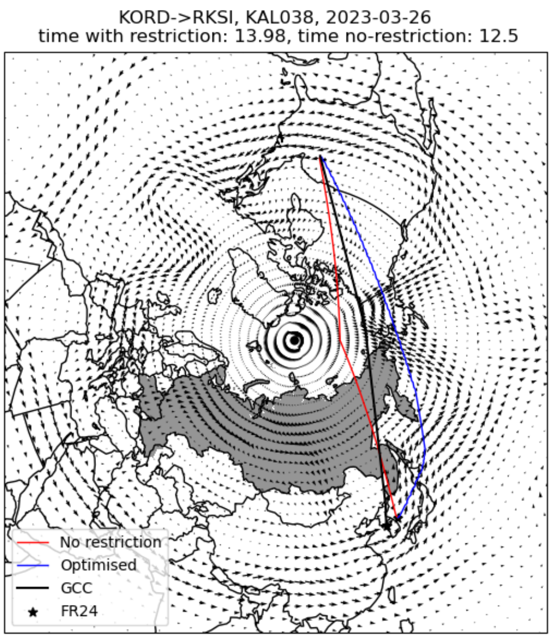


(c) Flight from Doha to Nairobi.

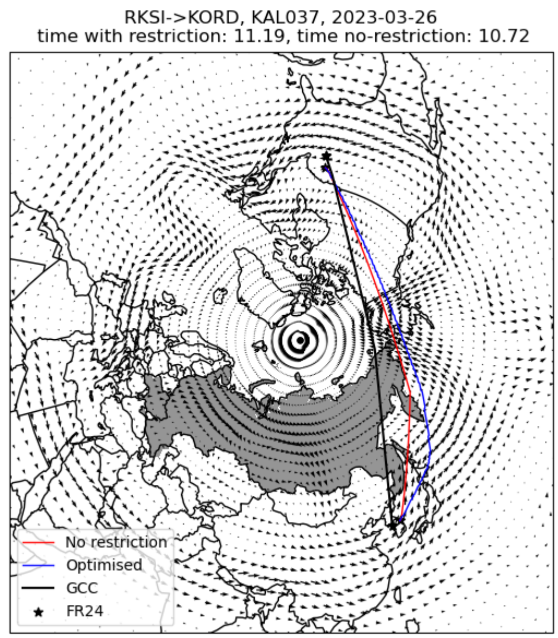


(d) Flight from Moscow to Cuba.

Figure S7. Examples of flights that are affected by different airspace restrictions around the world according to our optimisation model. (a) Flight from Antananarivo to Paris CDG that would have crossed the Libyan airspace, (b) Flight from Bahrain to London Heathrow that would have crossed the Syrian airspace, (c) Flight from Doha to Nairobi that would have crossed the Yemen and (d) Russian flight from Moscow to Cuba that would have cross the European Union airspace. The geodesic path (or great circle) between the two airports is shown in black. The geodesic path between the two airports is shown in black. The optimal trajectories with and without restriction are shown in blue and in red, respectively. The wind pattern at 250 hPa is shown with the black arrows. The restricted airspace is shaded in grey. The route, callsign, date and the optimised cruising times (in decimal hours) with and without restriction are also displayed in the headers.



(a)



(b)

Figure S8. Same as Fig. S7 but for (a) a flight from Chicago to Seoul and (b) a flight from Seoul to Chicago affected by the Russia airspace restriction.

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