

Assessing Climate Effects Resulting From Airspace Closures Following the Ukrainian Crisis

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Abstract

Closures of the Russian and Ukrainian airspace following the Russian invasion of Ukraine in February 2022 have influenced international air transport. Flights have to be re-routed leading to increases in mission distance, flight time, fuel consumption and CO₂ emissions. However, the climate impact of aviation is also significantly determined by non-CO₂ effects which do not only depend on emission quantities but also emission location and time. Therefore, this paper aims to quantify the climate impact from Russian and Ukrainian airspace closures in context of the Ukrainian crisis. The analysis is built on open-source flight track data as provided by *The OpenSky Network* applied in the *Integrated Trajectory Calculation Module*. Climate impact evaluation is performed in a climatological approach using climate chemistry response model *AirClim*. The analysis confirms an increase in fuel consumption and CO₂ effects for a mission-specific comparison of pre invasion and post invasion air traffic scenarios. By contrast, the climate impact from non-CO₂ species decreases disproportionately leading to a slight reduction of the total climate impact. This is caused by changes in emission latitude and altitude. On a larger temporal scale, a comparison of annual pre and post invasion scenarios is also influenced by changes in flight plans and fleet composition. While airspace closures have significantly influenced aviation in terms of fuel consumption, flight time and operating cost leading to economic disadvantages, an environmental disadvantage regarding the climate impact of aviation cannot be confirmed.

Keywords: trajectory calculation, climate impact assessment, air transport operations, non-CO₂ effects, re-routing

1. Introduction

The Russian invasion of Ukraine in February 2022 has strongly influenced flight operations due to a general closure of Ukrainian airspace and a ban of overflights for Russian airspace resulting from sanctions applicable to a large set of Western countries [1, 2]. The resulting changes of flight tracks lead to significant detours which do not only influence travel time and fuel consumption, but also emission quantities and climate impact as well as operating cost. In particular, the climate impact requires detailed investigation due to multi-layered dependencies when quantifying aviation effects as the climate impact of aviation is not only influenced by carbon dioxide (CO₂) emissions, but also by non-CO₂ effects.

With very long atmospheric life times of CO₂ leading to a homogeneous distribution within the atmosphere, the associated climate effect is assumed to be independent of emission location and time and proportionate to the emission quantities and thus fuel burn. Consequently, longer flight routes, e.g. from airspace closures, leading to higher fuel consumption are expected to result in a higher CO₂ climate impact on the one hand. On the other hand, non-CO₂ emissions perturb the radiative balance through (i) direct green-house effects from water vapor (H₂O), (ii) indirect greenhouse gas effects through ozone, methane as well as water vapor changes induced by the emission of nitrogen oxides (NO_x), (iii) the formation of contrail cirrus (contrail-induced cloudiness, CiC), and (iv) aerosols with direct radiation and indirect cloud effects [3, 4]. These effects do not only depend on the amount of fuel burnt, but also on the technical and operational conditions (e.g. for the amount of NO_x emissions), meteorological conditions (e.g. for the formation of contrails in dependence of pressure and humidity), lateral and vertical emission location (e.g. for H₂O and NO_x-induced climate effects) as well as time of emission (e.g. for CiC effects in dependence of existing solar radiation) [3, 4, 5, 6]. The non-CO₂ effects of aviation are expected to account for approximately two thirds of the total effect [4]. Therefore, the total climate impact does not necessarily increase as a consequence of changed routing. Lateral and vertical shifts could potentially also reduce the climate effect from non-CO₂ emissions, thus compensate the increase in CO₂ effects. However, the quantification of climate effects from non-CO₂ emissions in aviation underlie large uncertainties estimated approximately eight times higher than non-CO₂ effects [4]. Especially CiC and aerosol effects are associated with high uncertainties and low confidence levels as underlying effects cannot yet be modeled to their full extent [4].

Based on a gap in previous research (see section 1.1), an analysis of the climate impact from the airspace closures in context of the Russian invasion is examined in the following study (detailed research objective in section 1.2).

1.1 Previous research

The impact from the Russian invasion on the global air transport system has been subject to previous research. These studies can be divided into (i) environmental investigations analyzing additional fuel consumption, resulting emission increases, and climate effects, and (ii) economic investigations focusing challenges for operators and possible competitive disadvantages.

On the one hand, An et al. (2023) investigate the environmental effect on 23 connections from North America's biggest airports to Asia based on ADS-B data and compare affected pre-conflict routes to routes after the Russian invasion. The authors apply a simplified open source emissions calculator estimating CO₂ emissions and CO₂ equivalents showing a significant increase of on average 1.4 % in CO₂ equivalent emissions. However, the authors do not consider location dependent climate sensitivities of non-CO₂ effects [7]. Moreover, Darnet et al. (2025) investigate theoretical influence from airspace closures following the Ukrainian crisis, building their analysis on time-optimized flight routes considering airspace restrictions. The study reveals substantial changes in fuel consumption for flights to and from Europe compared to flights to and from North America increasing global aviation emissions by 1 % in 2023 [8].

On the other hand, Chu et al. (2024) investigate ADS-B (Automatic Dependent Surveillance - Broadcast) flight trajectories from February and March 2022 and identify a share of more than 6 % of global flights being re-routed leading to a 0.6 % increase in cost. The authors find a share of 3.2 % of international flights being canceled on a global scale decelerating recovery from COVID19 traffic declines in aviation [9]. Furthermore, Grimme et al. (2024) investigate demand and supply data to determine changes in traffic volumes and revenues over a time period from 2000 to 2024. Results demonstrate a decline in international traffic from Russia to Western Europe and North America comparing 2019 to 2023. By contrast, the traffic to non-sanctioning countries, for instance in Central Asia or the

Gulf region and Turkey, has increased providing higher revenues for airlines from those countries. On this basis, economic advantages could be observed for airlines from non-sanctioning countries underlining downsides of such policy instruments [10]. Ivashchuk & Ostroumov (2023) focus on flights to and from Ukrainian airports showing marked reduction in flights, flight time, and traffic volume and identify a reduction of 3 billion available seat kilometer (ASK) for the studied airlines [11].

In general, existing studies show a strong impact on the air transport system through re-routing and flight cancellations as well as an increase in flight distance, fuel consumption and CO₂ effects for the re-routed flights. While these results illustrate operational consequences as well as higher climate impact from CO₂ emissions following the imposed sanctions, there is a research gap regarding the change in climate impact from CO₂ and non-CO₂ emission species caused by the required re-routings. This is addressed in a master thesis by Kumpa (2024) representing the basis for the following analysis of this paper [2].

1.2 Objective and structure of this study

A detailed investigation of the climate impact considering both emission quantities and location changes has not yet been performed. Furthermore, a detailed trajectory assessment considering lateral and vertical changes has so far been investigated for selected individual flight missions only. This is addressed in the following study, where we analyze a large sample of flights crossing the Ukrainian or Russian airspace prior to the Russian invasion in February 2022 (*pre invasion*) and compare trajectories including relevant mission characteristics such as fuel burn, travel time, and emission quantities to equivalent missions after the Russian invasion (*post invasion*). In addition to trajectory and emission assessments, we investigate climate effects considering both changes in emission quantities as well as location changes due to re-routing. Hence, this work addresses the research objective of quantifying the climate impact of the Russian invasion based on openly available data.

The study is structured as follows: Following this introduction, section 2 describes the applied method with required advancements of an existing modeling workflow as well as applied data sets for both trajectory and climate impact assessment. Subsequently, section 3 presents the results in two sub-studies with different temporal scopes. The paper closes with a final discussion and an outlook on future research (section 4).

2. Method & Data

The assessment is performed with an integrated modeling workflow divided into three steps (cf. Figure 1), which consists of trajectory calculation (section 2.1), emissions modeling (section 2.2) and climate impact assessment (section 2.3). Section 2.4 describes the set-up of the study as well as the data sets applied. Based on representative mission descriptions for pre and post invasion air traffic scenarios, changes in mission-related key figures can be compared.

2.1 Trajectory simulation

Trajectory calculation is performed with German Aerospace Center's (DLR) *integrated Trajectory Calculation Module (iTCM)*, which represents an extension of the Trajectory Calculation Module (TCM) developed at the DLR Institute of Air transport [12, 13, 14]. iTCM simulates relevant flight performance parameters, such as speeds, accelerations, forces and fuel consumption, based on aircraft specific flight performance data sets. It applies a total-energy-model approach meaning the rate of work performed by the forces acting on the aircraft is equivalent to changes in potential and kinetic energy (see equation 1, where Th represents Thrust, and D represents aerodynamic Drag;

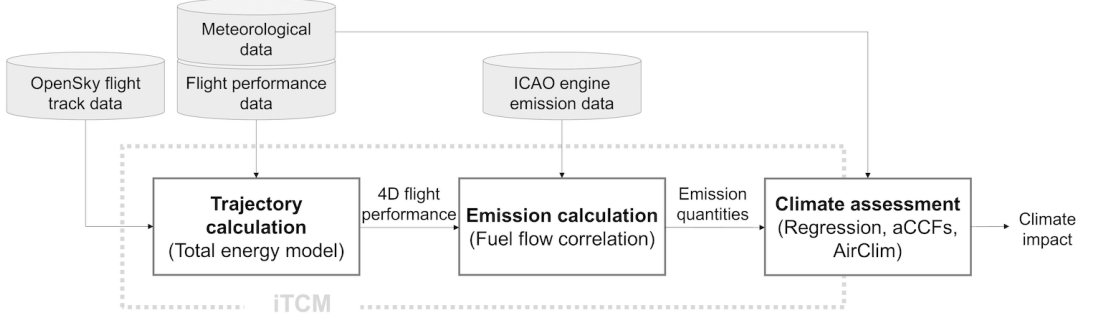


Figure 1. Schematic illustration of workflow including applied data sources.

v_{TAS} describes the true air speed of the aircraft, m the aircraft mass, h the aircraft altitude and g the acceleration of gravity).

$$\underbrace{(Th - D) \cdot v_{TAS}}_{\text{Excess of power}} = \underbrace{m \cdot g \cdot \frac{dh}{dt}}_{\text{Change in potential energy}} + \underbrace{m \cdot v_{TAS} \cdot \frac{dv_{TAS}}{dt}}_{\text{Change in kinetic energy}} \quad (1)$$

Moreover, meteorological information can be considered especially in terms of wind, temperature and pressure data for aircraft speed and engine performance calculations.

Recent advancements of the iTCM have been implemented and applied supporting the objective of this study. In addition to the generation of realistic trajectories for a given origin-destination (OD) combination based on mission length and aircraft type, we extend the modeling capabilities, so that iTCM is now also capable of recalculating actually-flown three or four dimensional trajectories. For a three-dimensional re-modeling of actual point profiles (without temporal information), the route is laterally discretized into segments between the considered waypoints assuming a direct great-circle connection. Vertically, a standard phase description is adjusted inserting step climbs and descents based on a detection from the actual flight profile [13]. Four-dimensional reconstruction is performed considering a *Reverse approach* based on altitude and speed changes derived from the point profile description. Hence, the total-energy-model equation (equation 1) can be rearranged to calculate thrust requirements for every flight segment as displayed in equation 2.

$$Th = D + m \cdot \left(\frac{g \cdot \frac{dh}{dt}}{v_{TAS}} + \frac{dv_{TAS}}{dt} \right) \quad (2)$$

Drag values can be calculated based on aerodynamic information for the considered aircraft type in dependence of aircraft weight, speed and position. Consequently, fuel burn and aircraft mass changes can be calculated in dependence of the required thrust based on the respective engine performance deck.

Furthermore, iTCM is extended with the option to use different flight performance data sets. In addition to the licensed BADA4 library, we are now able to also consider open-source models in the trajectory calculation, namely *OpenAP* and *Poll-Schumann Model* [15, 16, 17]. Further advancements comprise a direct link to additional interfaces for emission modeling (see section 2.2) and open source climate impact assessment tools, namely *algorithmic climate change functions* (aCCFs) and *Contrail Cirrus Prediction* (CoCiP) model implemented in *pycontrails* [18, 19, 20].

2.2 Emissions modeling

Based on fuel flow values from flight performance simulations (see section 2.1), emission flows and quantities can be determined. While CO_2 and H_2O are estimated to be proportional to fuel burn, i.e. constant emission indices per mass of burnt fuel can be assumed, NO_x , HC, CO and soot emission indices are estimated using fuel flow correlation methods. In the course of this study, we apply DLR's fuel flow correlation method to estimate the required NO_x emission indices [5]. Based on reference emission indices obtained at engine test bench at sea level, in-flight values are determined based on in-flight fuel flow and considering changed boundary conditions at flight altitude such as ambient meteorology of the respective trajectory segment [21, 5]. In addition, iTCM also includes emission interfaces to further emission calculation routines, e. g. Boeing Fuel-Flow correlation method (BFFM2) [22].

For efficient trajectory calculation, we have established *Reduced Emission Profiles (RedEmP)* which are especially suitable in case of large inventory calculations for scenarios consisting of many different flight missions [14, 23]. The data sets comprise standardized flight trajectories for different seat load factors, flight distances and aircraft-engine combinations assuming fuel-optimized altitude profiles including step climbs. Each trajectory is reduced to characteristic points describing representative flight phases for which state variables from trajectory and emission flow calculations are stored based on detailed trajectory simulations. RedEmPs are adjusted to the respective flight mission by adjusting the length of the cruise segments. By applying RedEmPs computational effort can be reduced while keeping accuracy of fuel flow values within acceptable limits of deviations up to 2 % [23].

The *Global Air Traffic Emission Distribution Laboratory (GRIDLAB)* is applied to efficiently calculate high-resolved gridded emission distributions for global scenarios as an input for climate response modeling [23, 14]. In this context, detailed flight track information can be considered. Actually flown trajectories can either be specified explicitly or picked randomly from an underlying database of flight track data for multiple years. Further settings contain the option to only consider trajectories not crossing a certain airspace (e.g. Russian or Ukrainian airspace) on a mission level. A flight mission with a specific frequency in a given time period can be represented by multiple flight tracks. For every considered flight track, the most suitable RedEmP adjusted to the flight distance and geographically projected onto the actual flight path between origin and destination airport. Finally, all considered trajectories are stored in a numerical three-dimensional grid with a resolution of $0.25^\circ \times 0.25^\circ \times 1000\text{ft}$ for visualization and the following climate impact assessment. In addition, GRIDLAB is directly linked to iTCM, so that emission grids can also be calculated directly for detailed trajectory calculations considering detailed lateral and vertical flight profiles.

2.3 Climate impact assessment

The iTCM provides several interfaces to different climate impact assessment tools. While aCCFs [18], pycontrails [19, 20] and simplified regression formulas [24, 25] can directly be evaluated within the iTCM, the climate response model *AirClim* [26, 27] evaluates trajectory calculation results via emission grids resulting from GRIDLAB. AirClim is a non-linear climate-chemistry response model for assessing the climate impact from aviation emissions focusing CO_2 , H_2O , NO_x and CiC effects. Changes in radiative forcing are described as a function of lateral and vertical emission location based on pre-calculated values for normalized emissions. For this purpose, AirClim follows a climatological assessment approach, where the climate impact is averaged over all weather situations which occurred in three years of simulation. Hence, the modeling chain does not consider actual meteorological conditions along the flight route, e.g. influencing the formation of contrails. However, the underlying multi-annual simulation provides reasonable accuracy to estimate climate response in comparison with other models especially when focusing on the analysis of long-term air traf-

fic scenarios and emission location shifts [26, 28]. While AirClim can be directly be linked to iTCM with an internal modeling chain via a remote component environment, an open source version *Open AirClim* is currently under development [29, 30].

To assess the climate impact from CO₂ and non-CO₂ emission species, different climate metrics have been investigated in literature. A climate metric is typically determined by an indicator (e.g. radiative forcing, global warming potential, average temperature response), an emission scenario (e.g. pulse, sustained, future emission development) and a time horizon (e.g. 20, 100 or 500 years), which implicitly determine the relative weight of the different emission species' effects to the total climate impact [31, 32]. Our analysis focuses on average temperature response over 100 years (ATR100) assuming a business-as-usual (BAU) future emission scenario as described by Grewe et al. (2021) [33]. ATR is identified as a suitable metric when assessing different technological or operational scenarios due to its reduced dependence from the time horizon and its direct representation of the average near surface temperature change [32, 34]. A time horizon of 100 years balances short and long-lived climate forcers in contrast to shorter or longer time horizons between 20 and 500 years. We utilize a future emission scenario development as the investigated operational changes are expected to be relevant for a longer time horizon and due to our focus on the comparison of different air traffic scenarios. By contrast, consideration of pulse emissions are suitable for analyzing single flights or changes to the air transport system which occur only for a very limited time period.

2.4 Study set-up and applied data sources

The modeling chain will be applied in the study set-up defined in section 2.4.1 using data sources described in section 2.4.2.

2.4.1 Study design and boundary conditions

This analysis focuses on a direct comparison between two selected case study days, one representing a *pre invasion* air traffic scenario, the other representing a *post invasion* air traffic scenario. To this end, two dates, four weeks prior to and after the Russian invasion of Ukraine, are selected to focus on a standing situation excluding effects shortly before and after the start of invasion. Therefore, we can assume stable and representative operations pre and post invasion, e.g. sanctions have been implemented and airline operations has been adjusted to the new situation post invasion. Consequently, we select January 28, 2022 and March 25, 2022, both Fridays, representing days of high traffic volume in the European area. Affected missions are identified based on flight tracks. We restrict our analysis to those missions that have crossed the Russian or Ukrainian airspace in the pre invasion scenario (cf. Figure 2). Based on a comprehensive manual matching process, comparable missions for both selected case study days have been identified considering airline and OD combination leading to a sample of 252 flight missions that can be compared in both scenarios. In this context, we apply detailed trajectory modeling and emission calculations with iTCM. We use realistic lateral flight tracks while we assume fuel-optimized step climbs to ensure comparability for the vertical trajectory profile. The resulting emission grids per flight as well as aggregated emission grids for pre and post invasion scenarios are evaluated with AirClim. We assume the changes in flight tracks to be representative for changes in operations for a larger time period justifying the application of the climatological assessment approach.

In addition, we perform a validation of results targeted in a sub-study analyzing a larger air traffic scenario applying simplified trajectory and emission calculation with RedEmPs and GRIDLAB. Climate response modeling is performed with AirClim due to the large-scale study summarizing one year of operations in both scenarios. The comparison is performed based on one aggregated emission grid representing the pre invasion air traffic scenario and one aggregated emission grid representing the post invasion air traffic scenario. Selection of relevant routes is based on the air

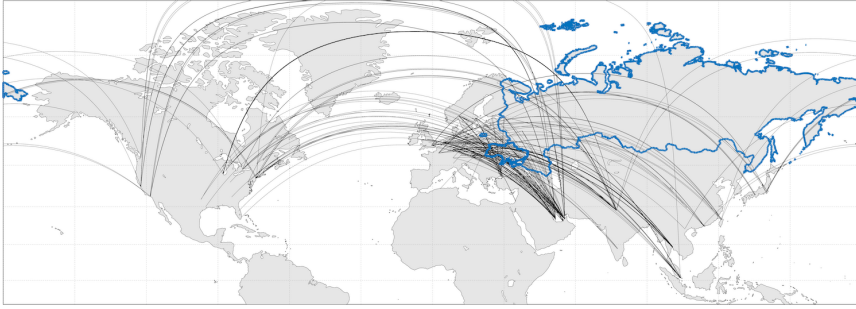


Figure 2. Investigated flight missions in the pre invasion scenario illustrated as great circle connections crossing Ukrainian or Russian airspace (in blue)

traffic in 2019 and 2023. The analysis focuses on OD combinations from the long-range segment, i.e. a great circle distance of more than 3,000 kilometers, and missions with their great circle connection crossing a simplified bounding box enveloping Russian and Ukrainian airspace (see Fig. 3, left). The analysis is further restricted to the most relevant OD combinations representing 95 % of the traffic volume in terms of available seat kilometers (ASK). By doing so, we can reduce the analysis scope to approx. 5,000 different missions per scenario (representing more than 10,000 individual flights) while still making sure to cover a relevant share of air traffic (see Fig. 3, right). In a next step, the analysis is restricted to these OD pairs where flight track data is available (approx. 43 %). To consider actual flight trajectories and resulting spatial variance in trajectories, a set of different flight tracks is considered for each flight mission defined by OD pair and aircraft type. Depending on the actual frequency per flight mission, the number of different flight tracks considered is determined, i.e. we use a number of different flight tracks representing 20 % of the actual frequency of this mission, but at least 20 different flight tracks. We apply a random pick approach to select flight tracks from the underlying data base assuming a valid representation of flight tracks on a large scale, while mission-specific deviations from the actual distribution along different flight tracks may occur.

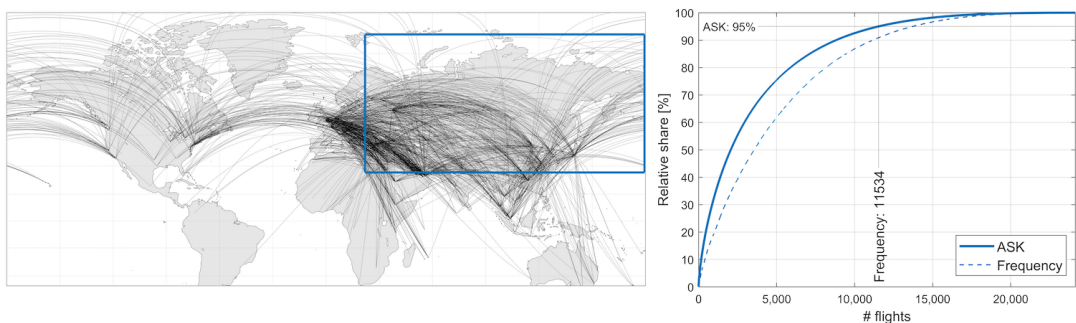


Figure 3. Definition of air traffic scenario in validation case study in post invasion air traffic scenario for 2023: Restriction to great circle connections crossing the considered airspace (left) and relevant air traffic volume (right)

2.4.2 Data sources

Prior to the trajectory calculation, the scenario to be investigated is prepared by extracting four-dimensional description of flown trajectories from OpenSky database for the selected case study days in January and March 2022 [35]. The obtained data set is filtered and processed to comparably describe a representative air traffic situation pre and post invasion [2]. Flight performance data is derived from EUROCONTROL's BADA4 model [36]. Reference emission indices for fuel-flow

correlation methods are derived from ICAO Engine Emissions data bank (EED) [37].

For the validation study, we apply model 3 data provided by the EUROCONTROL Demand Data Repository 2 (DDR2) for trajectory description [38] and RedEmPs based on BADA4 flight performance data. Relevant mission information for 2019 and 2023 are derived from Sabre Market Intelligence (MI) data base [39].

3. Results

The analysis is performed in two steps. Section 3.1 analyses changes in specific flight missions for pre and post invasion scenario ensuring a direct comparability of the individually considered missions. In addition, Section 3.2 comprises a validation of the achieved results by investigating an annual large-scale air traffic scenario.

3.1 Mission specific analysis

The mission specific analysis focuses on a set of 252 comparable flight missions as identified from the OpenSky data sets for pre and post invasion case study days. Distribution of flight distances along the mission sample as well as considered airlines are depicted in Figure 4, showing broad variability in mission length as well as differences in considered airlines. Operating airlines with the highest share of considered missions, namely Emirates, Qatar Airways and Air India, are not obliged to comply with the sanctions avoiding the Russian airspace.

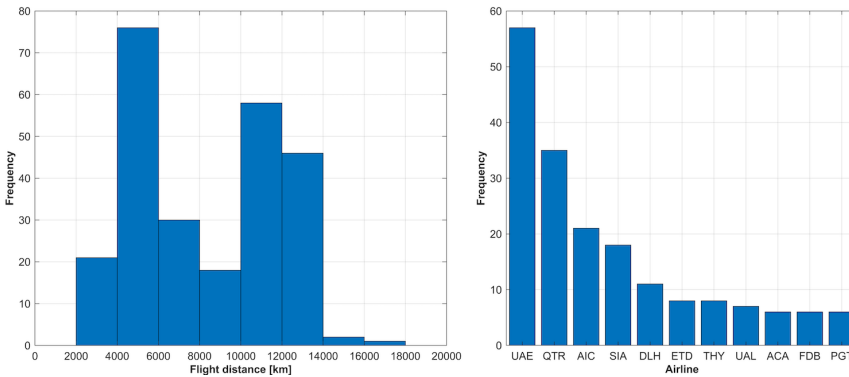


Figure 4. Descriptive statistics for flight sample in mission specific analysis regarding flight distances (left) and airlines (right)

In a first step, we exemplarily illustrate results from mission-individual comparisons for selected OD pairs in section 3.1.1. On this basis, we extend the analysis to the full sample of all considered missions in section 3.1.2.

3.1.1 Mission-individual case studies

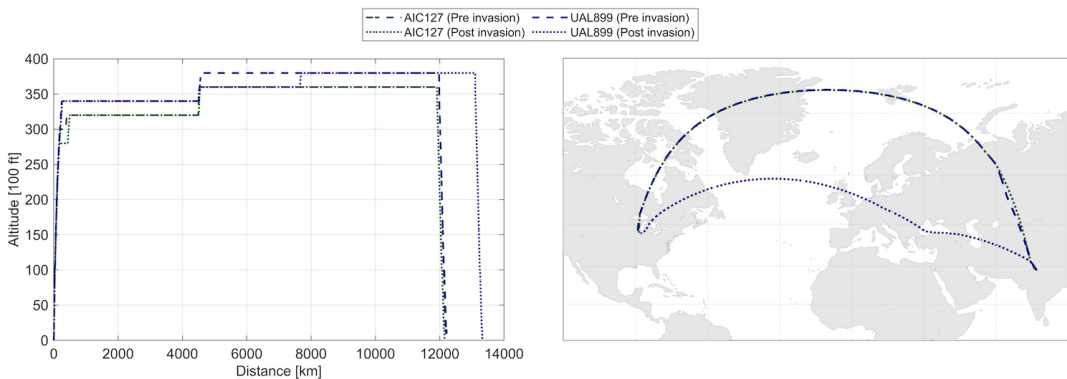
Mission-specific results in terms of fuel consumption and flight time show a significant impact of airspace closures resulting from the Russian invasion of Ukraine indicated in Table 1. For instance, we observe significant changes in mission specific figures for a flight from Helsinki (HEL) to Singapore (SIN) operated by Finnair (FIN), e.g. an increase in flight distance and flight time by approx. 14 % comparing the trajectory from March 25th, 2022 with January 28th, 2022. Consequently, fuel burn increases by 19 %, while NO_x emissions increase by 16 %. This leads to a rise in climate impact of 8 % in ATR100.

Table 1. Exemplary results showing changes post invasion mission characteristics in relation to pre invasion flights

Mission		Distance	Duration	Fuel burn	NO _x emissions	F-ATR100
FIN131	HEL - SIN	+13.7 %	+ 14.1 %	+18.6 %	+16.0 %	+8.3 %
AIC127	DEL - ORD	-0.6 %	-0.5 %	-0.7 %	-0.9 %	-0.9 %
UAL899	DEL - ORD	+10.3 %	+ 15.7 %	+11.6 %	+14.5 %	+3.8 %

Furthermore, we observe significant differences in considered key figures for the same OD pair caused by varying operating airlines due to differences in the relevant regulations. This is illustrated in Table 1 for a mission from Chicago (ORD) to New Delhi (DEL), which is operated by Air India (AIC) as well as United Airlines (UAL). While flights operated by AIC can still cross the Russian airspace, UAL is affected by the airspace closures. In this course, flight distance and fuel consumption increase markedly for UAL, leading to an increase in climate impact of 3.8 % in ATR100. By contrast, flight distance and fuel consumption decrease by approx. 1 % for the same OD pair if operated by AIC. These results indicate a possible advantage for airlines, which are still allowed to cross the Russian airspace, possibly benefiting from higher routing efficiency and lower traffic density. This results in a slight decrease in ATR100. Changed routings are illustrated in Figure 5.

Moreover, we observe a disproportionately lower increase in climate impact in relation to the fuel consumption increase for the flights re-routed in the post invasion scenario (FIN131 and UAL899, cf. Table 1). For instance, the climate impact from CO₂ and NO_x increases for UAL889 post invasion due to the increased emission quantities, while the climate impact from H₂O (-6.4 %) and CiC (-8.0 %) decreases reducing the overall climate impact increase. This can be explained by the shift to lower latitudes (e.g. approx. -20 % in mean latitude; see Figure 5, right) as well as lower flight altitudes due to the longer flight mission and higher take-off weights. Figure 5 (left) shows a later step climb when climbing to flight level (FL) 380 in the post invasion scenario leading to on average lower flight altitudes for UAL899 in the post invasion scenario. The overall climate sensitivity of non-CO₂ emissions decreases in general with lower altitudes as well as lower latitudes as the tropopause height, which is relevant for climate impact, also decreases with latitude [26] explaining the limited increase in ATR100.

**Figure 5.** Vertical (left) and lateral (right) visualization of flight track changes due to imposed airspace closure sanctions.

3.1.2 Comparable scenario analysis

Extending the analysis to the full sample of flights (252 missions crossing Russian or Ukrainian airspace pre invasion), increases in fuel consumption and flight time in the post invasion scenario

can be confirmed. We observe an overall increase in flight distance and duration of approx. 2 %. This causes an increase in fuel consumption and CO₂ emissions of 2.1 % as well as an increase in NO_x emissions of 2.7 %. However, the climate impact in ATR100 does not increase with the changes in flight tracks. On the contrary, we observe a slight decrease in ATR100 for this case study as illustrated in Figure 6. While the climate impact from CO₂ emissions increases proportionate to the additional fuel consumption, the climate impact from non-CO₂ species is not only determined by the emission quantity but also by the emission location. Therefore, changes in vertical and lateral routing lead to changes in climate sensitivity for H₂O, NO_x and CiC, so that the increase in CO₂ effects is overcompensated by the decrease in non-CO₂ effects. In particular, we observe a marked decrease in H₂O effects which are reduced by more than 10 % while CiC effects decrease by approx. 2 %. NO_x effects are slightly reduced by 0.8 %.

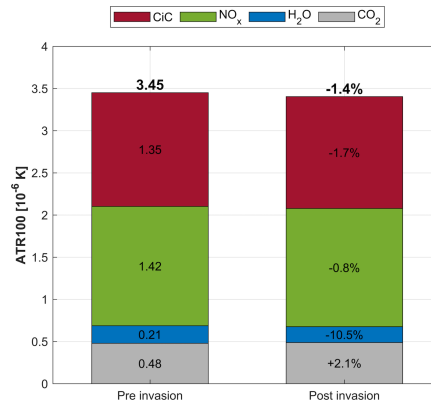


Figure 6. Comparison of climate impact for pre invasion and post invasion scenario for sample of 252 comparable flight missions

This can be explained by a shift to lower latitudes to avoid the Russian airspace, which can in most cases only be achieved with a southern detour, as well as lower altitudes caused by higher fuel needs, thus heavier aircraft at take-off. A detailed investigation of both lateral and vertical distribution of fuel burn and CO₂ emissions in Figure 7 shows a decrease in fuel-weighted mean latitude by 2 degrees (from 46.7 to 44.7) as well as a slight shift of fuel-weighted mean altitude (from 34,606 ft to 34,303 ft). With smaller climate sensitivities for lower emissions altitudes in relation to the tropopause [26], routing changes due to the imposed airspace closures do not lead to an increase in the climate impact.

To investigate the differences resulting from varying operating airlines (cf. section 3.1.1), the sample can be divided into two sub-samples, one representing airlines that can still cross the Russian airspace (*unaffected airlines*, 61.9 % of the sample) and airlines who have to take detours due to the imposed sanctions (*affected airlines*, 38.1 % of the sample). On this basis, a comparison along identified missions and climate indicators can be performed. Figure 8 illustrates the differences between the two sub-samples indicating higher fuel burn and CO₂ emission increases for those airlines affected by the sanctions to avoid the Russian airspace. On average, fuel consumption and CO₂ emissions increase by 4 %, while the climate impact is reduced by 2.6 % due to changes in flight tracks. By contrast, airlines which can still cross the Russian airspace are associated with on average 0.7 % higher fuel consumption and climate effect from CO₂ emissions, while the climate impact in ATR100 decreases slightly by 0.4 %. These small changes can be explained by the closure of the Ukrainian airspace which is avoided by all airlines leading to an average increase in flight distance as well as day-dependent changes in routing caused by air traffic management influencing flight tracks both vertically and laterally (+ 0.7 % in flight distance, -0.45° in mean latitude comparing post to pre in-

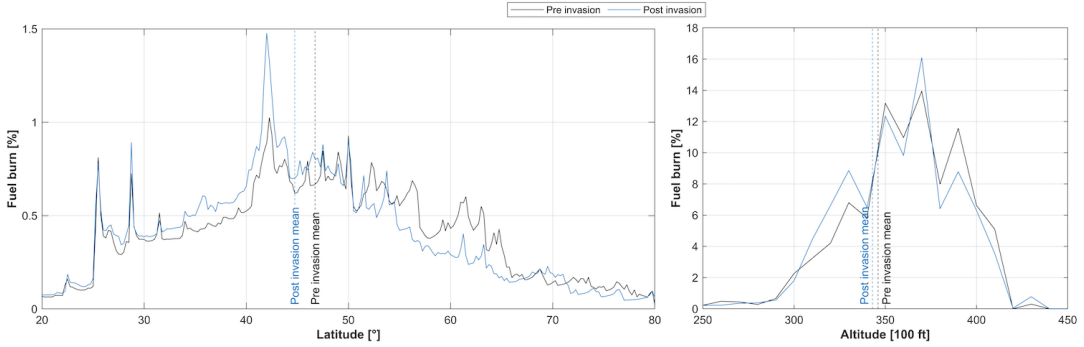


Figure 7. Comparison of latitude (left) and altitude distribution (right) for pre invasion and post invasion scenario for sample of 252 comparable flight missions

vasion scenario for unaffected airlines).

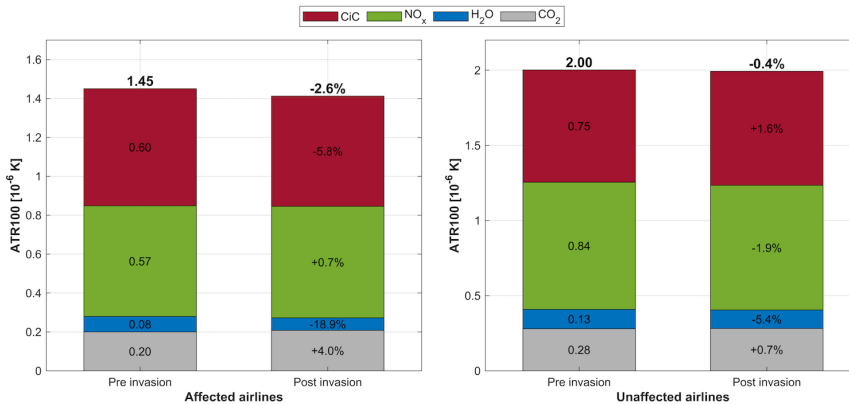


Figure 8. Comparison of climate impact for pre invasion and post invasion scenario for sample of 252 comparable flight missions divided by operating airline affected by sanctions (left) and unaffected by sanctions (right)

3.2 Validation in emission grid analysis

Results from the mission-specific analysis can be validated in a larger air traffic scenario. For this purpose, we compare fuel consumption, flight distance, emission quantities and climate impact for a traffic scenario from 2023 to 2019. Resulting global emission grids are displayed in Figures 13 - 14 (Appendix).

In contrast to the study in section 3.1, a direct comparability of the considered flight missions is not forced leading to changes in the traffic scenario regarding considered OD combinations, aircraft types and operating airlines. All in all, the air traffic volume in terms of ASK changes by -2.3 % in the 2023 scenario compared to 2019. This can be explained by the influence of traffic cutbacks in course of the COVID19 pandemic [33] as well as changes in offered connections in course of the Russian invasion of Ukraine [10]. Furthermore, we observe slightly shorter great circle distances of considered missions in 2023 compared to 2019 (-1.1 %, see Figure 9, left) as well as changes in the aircraft fleet (see Figure 10).

While great circle distances of considered missions decrease from 2019 to 2023 due to differences in considered missions, track distance increases by approx. 2.4 % on average demonstrating addi-

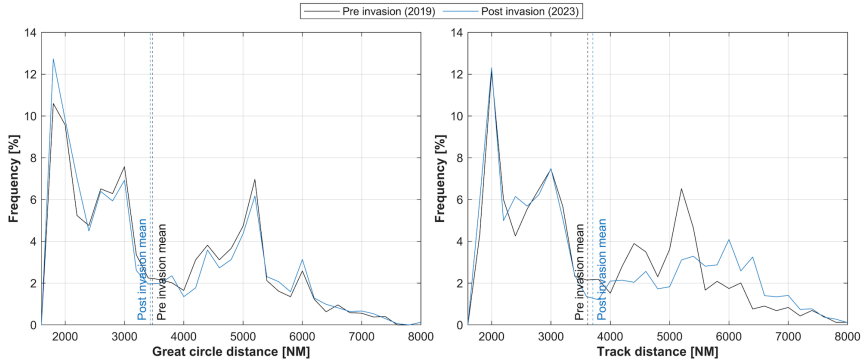


Figure 9. Comparison of great circle distance (left) and track distance (right) in considered pre and post invasion traffic scenarios in 2019 and 2023 in validation case study

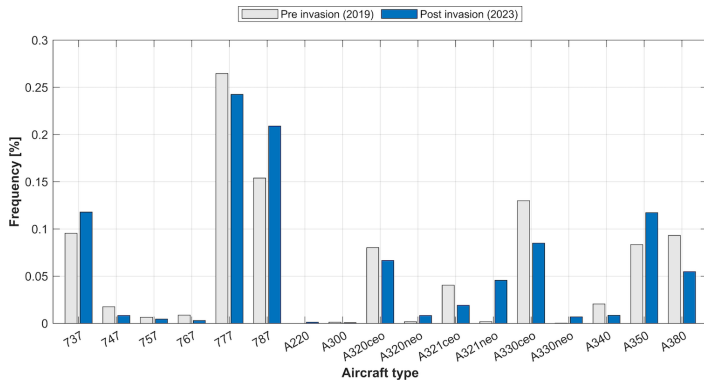


Figure 10. Comparison of aircraft fleet composition in considered pre and post invasion traffic scenarios in 2019 and 2023 in validation case study

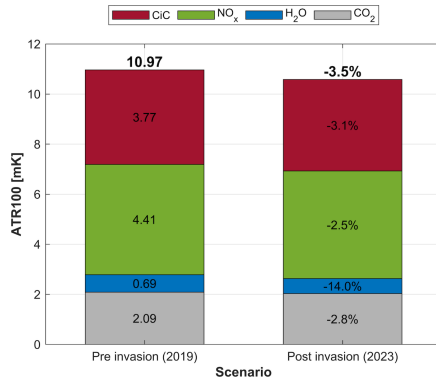


Figure 11. Comparison of climate impact for pre invasion (2019) and post invasion air traffic scenario (2023) in validation case study

tional routing inefficiencies due to the airspace closure as displayed in Figure 9. Simultaneously, fuel consumption decreases by 2.3 % what can be traced back to changes in fleet composition. Figure 10 illustrates the fleet overhaul, i.e. older less efficient aircraft are replaced by newer more efficient aircraft. For instance, utilization of large wide-body aircraft such as Airbus A380 is reduced in 2023

while utilization of more efficient aircraft such as Airbus A350 increases. The same holds true for the short and medium range segment, e.g. with Airbus NEO (new engine option) aircraft. CO₂ and H₂O emissions change proportional to fuel burn, i.e. decrease by 2.7 % in 2023, while NO_x emissions do not change markedly (-0.04 %).

The climate impact assessment shows an ATR100 reduction of 3.5 % (Figure 11). Consistent with the mission specific analysis (section 3.1), we observe a disproportionate decrease of non-CO₂ effects (-3.7 % in ATR100) in relation to CO₂ effects (-2.8 % in ATR100). The largest species-individual decrease is found for water vapor effects (-14 % in ATR100). The decrease in CiC effects in ATR100 also exceeds the reduction in CO₂ effects (-3.1 % in ATR100) and NO_x-induced effects are reduced by 2.5 %. Analogous to the results from section 3.1, this can be explained by lateral shifts of the flight trajectories (-3.2° in fuel-weighted average latitude; see Figure 12, left) as well as vertical shifts (approx. -100 ft in fuel-weighted average altitude; see Figure 12, right).

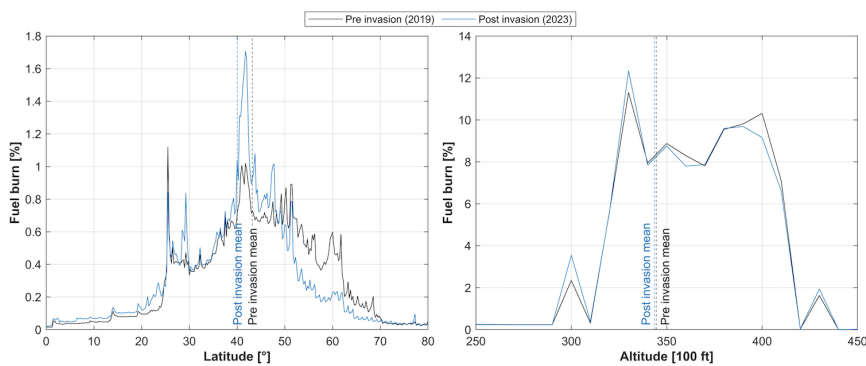


Figure 12. Comparison of latitude and altitude distribution for pre invasion (2019) and post invasion air traffic scenario (2023) in validation case study

All in all, the validation analysis confirms a decrease in climate impact from airspace closures following the Western Sanctions due to the Russian invasion of Ukraine. However, the climate impact change is not only caused by additional detours, but also results from changes in the entire air traffic scenario between the two considered years. In addition to track distance increases, latitude and altitude decreases, changes in considered OD pairs and aircraft fleet composition contribute to the decrease in climate impact.

4. Discussion & Outlook

This study investigates the changes in climate impact measured in ATR100 resulting from closures of Russian and Ukrainian airspace following the Russian invasion of Ukraine. In this course, we contribute to the current state of literature by extending the environmental assessment of CO₂ emissions to the non-CO₂ effects of aviation. We consider actually flown trajectories in course of the *integrated Trajectory Calculation Module* representing pre and post invasions scenarios. NO_x mission quantities are determined with DLR's fuel flow correlation method and climate impact from these emissions is assessed with climate response model *AirClim*. Consistent with previous literature studies [7, 8], we confirm an increase in track distance, flight time and fuel consumption leading to an increase in CO₂ emissions and the related climate impact. Our study also supports the findings of other studies showing economic disadvantages, as we expect a rise in operating cost due to an increase in fuel burn and flight time. Nevertheless, we cannot confirm an increase of the overall climate impact determined by CO₂ and non-CO₂ effects. In contrast to An et al. (2023) [7], we consider variations in climate sensitivity with emission location and time leading to an overcompensation of increased

CO₂ effects by a reduction in non-CO₂ effects. This is caused by both lateral and vertical shifts of flight tracks to lower latitudes and altitudes. Due to a downward shift of emission altitudes relative to the tropopause, climate impact from non-CO₂ emissions is reduced. An extension of the analysis to the comparison of global annual flight traffic scenarios from 2019 representing the pre invasion situation and 2023 representing the post invasion situation also shows a reduction of the climate impact. In this case, differences in fleet composition and considered flight routes further impact the comparison.

However, an interpretation of the results has to consider the uncertainties and inaccuracies of the applied approach. Firstly, trajectory calculations with given flight performance data is subject to uncertainties estimated around 5 % [36]. Further simplifications were made in the context of this study assuming a constant load factor for all flights as well as efficient re-fueling and excluding realistic meteorological conditions especially in the context of head and tail winds. The latter two assumptions are expected to lead to an underestimation of fuel consumption [23]. However, the resulting inaccuracies are expected to be negligible due to the relative comparison in this study. Secondly, uncertainties of emission quantification with fuel flow correlation methods are estimated around 10 % for NO_x emissions in cruise [5]. Finally, the climate impact assessment of aviation in general and of non-CO₂ effects in particular is subject to large uncertainties [4]. Especially the trade-off between an increase of certain CO₂ effects and a reduction in uncertain non-CO₂ effects needs to be interpreted with care. As our study shows an increase in CO₂ effects but a reduction in non-CO₂ effects in the comparable scenario analysis (section 3.1.2) an overestimation of non-CO₂ effects could lead to an overall increase in the climate impact. However, Dahlmann et al. (2016) confirm the possibility of comparing different air traffic scenarios regarding relative changes of the climate impact with *AirClim* despite large uncertainties of non-CO₂ climate effects [26]. As the large-scale validation case study (section 3.2) shows a decrease in both CO₂ and non-CO₂ effects, we expect the identified overall climate impact reduction including flight plan changes to be robust against the identified uncertainties.

The significance of this study can be improved by broadening the study scope especially regarding the mission-specific analysis. An extension to more case study days could help to also investigate the general variability along comparable route samples in both pre and post invasion scenarios. Further systematic investigation of annual validation scenarios could help to differentiate multiple influencing factors leading to changes in fuel consumption, emission quantities and climate impact as these aspects could not be decoupled and investigated individually in this study.

Future research could help to extend the results of this study in a meteorological climate impact investigation considering the actual weather situation along the selected flight routes. In this case, the investigation should be extended to several meteorological situations instead of one representative case study for both scenarios. Moreover, the results of the ecological assessment could be combined with further economic analyses regarding detailed changes in direct operating cost as well as further consequences for the stakeholders of the air transport system. For instance, passenger acceptance is expected to decrease with longer travel times. Hence, economic advantages and competitive distortion can result from different regulations for different airlines.

In addition to the humanitarian disaster, the Russian invasion of Ukraine has significantly influenced air transport from operational and economic perspective. All in all, track distance, flight time and fuel consumption increased markedly for missions which cannot cross the Russian airspace anymore. By contrast, other airlines which are not affected by airspace closure sanctions can potentially even benefit from increased efficiencies and competitive advantages. An increase of the climate impact cannot be confirmed due to changed routings with reduced climate sensitivities at lower latitudes and altitudes.

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We appreciate the work of OpenSky network for making flight track data available to the aviation community. Furthermore, we would like to thank EUROCONTROL for providing the applied data in course of the project DIAL.

Appendix 1. Emission grid figures

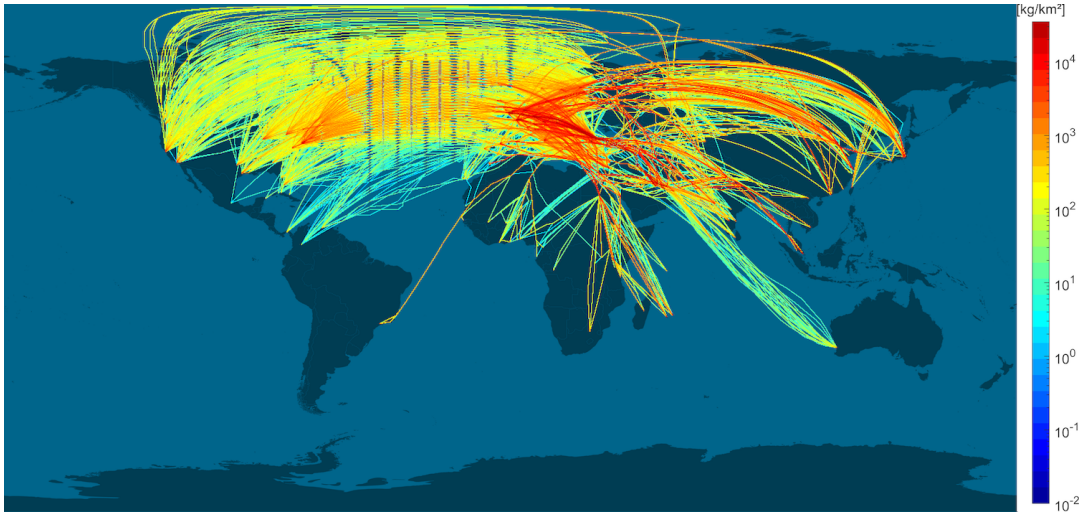


Figure 13. Vertically aggregated CO₂ emissions for pre invasion scenario in 2019 in validation case study

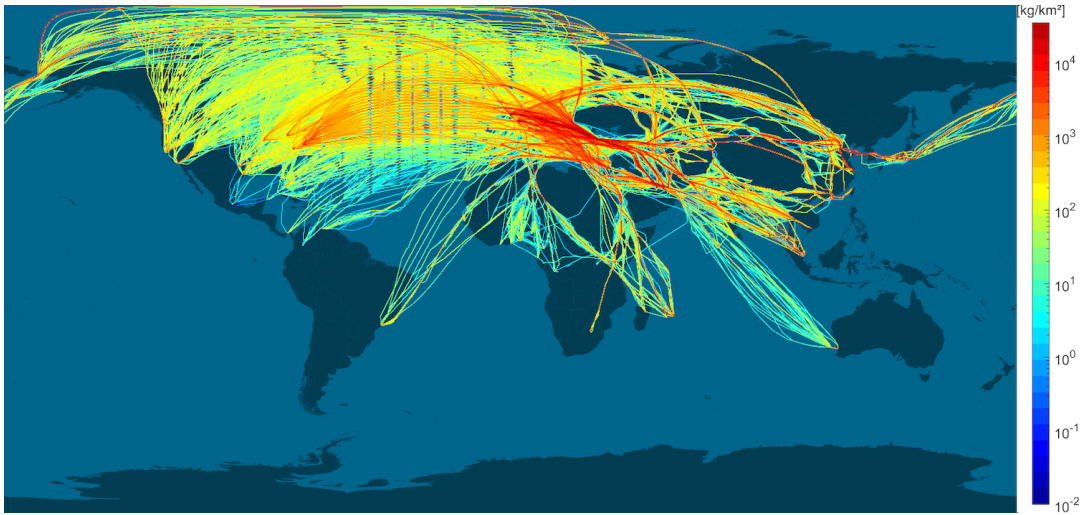


Figure 14. Vertically aggregated CO₂ emissions for post invasion scenario in 2023 in validation case study

Author contributions

- Z. Zengerling: Conceptualization, Investigation, Methodology, Software, Validation, Visualization, Writing (Original draft)
- S. Kumpa: Data curation, Formal Analysis, Investigation, Validation
- M. Clococeanu: Visualization, Investigation, Methodology, Software, Writing (Original Draft)
- M. M. Meuser: Data Curation, Software, Writing (Review and Editing)
- J. Solzer: Data Curation, Writing (Review and Editing)
- K. Dahlmann: Software, Validation, Writing (Review and Editing)

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Open data statement

ADS-B data used in this study has been provided by OpenSky. Flight performance data and route information for the validation data set are provided by EUROCONTROL and SABRE MI data base and are subject to restrictions regarding their open publication. Flight profile data, emission grids and results of this study are provided via Zenodo: <https://doi.org/10.5281/zenodo.15143508>

Applied models are proprietary models by DLR. Alternative data sources and models are provided in the *Reproducibility statement* below.

Reproducibility statement

Open source alternatives for trajectory calculation are *OpenAP* (<https://github.com/junzis/openap>) or *Poll-Schumann model* implemented in *pycontrails* (<https://github.com/contrailcirrus/pycontrails>). These models also comprise alternative flight performance data sets. An open source version of climate response model AirClim called *Open AirClim* can be accessed via Github (<https://github.com/dlr-pa/oac>). An extension of this open source model with GRIDLAB to include the calculation of gridded emission distributions is currently under development and expected to be published open source as soon as possible. Alternative open source climate impact assessment tools are *algorithmic climate change functions* (<https://github.com/dlr-pa/climaccf>) as well as *pycontrails* (<https://github.com/contrailcirrus/pycontrails>). Alternative flight track data for the validation study can be derived from OpenSky.

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