nature portfolio

Peer Review File

Private aviation is making growing contribution to climate change

Corresponding Author: Professor Stefan Gössling

This manuscript has been previously reviewed at another journal. This document only contains reviewer comments, rebuttal and decision letters for versions considered at Communications Earth & Environment.

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Professor Gössling,

Your manuscript titled "Private aviation makes growing contribution to climate change" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns.

In particular, we require that you:
-rigorously demonstrate that private aviation is making a growing contribution to climate change.
-employ calculations/modelling that acknowledge variations in fuel consumption, including a full treatment of uncertainties in calculation.
-place your study in the context of past literature and other data sources.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

When resubmitting, please provide a point-by-point response to the reviewers' comments. Please submit your responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred.

Important: The response to reviewers must not include any figures, tables or graphs. If you wish to respond to the reviewer reports with additional data in one of these formats, please add them to the main article or Supplementary Information, and refer to them in the rebuttal. Due to current technical limitations, any figures, tables, or graphs embedded in your rebuttal will not be included in the peer review file, if published.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

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Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Alice Drinkwater, PhD
Associate Editor
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REVIEWER COMMENTS:

Reviewer #2 (Remarks to the Author):

General Comments

Dear authors,

I have read your manuscript thoroughly and with great interest. You have correctly identified private aviation as an understudied part of the air transport system, which is already very energy intensive and difficult to decarbonize.

Your research investigates the total carbon emissions of private aviation activity globally, its geographic scale and distribution, the role of events in attracting private aviation, individual patterns of aircraft use, as well as travel motives and growth trends.

Unfortunately, I cannot recommend your manuscript for publication in Communications Earth & Environment. What is more, I recommend the authors make major modifications to their manuscript before they re-submit to a more appropriate journal.

While some of the data (and associated source code) you provide will surely be of interest to other researchers, neither your core method, nor your conclusions meet the criteria for publication laid out by the journal. For instance:

• The conclusions are novel

I find it difficult to identify any novel conclusions other than the numbers provided for carbon emissions from private air transport. The strongest claim seems to be one on the "(…) travel motivations (…) reflective of global power structures". It

seems to me that the current manuscript does not back up this already very vague claim.

• The underlying data are generated and processed at a state-of-the-art level, including tracking of uncertainties

No treatment of uncertainties is provided. Neither fuel burn (and associated uncertainties, such as block time vs airborn time) nor the difference between actual routes and great-circle distances are considered. No attempt was made to confirm the data coverage provided by the primary (and only) data source used by the authors.

• The manuscript is important to scientists in the specific sub-field of the Earth, environmental or planetary sciences.

It seem to me that the primary reason other scholars would cite this publication will e be to quantify the carbon emissions of private travel. However, the underlying calculations are rough approximations only- it is doubtful if a specialized aviation-related scientific journal would publish numbers based on this method at all.

In summary, I believe that the research topic of private aviation climate impact is timely and of interest to a general readership. Unfortunately, the authors do not provide any treatment of uncertainty in their values. They use only a single data source, which for (at least) 2023 may have experienced deteriorating global coverage. The conclusions that the authors draw from a brief analysis of travel to different international events are not backed up by the data they provide. They lack a basic understanding of the geographic terminology they use to describe the maps they rendered for this manuscript.

I would recommend a journal focusing on research data (or open source software) for the author's consideration.

Specific Comments

Abstract

• "(…) specific fuel consumption in gallons per hour."

What does "specific" in this statement refer to? Usually, the term "specific" in the context of fuel burn is used in the THRUST-SPECIFIC fuel consumption [g/(s·kN)] metric.

As a minor note, I found two fuel burn values which are not supported by the literature you cite in the CSV file (https://github.com/jorgecardleitao/private-jets/blob/main/src/models.csv):

BEECH 200 Super King Air
DASSAULT Falcon 6X

• "We use ADS-B Exchange data that contains a timestamp, latitude, longitude, and barometric altitude."

At the very least, a qualifying statement is in order. You present your data as authoritative, without ever discussing the potential limitations of using this single data source. A comparison with data from FlightRadar24 or other established ADS-B tracking sites should be provided to allow the reader to gauge the quality of the data the authors are basing their analysis on. Perhaps Dr. Juntsi Sun of TU Delft can help the authors in this regard. He is involved in an ADS-B tracking site focused on air transport researchers.

The authors should further mention the recent acquisition of ADSB Exchange by a private company, which has led to some "feeders" (users contributing data to the site) to end their relationship with the site. A short inspection of the (former) ADSB Exchange users community on Discord will confirm that it is at the very least a real possiblity that the data coverage of ADSB Exchange had deteriorated noticably after January 2023. In light of this, I would expect the authors to show that their data for 2023 is not biased due to lower data coverage.

• "Flight times for 25,993 private jets (…)"

The authors later include turboprop aircraft like the Pilatus PC-12 and the Piper PA-46 in their scope, which suggest a more appropriate wording here (and elsewhere in the text!) would be "private aircraft". This is affirmed by the average speed of only 575 km/h which they mention later in the text.

• "We find that private aviation contributed 15.6 Mt CO2 in direct emissions in 2023, or 3.6 t CO2 per flight."

A qualifying statement is in order. Given the highly approximative way in which you compute fuel consumption, you might say "we find that aviation contributed at most (…)".

• "Flight pattern analysis confirms extensive travel by owners of private aircraft, also for leisure purposes."

Since travel is the primary purpose of an aircraft, this is not a surprising finding. The authors should consider removing this truism from the abstract. What is more, the authors did not convincingly analyze the travel habits of aircraft owners – they were able to track aircraft, not owners.

Main

• “Industry estimates suggest growth rates of 4.5% per year (revenue passenger kilometers, RPK) over the next two decades (Airbus 2023; Boeing 2023).”

The Airbus market forcast cited gives a number of 3.6%/year for pax-traffic. The Boeing market forecast cited gives a number of 6.1%/year for all traffic. Neither source therefore supports the claim of the authors. Perhaps the authors mis-interpreted the figure on page 8 of the Airbus market forecast, which gives a historical growth rate of 4.8%/year between 1990-2019.

• “(…) policies (…) need to consider such complexities of growth, distribution, and energy-intensity.”

Could the authors specify what they mean by “distribution”?

• “(…) industry expectations point to continued growth, from a current value of US$44 billion (…)”

What is the “value” referred to here? Is this annual revenue, profit, value of aircraft, ..?

Energy Intensity and Distribution

• “There are 72 PA models in use worldwide (…)”

This is a very strong claim. The authors were able to identify 72 models. Unless the authors can show convincingly that no other models are currently in use worldwide, a more humble formulation might be in order.

• “(…) as PA travel at above 40,000 feet (ADS-B Exchange 2024).”

Clearly, not all PA travel at this altitude. This includes some of the most popular turboprop-driven models the authors included in their scope. This becomes even more clear from the average speed the authors note in the next paragraph: “only” 575kph. The statement and the associated reference on flight altitude should therefore be re-formulated.

Figure 1

• “There is very limited private air transport in all of Africa, with the exception of South Africa and Nigeria.”

While this seems plausible, the method employed by the authors hardly allows for a definitive statement of this nature. After all, I expect the ADS-B Exchange data coverage to be lacking in large parts of Africa. This highlights the importance of checking the quality/coverage of ADSB Exchange data against other sources (see my earlier comments).

• “In comparison to population distributions, PS is concentrated in affluent countries.”

It seems to me that PS would be concentrated in affluent countries regardless of “population distribution”. Perhaps the authors could clarify this statement.

Table 2, Table 5, Figure 7

I must strongly discourage the authors from using bubble charts to compare a single variable. Since circle area does not scale linearly, an immediate visual comparison is almost impossible. This readability issue has been replicated in recent studies (cf. https://doi.org/10.1109/TPC.2020.3032053, section “Perception of Graph Readability”):

A bar chart will perfectly convey the author’s data in these tables/figures.

Methods

• “For air traffic control and monitoring, aircrafts are required to switch on the Automatic Dependent Surveillance – Broadcst(ADS-B) transponder during flight (FAA 2023).”

The reference (FAA 2023) does not exist. I can only infer that the authors mean to cite an authoritative reference like 14 CFR 91.225 (https://www.ecfr.gov/current/title-14/section-91.225). However, this would only apply to US-registered aircraft and/or those foreign-registered aircraft operating in US airspace.

• “ADS-B Exchange (…) a platform that provides comprehensive and unfiltered traffic data for every aircraft on a 60 second basis.”

See my other comments about this data source.

• “For this project, the entire database for private aircraft was retrieved (…)”

On what basis is the determination of “private” made? The authors mention this later on in the text. The reader would benefit from a definition at this point.

• “The flight data does not consider a share of flights using third-party flight ID. Under the Federal Aviation Administration’s ADS-B Privacy program, aircraft registered in the US and flying in US managed flight information regions can apply for Privacy ICAO aircraft addresses (PIA). These are temporary ICAO aircraft addresses not assigned to the owner in the Civil Aircraft Registry (CAR) (FAA 2024).”

The inclusion of this information is greatly appreciated. It is particularly helpful to readers unfamiliar with aircraft registration procedures. I strongly suggest the authors include a paragraph discussing future challenges resulting from newly introduced legislation. This is particularly important since other researchers may be more limited in their tracking of aircraft in the future. The authors should think about mentioning this change more prominently. It seems that other researchers “may never again get such good data”.

• “All fuel use considered refers to aircraft being in flight (…)”

Where do the sources from which the authors have extracted fuel consumption data state this explicitly? It seems plausible that this number may be an average across taxi, takeoff, climb, cruise, descent, landing, taxi (for an average trip length).

• “and was deemed accurate.”

Were any discrepancies found? If so, how many?

• “By tracking the position of each aircraft over time, flight legs, distances, and flight times can be calculated. From the position of the jet over time the flight legs, flown distance, and flight times are calculated.”

I assume the authors forgot to de-duplicate this sentence?

• “The focus on CO2 ignores non-CO2 effects at flight altitude (Lee et al. 2021), as well as scope 3 emissions (Gössling et al. 2024).”

I would recommend the authors re-consider the utility of mentioning different scope emissions in this context. They are estimating the carbon emissions associated with burning a certain amount of jet fuel. This is alone is neither scope 1 nor 2, but only a part of the emissions scope of an entity.

• “When the signal is lost for more than 5m”

Presumably the “m” stands for “minutes”?

Air Transport Patterns

• “Further insights can be derived from the analysis of spatial patterns, such as the importance of global events, or the travel patterns of individuals.”

I am wondering what insights this is providing. The authors do not specify this in the text. It is well known that high-level gatherings such as the World Economic Forum of the COP climate conferences attract a large number of private aircraft. While the maps provided for these events are visually appealing, I am missing the insight the authors are claiming.

• “Total emissions from events are higher (…)”

Since the authors are looking only at emissions from private aircraft, this is to be expected. What are the authors trying to convey with this statement?

• “The analysis of the spatial movement patterns of individual air travellers reveals considerable differences in flight numbers, emissions, min-max, and average distances (Figure 6, 7). These require further investigation, as very short flights (13 km to 72 km) suggest that aircraft are moved for parking and pick-up/delivery patterns, business and leisure flights (Figure 8).”

Again, I fail to see what could be accomplished by “investigating” positioning flights in the context of large events. If the objective of the authors is to compute carbon emissions, they already have sufficient data.

• “A considerable, but undeterminable share of flights is made empty.”

These are known are positioning flights. While they certainly play a role in private air transport, I am wondering how the

authors can both claim that their number is “considerate”, but also “undeterminable”.

• Figure 7: “(…) based on Forbes (2024)”

Like the reference (FAA 2023) mentioned earlier, this reference also does not seem to exist. Further, “Global celebrities’ private air travel” seems to me to be an insufficient figure caption. Who counts as a celebrity? Is Elon Musk a celebrity, or does he count as a corporate traveller? Presumably, the authors used the definition of Forbes – but the missing reference did not allow me to check that.

• Figure 8: “206 (11.6%) went to Switzerland and 134 (7.6%) to Scotland, indicating second home ownership. Another 54 flights were made to Florida, USA.”

Was the assertion of second-home-ownership made arbitrarily? Why was this not deemed to be the case for Florida?

Travel Motives

• “Arrivals are also concentrated on weekends, suggesting that travel motives are leisure-dominated.”

Why are weekend arrivals indicative of leisure travel? Surely this would only be the case if both the arrival and departure are on the same weekend?

• “Data also reveals that travel motives overlap. (…) For example, 172 of the 595 aircraft trail numbers appearing at the World Economic Forum (WEF) in Davos also served the Cannes Film Festival, and 65 identical tail numbers were identified at both the WEF and COP28. (…) This data suggests that there is a co-attendance of these events and an amalgam of travel motivations across political, economic, and cultural dimensions that is also reflective of global power structures.”

For these claims to hold, the authors MUST show that (the majority) of private aircraft that were found to attend both events are in fact owned by single individuals. It seems to me rather plausible that private aircraft owned by companies such as Jet Aviation (https://www.jetaviation.com) would attend both events – but not necessarily with the same passengers. Also, fractional ownership of private aircraft is a popular legal ownership model. The authors themselves mention different ownership models earlier in their manuscript.

For instance, the owners.csv file the authors provide on their GitHub repository does not list a single aircraft owned by a private individual. It only lists corporations.

I must stress the importance of this point. The claim of the authors make a vague claim about global power structures (“an amalgam of travel motivations (…) that is also reflective of global power structures.”) based on the fact that some of the same aircraft are used to fly to different events.

If the authors are able to show that the same individuals use these same aircraft to attend different events, I would appreciate some clarification on what it means for our understanding of “global power structures”.

Conclusions

• “Given limited evidence of emission-intensity gains (…)” – The authors have provided no such evidence.

While the authors may argue that efficiency gains have not been able to keep up with increasing demand, the original claim (“limited evidence of emission-intensity”) is false and misleading. While it is difficult to compare aircraft in the list directly, a brief look at two Gulfstream aircraft:

Gulfstream V, 1997, 500gph
Gulfstream G500, 2015, 430gph

Shows a 14% decrease in fuel burn between 1997 and 2015. This seems to be at the very least comparable to similar efficiency gains in cars during the same period.

• “To properly assess the system of private aviation, it would also be necessary to consider taxiing, or helicopters that are used to reach final destinations.”

This seems of secondary importance to me. Much more important would be a more sophisticated approach to fuel consumption calculations. Or the distance actually flown, as opposed to great-circle distances.

Development of Maps

While the attempt to describe the mapping methodology in detail is appreciated, the current section shows a lack of geographic understanding:

1. WGS84 is NOT a projection. Rather, it is a Geographic Coordinate System. Only a Projected Coordinate System has a projection. However, the authors never disclose the projection they use in their maps. The absence of the poles (the South Pole, at the very least) suggests their projection is a Mercator-like projection. They authors may be forgiven for this misunderstanding, since this seems to be a popular point of confusion: https://gis.stackexchange.com/q/73576, https://gis.stackexchange.com/q/149749. Also, the popular GeoPandas open-source GIS package for Python incorrectly uses the term "WGS84 latitude-longitude projection" on one of their documentation pages (https://geopandas.org/en/stable/docs/user_guide/projections.html).
2. WGS84 is also NOT based on an ellipsoidal earth model. It IS one.
3. "This system is widely used for GPS" – GPS ONLY provides WGS84 coordinates. Decoding the GPS satellite signal ONLY provides WGS84 coordinates. Of course, these can be converted to another coordinate system.
4. What is an "imperfect sphere"?
1. "ADS-B transponder data for departure and arrival points are transferred to the map, representing great circle distances, i.e. the shortest path between two points on the surface of a sphere." – This sentence is not clear to me. Do the authors mean to imply that the (flight) distance between two points was calculated based on the great circle distance? Also, the authors just a few sentences ago mention that they are not assuming the earth to be a perfect sphere. Now they use the approximation of the sphere for calculating great-circle distances?
1. "It needs to be considered that any two-dimensional map introduces visual distortion, as the length of lines indicating flight distances is not proportional to actual distances." – This sentence is simply nonsensical. Do the authors mean to imply that they: 1) calculated distances based on the great-circle distance, but 2) were unable to show these great circle distances on the map? It is obviously possible to draw the great circle distance on any projection – it may just turn out not to be a straight line (cf. https://transportgeography.org/contents/chapter1/transportation-and-space/great-circle-distance/).

This section and the maps in the manuscript require a complete re-writing, ideally after the authors have consulted with a colleague with a background in GIS.

Reviewer #3 (Remarks to the Author):

The presented paper 'Private aviation makes growing contribution to climate change' submitted by Stefan Gössling, Andreas Humpe and Jorge Cardoso Leitão for publication in 'Communications Earth & Environment' estimates CO2 emissions from private aviation (PA) from 2019 to 2023 and analyzes the results with regard to geospatial patterns, global events, celebrities private air travel, company flight patterns, and annual as well as seasonal developments. The authors apply a simple method to estimate CO2 emissions based on a comprehensive data base resulting from combining ADS-B data with fuel consumption data from marketing material for 72 identified PA aircraft. The authors show PA's significant contribution to aviation CO2 emissions in general as well as a significant annual growth over the investigated time period. Moreover, the results show a high concentration of PA in certain regions, a strong relation to global events such as FIFA world cup, high impact from individual celebrities' private travel and strong seasonal effects.
The study's focus on PA as a sector of aviation provides new insights leading to original findings regarding global events, company flight patterns and seasonal effects. In general, the manuscript is well-written, easy to follow and the figures underline the content of the manuscript. Most of the taken assumptions are well explained and seem reasonable. The underlying data base is comprehensive and perfectly suited for the analysis. Furthermore, I highly appreciate the open source availability of all data bases and software code increasing the studies. However, the applied method is associated with significant simplifications, which does not represent the current state of emissions modelling in aviation climate assessment. Furthermore, reference to previously published research in this context (refer e.g. Sun et al. 2023, Joseph & Mumbower 2022) is missing as well as an explanation on how the findings of this work advance previous work as, for instance, conducted in Sun et al. (2023). Sun et al. (2023) also deal with an extensive assessment of CO2 emissions from business and private aviation applying more sophisticated methods.
All in all, I can recommend to accept this manuscript for publication after a comprehensive revision including reference to previous work in this context as well as the points mentioned below. Nevertheless, this paper contains several valuable contributions to emission quantification for private aviation, which has not yet been studied comprehensively in the current state of literature.
Major comments:
• Climate change vs. CO2 emissions: The study states to address PA's contribution to climate change, but concentrates on CO2 emissions only. As demonstrated in many previous studies (e.g. Lee et al. 2021), the climate impact of aviation is not only influenced by CO2 emissions but also significantly by non-CO2 emissions. In contrast to CO2 climate effects, non-CO2 emissions vary significantly with location and time of emission as well as meteorological boundary conditions. A simple scaling with a factor between 3 and 4 (as introduced in lines 237-239) represents a strong simplification of these processes and requires evidence for private aviation aircraft and their specific operating conditions (high altitudes, medium latitudes, short distances). The scope of this study is restricted to CO2 emissions only and omits other species such as nitrogen oxides (NOx), water vapor (H2O) and aerosols. Therefore, I am of the opinion that the restricted scope of the study does not match the research objective of targeting the contribution of PA to climate change as major climate forcing effects are excluded from the analysis. I am convinced that the quality of the manuscript will improve significantly, if non-CO2 emissions and their climate effects are additionally considered in the analysis.
• Modelling methods: The modelling method for assessing CO2 emissions resulting from PA is rather derivative and does not represent the current state of research regarding emissions modelling. For instance, Teoh et al. (2024) or Sun et al. (2023) present high-fidelity modelling techniques for larg traffic samples of ADS-B data. Current state of emission quantification methods typically considers variations in fuel consumptions according to detailed trajectory simulations. Assuming a constant fuel consumption (per flight hour) marks a significant simplification excluding effects from different

aircraft masses (load factor, but also including fuel for fuel effects for long-range missions), different flight altitudes, different flight speeds as well as different phases of the flight (i.e. take-off, cruise and descent). Furthermore, I assume that marketing materials provide an optimistic estimate of fuel consumption so that actual values could be strongly underestimated. I am aware of the fact that more detailed flight performance data for PA aircraft is difficult to access, but there are approaches in literature that aim to address this lack of data availability (e.g. OpenAP model as applied in Sun et al., 2022)
Minor comments:
• Title: From my point of view the title “Private aviation makes growing contribution to climate change” does not meet the content of the study as it is restricted to CO2 emission quantifications.
• Abstract: I suggest the abstract to be rewritten as it does not conclude the major outcomes of this study regarding the growing contribution to climate changes. Also, I recommend to provide more details regarding the research objective to be addressed as well as the emissions modelling approach.
• Lines 92-94: Is there evidence for higher flight altitudes in PA? It might make sense to introduce another figure to highlight the distribution of emissions in PA in comparison to commercial aviation? Is there further evidence for a disproportionate increase as indicated in line 93? I am wondering if emission quantities decrease for higher altitudes and therefore potentially compensate higher climate sensitivity in those regions.
• Lines 101 – 107, Table 1, lines 319-320, lines 397-399, Figure 1 (Method): Do you consider track distances or great circle distances in your analysis? It is possible to derive the detailed track data from ADS-B points; thus, it would be good to represent this information in the data analysis and figures instead of simplified great circle connections.
• Line 126: How are affluent countries defined? It would be great to incorporate a related KPI to Table 2.
• Figure 7: Are the results presented based on Forbes (2024) only or do you also consider your data in this analysis?
• Line 263-264: Could you provide some evidence for why you expect PA to replace cars.
• Abbreviation PIA is not introduced in the main part of the paper.
• Figure numbering is not consistent from my point of view.

Added References:
Junzi Sun, Xavier Olive, and Martin Strohmeier (2023): Environmental Footprint of Private and Business Jets. Engineering Procedings, 28 (13). https://doi.org/10.3390/engproc2022028013.
Joseph B. Sobieralski, and Stace Mumbower (2022): Jet-setting during COVID-19: Environmental implications of the pandemic induced private aviation boom, Transportation Research Interdisciplinary Perspectives, 13. https://doi.org/10.1016/j.trip.2022.100575.

Reviewer #4 (Remarks to the Author):

The work proposed by the authors is significant and interesting. It provides a comprehensive analysis of the environmental impact of private aviation. It uses ADS-B Exchange data to quantify emissions from private aviation over a five-year period (2019-2023). The paper highlights the significant contribution of private aviation to CO2 emissions, the geographical concentration of private flights, and the growth trends in private aviation. It also explores the implications for climate policy and social justice. The analysis of the air transport patterns with respect to major events is a significant contribution that should be more underlined in the abstract and maybe the title.

The paper is well-written and generally easy to follow. Overall the figures and tables are clear and relevant except two figures that are mentioned in the detailed comments which require modification.

Overall the references are up-to-date and relevant. However, there are a few recent key publications missing directly linked to the problem addressed or that bring significant context to the overall topic (cf. detailed comments in attached file).

Also, no concrete policy recommendations are proposed which is in contradiction with the conclusions on the necessity to have simultaneously an efficient climate policy and social justice.

For these reasons, I recommend to accept the publication with major revisions.

they must do so prior to acceptance.
https://www.springernature.com/gp/researchers/orcid/orcid-for-nature-research

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Version 1:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Professor Gössling,

Your manuscript titled "Private aviation makes growing contribution to climate change" has now been seen by 3 reviewers, and we include their comments at the end of this message and in the attached pdfs (for reviewer #2). Overall, they appreciate and acknowledge the improvements made to the manuscript, finding your work of interest. However, they raise a few points which persist. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Please submit your point-by-point responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred.

Important: The response to reviewers must not include any figures, tables or graphs. If you wish to respond to the reviewer reports with additional data in one of these formats, please add them to the main article or Supplementary Information, and refer to them in the rebuttal. Due to current technical limitations, any figures, tables, or graphs embedded in your rebuttal will not be included in the peer review file, if published.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:
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We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Alice Drinkwater, PhD
Associate Editor
Communications Earth & Environment
@CommsEarth

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and also in our style and formatting guide Communications Earth & Environment formatting guide .

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All Communications Earth & Environment manuscripts must include a section titled "Data Availability" at the end of the Methods section or main text (if no Methods). More information on this policy, is available at http://www.nature.com/authors/policies/data/data-availability-statements-data-citations.pdf.

In particular, the Data availability statement should include:
- Unique identifiers (such as DOIs and hyperlinks for datasets in public repositories)
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Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

REVIEWER COMMENTS:

Reviewer #3 (Remarks to the Author):

Revised manuscript review:

The quality of the manuscript has increased significantly in course of the revision process. I highly appreciate the consideration of uncertainties in the methodology section which clearly improves the paper. From my point of view, the paper can be accepted for publication. Nevertheless, the following remarks are remaining from my side:
- Page 3: ‘Considering altitude warming effects, the relevance of PA for climate change is even greater (Lee et al. 2021; Lee et al. 2023). Private aircraft spend 45.4% of the total flight time at >30,000 and 21.4% at >40,000 feet, making PA emissions specifically relevant in the highly frequented North Atlantic (Figure 2).’
From my perspective, it is not clear why the flight level distribution shows that PA emissions are highly relevant in the North Atlantic. I assume, that rephrasing the second part of the sentence will clarify the context. Also, I am confused in how far this is related to the relevance of PA for climate change. Why do you expect the relevance to be even greater? From my point of view, this is only the case if the non-CO2 effects of PA are disproportionate in comparison to other sectors of aviation. The paper is not providing any data to draw this conclusion as non-CO2 effects vary with altitude and lateral position as well as time. A more detailed investigation is required from my point of view to support this point.

- Page 3, Table 1: Great circle distances. Real distances are 10.1% longer.

I suggest to rephrase “Real distance are on average 10.1% longer”, as I assume the relative difference is larger for shorter distances and smaller for longer flight distances.

- Abstract & Conclusion: The study provides a first understanding of global private aviation’s role in climate change. Total direct emissions of 15.6 Mt CO2 in 2023 amount to 1.7% to 1.8% of commercial aviation’s CO2 emissions. The sector’s contribution to climate change is considerably larger if non-CO2 warming is considered (Lee et al. 2021; Teoh et al. 2024b). Again, I am not sure if this conclusion can be drawn from the results presented in this paper. There is no evidence in the data for higher non-CO2 effects of PA compared to commercial aviation as these effects are non-linear depending on location and time of emission which is not sufficiently covered in this paper. Furthermore, I still think, that the paper only covers the CO2 part of the climate impact, which requires clarification in title, abstract and conclusion from my side.

- Page 12 (Method): The focus on CO2 ignores non-CO2 effects at flight altitude, and thus represents a significant underrepresentation of the sector’s contribution to radiative forcing (Lee et al. 2021; Teoh et al. 2024b). To assess this contribution, we use ADS-B Exchange data for an analysis of the flight time spent at altitudes >30,000 and >40,000 feet, finding that 21.4% of flight hours are spent at >30,000 feet, and 45.4% at <40,000 feet. This is not proportional to emissions at these altitudes, as larger aircraft models are more likely to fly at these altitudes. The data is available at https://private-jets.fra1.digitaloceanspaces.com/leg/v2/all/year={year}/data.csv.
This contradicts the information on page 3, where the authors state that 21.4% of the flight time is above 40,000ft and 45.4% are above 30,000ft. A clarification is needed here.

Reviewer #4 (Remarks to the Author):

Thank you authors for the revised manuscript.

The majority of my comments have been addressed satisfactorily.

There are two remaining issues for me.

First, the authors mention that a comparison of the methodology proposed and that of the literature has been achieved and that it has been summarized in a table. I do not see that "Table 1"?

Then, I think the flight patterns figures do not meet the quality and does not provide the insights required for such journal. I suggest again using alternative libraries such as plotly (https://plotly.com/python/scatter-plots-on-maps/). Also, I am still convinced that a figure of the patterns of CO2 emissions would be of interest (maybe even mandatory if you look at the paper title) to answer the question "what is the distribution of private aviation emissions with respect to countries/continent/macro routes?".

Version 2:

Decision Letter:

Dear Professor Gössling,

Your manuscript titled "Private aviation makes growing contribution to climate change" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

EDITORIAL REQUESTS:

Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

*****Please take care to match our formatting and policy requirements. We will check revised manuscript and return manuscripts that do not comply. Such requests will lead to delays. *****

Please outline your response to each request in the right hand column. Please upload the completed table with your manuscript files as a Related Manuscript file.

If you have any questions or concerns about any of our requests, please do not hesitate to contact me.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Alice Drinkwater, PhD
Associate Editor
Communications Earth & Environment
@CommsEarth

REVIEWERS' COMMENTS:

Reviewer #2 (Remarks to the Author):

I appreciate the patience of the authors and the diligence with which they have gone through my comments. I believe that their last revision has - again - greatly improved the clarity of their manuscript. After my last point below is addressed, I will be happy to recommend their article for publication without further changes:

The authors in response to my own last comment about their maps mention that “Maps serve as illustrations.” This, as they would surely agree, is a truism that has no bearing on my comment. Naturally maps serve an illustrative purpose.

The real question is about the distortion that maps introduce. It might well be that maps greatly distort reality in order to better convey a specific message. Subway maps are perhaps the most well-known and well-motivated such example. However, here the authors have no reason NOT to CORRECTLY render great-circle distances on a map that is clearly using an isogonal projection.

Since the authors are submitting to Nature Comms. Earth and Environment, a reasonable level of accuracy on maps is to be expected of all submissions. I must insist they provide a map which CORRECTLY renders great circle distances. Foruntately, a master's students with basic knowledge of Python-based plotting libraries such as Plotly (helpfully suggested by Reviewer #4) will be able to re-render the entire set of maps in a single afternoon.

Reviewer #3 (Remarks to the Author):

Thanks to the authors for providing another revision of the manuscript. From my point of view, all remarks have been addressed sufficiently, hence i recommend the article to be accepted for publication.

Reviewer #4 (Remarks to the Author):

Dear authors,

Thank you for your response.

Since I do not have access to the high-quality figures to judge, I will leave the appreciation to the Editor.

I have no further comments.

Response to reviewers: COMMSENV-24-1205-T

Reviewer #2 (Remarks to the Author):

General Comments

Dear authors,
I have read your manuscript thoroughly and with great interest. You have correctly identified private aviation as an understudied part of the air transport system, which is already very energy intensive and difficult to decarbonize.
Your research investigates the total carbon emissions of private aviation activity globally, its geographic scale and distribution, the role of events in attracting private aviation, individual patterns of aircraft use, as well as travel motives and growth trends.
Unfortunately, I cannot recommend your manuscript for publication in Communications Earth & Environment. What is more, I recommend the authors make major modifications to their manuscript before they re-submit to a more appropriate journal.
While some of the data (and associated source code) you provide will surely be of interest to other researchers, neither your core method, nor your conclusions meet the criteria for publication laid out by the journal. For instance:
• The conclusions are novel
I find it difficult to identify any novel conclusions other than the numbers provided for carbon emissions from private air transport. The strongest claim seems to be one on the "(…) travel motivations (…) reflective of global power structures". It seems to me that the current manuscript does not back up this already very vague claim.
The following elements of the paper are novel in the sense of not having been addressed earlier:
1. Calculation of fuel intensity of PA, also in relation to distances flown.
2. Global assessment of CO2 emissions from private aviation.
3. Patterns of use of private aircraft, including geospatial distribution and events.

• The underlying data are generated and processed at a state-of-the-art level, including tracking of uncertainties
No treatment of uncertainties is provided. Neither fuel burn (and associated uncertainties, such as block time vs airborn time) nor the difference between actual routes and great-circle distances are considered. No attempt was made to confirm the data coverage provided by the primary (and only) data source used by the authors.
We have now addressed all uncertainties in the revised version of the manuscript. Please see our following comments.

• The manuscript is important to scientists in the specific sub-field of the Earth, environmental or planetary sciences.
It seem to me that the primary reason other scholars would cite this publication will e be to quantify the carbon emissions of private travel. However, the underlying calculations are rough approximations only- it is doubtful if a specialized aviation-related scientific journal would publish numbers based on this method at all.
We beg to disagree. As we show, our approach is now accounting for all uncertainties and results are certainly robust beyond a "rough approximation". Please also note that the authors cited for using models to assess emissions from global aviation have not validated these models, other than in comparison to other estimates.

In summary, I believe that the research topic of private aviation climate impact is timely and of interest to a general readership. Unfortunately, the authors do not provide any treatment of uncertainty in their values. They use only a single data source, which for (at least) 2023 may have experienced deteriorating global coverage. The conclusions that the authors draw from a brief analysis of travel to different international events are not backed up by the data they provide. They lack a basic understanding of the geographic terminology they use to describe the maps they rendered for this manuscript.
I would recommend a journal focusing on research data (or open source software) for the author's consideration.
We agree that uncertainties should have been discussed and accounted for. This, as well as other issues, are discussed in detail below.

Specific Comments

Abstract
• "(…) specific fuel consumption in gallons per hour."
What does "specific" in this statement refer to? Usually, the term "specific" in the context of fuel burn is used in the THRUST-SPECIFIC fuel consumption [g/(s·kN)] metric.
The wording has been changed to "thrust-specific".

As a minor note, I found two fuel burn values which are not supported by the literature you cite in the CSV file (https://github.com/jorgecardleitao/private-jets/blob/main/src/models.csv):
BEECH 200 Super King Air
DASSAULT Falcon 6X

The values are as follows:

- BEECH 200 Super King Air, the fuel burn is 106 gph. This value has been used in calculations.
- DASSAULT Falcon 6X: no fuel burn data was available for this aircraft model, and thus computed based on data provided in the manufacturer file. The calculation used was: 1,211,748 [$/400h] / 400 [h] / 7.23 [$/gal] = 419 gal/h. We have added this to the methodology to fully account for this detail.

"We use ADS-B Exchange data that contains a timestamp, latitude, longitude, and barometric altitude." At the very least, a qualifying statement is in order. You present your data as authoritative, without ever discussing the potential limitations of using this single data source. A comparison with data from FlightRadar24 or other established ADS-B tracking sites should be provided to allow the reader to gauge the quality of the data the authors are basing their analysis on. Perhaps Dr. Juntsi Sun of TU Delft can help the authors in this regard. He is involved in an ADS-B tracking site focused on air transport researchers.
Thank you. We agree that any source of real data has limitations, and have for this reason discussed the limitations of ADS-B exchange in the methodology section of the revised paper. The situation is as follows: Earlier papers have used data from providers OAG (Official Airline Guide), FlightRadar24, OpenSky, and Spire Aviation. Quadros et al. (2022) compare OAG, FlightRadar24 and OpenSky, finding that FlightRadar24 provides the comprehensive database. Quadros et al. (2022) also explicitly note that OpenSky "provides reduced global coverage compared with the other two sources".

Given that our study focuses on private aircraft and that *FlightRadar24* purposely hides ADS-B signals of private aircraft as part of FDA's LADD, this introduces a systematic error. ADS-B Exchange data, which does not hide signals, is thus likely superior to OAG, Open Sky, as well as FlightRadar24. To further verify this hypothesis, ADS-B data was compared to FlightRadar24 by checking on a sample of 10% of aircraft, of which 30% were found to operate under LADD. FlightRadar24 may be a reliable source of ADS-B signals for commercial aviation, where LADD is not applicable, but it is not for private aviation.

We have compiled a comparison of methodologies, including Quadros et al. 2022 and Teoh et al. 2024 (commercial/all aviation), as well as Sun et al. 2022 and Sobieralski and Mumbower 2022 (private aviation). The comparison shows that approaches are generally not comparable.

Teoh et al. (2024) use the most complex model to calculate global aviation emissions, including the military, for the period 2019-2022. ADS-B Data is obtained from Spire Aviation, but not discussed in regard to comprehensiveness, or in comparison to other data providers. They do use Cirium data, which contains "all specific aircraft variant and engine model for all registered aircraft globally", but this only allows for confirmation of aircraft model comprehensiveness, not signals. Teoh et al. use aircraft performance models provided by EUROCONTROL, and the International Civil Aviation Organization (ICAO) Aircraft Engine Emissions Databank (EDB) that contains the emission indices from aircraft gas turbine engines with rated thrusts above 26.7 kN. They include historical weather data from the European Centre for Medium-Range Weather Forecasts to account for weather patterns. While this model is certainly complex and very sophisticated, it has, as far as we can tell, not been validated - for instance by comparing model results for individual flights with fuel use reported by airlines for individual flights to ICAO. The only 'validation' of their results is the comparison to other studies. Teoh et al. do not specifiy the share of private aviation emissions in the overall total.

Similarly, Quadros et al. (2022) calculate global aviation without military for the period 2017-2020, based on OAG, FlightRadar24, and OpenSky. Emissions are calculated based on LTO cycles and modeled in a time-in-mode approach. Quadros et al. rely on some assumptions, as for example "fuel flow rate at a given thrust is piecewise linearly interpolated from available engine data". Even in this paper, it is unclear whether the model has been validated, or how large uncertainties may be. The paper likely underestimates number of private aircraft as it relies on FlightRadar24 and does not discuss the implications of LADD. The share of PA emissions in global emissions from aviation is not determined.

Sun et al. (2022) use OpenSky for their assessment of "250 private jets" in the period 2019-2022. As OpenSky has been shown to be unreliable by Quadros et al. (2022), it is unclear how reliable the data is. Sobieralski and Mumbower 2022 use FAA data to assess private aviation in the USA, between January 2019 and October 2021. They rely on FAA Enhanced Traffic Management System Counts, FAA Operations Network; FAA General Aviation Activity Survey, and Cirium data. Calculations are based on great circle distances and "specific fuel burn coefficients", i.e. likely to underestimate emissions on the real distances flown. Their data is not available outside the US.

Overall, we observe that all approaches rely on commercial data, but in fairness, it remains unclear whether any of the models yield more accurate emissions assessments than our study. While models can consider flight cycle elements, aircraft mass and payload, as well as weather conditions, fuel consumption in PA is also characterized by pilot "flight styles", which interviews with pilots tell us can be considerable. This last aspect in particular is difficult to take into account. Hence, the averaged fuel burn values used in our study provides a good starting point for the assessment of emissions. Brokers have an interest in providing accurate values, as the fuel economy of an aircraft is an important aspect for private aircraft charter companies to take into account. As our data contains min-max fuel ranges for the LTO cycle, we have used these to assess the uncertainty of our data, finding a SD of at most 10%. The approach is now detailed in the methodology section under Uncertainties, noting all limitations.

The authors should further mention the recent acquisition of ADSB Exchange by a private company, which has led to some "feeders" (users contributing data to the site) to end their relationship with the site. A short inspection of the (former) ADSB Exchange users community on Discord will confirm that it is at the very least a real possiblity that the data coverage of ADSB Exchange had deteriorated noticably after January 2023. In light of this, I would expect the authors to show that their data for 2023 is not biased due to lower data coverage.
ADS-B is a commercial platform, tied to community-led receivers, which impacts the quality of data. This is an issue for any provider of ADS-B signals (e.g. ADS-B Exchange, FlightRadar24, The OpenSky Network). A note on the commercial character of ADS-B data has been included in the methodology.

We note two central weaknesses with all ADS-B signal providers:
(i) limited coverage of ADS-B
(ii) hidden aircraft under FDA's LADD.

In light of the preceding observations, ADS-B exchange data seems the most reliable that is available, as it tracks a larger number of private aircraft without enforcing LADD. We have added this information to the methodology, including a note that it is possible that the data quality has declined since 2023 due to a greater share of hidden aircraft. Please also note that cases of ADS-B signals being lost in remote regions are rare, as we do not find this to be an issue in our data. Again, please refer to the new section Uncertainties for an overview and the scale of potential error.

• "Flight times for 25,993 private jets (…)"
The authors later include turboprop aircraft like the Pilatus PC-12 and the Piper PA-46 in their scope, which suggest a more appropriate wording here (and elsewhere in the text!) would be "private aircraft". This is affirmed by the average speed of only 575 km/h which they mention later in the text.
The wording has been changed throughout the text.

• "We find that private aviation contributed 15.6 Mt CO2 in direct emissions in 2023, or 3.6 t CO2 per flight."
A qualifying statement is in order. Given the highly approximative way in which you compute fuel consumption, you might say "we find that aviation contributed at most (…)".
We have now qualified the statement, noting that our calculations likely represent a lower boundary estimate.

• "Flight pattern analysis confirms extensive travel by owners of private aircraft, also for leisure purposes."
Since travel is the primary purpose of an aircraft, this is not a surprising finding. The authors should consider removing this truism from the abstract. What is more, the authors did not convincingly analyze the travel habits of aircraft owners – they were able to track aircraft, not owners.
The finding is quite relevant in our opinion, because private air travel for business is tax deductible. It appears that most flights are labelled business flights, as the IRS launched an initiative to check on private/business in February 2024. As our data illustrates, the share of leisure/private travel with company jets may be considerable, which is of relevance even though the reviewer correctly points out that we track aircraft not owners.

Main
• "Industry estimates suggest growth rates of 4.5% per year (revenue passenger kilometers, RPK) over the next two decades (Airbus 2023; Boeing 2023)."
The Airbus market forcast cited gives a number of 3.6%/year for pax-traffic. The Boeing market forecast cited gives a number of 6.1%/year for all traffic. Neither source therefore supports the claim of the authors. Perhaps the authors mis-interpreted the figure on page 8 of the Airbus market forecast, which gives a historical growth rate of 4.8%/year between 1990-2019.
It is correct that Airbus forecasts 3.6% growth in RPK for the period 2019-2041 (Boeing suggests 3.8%). This however includes the pandemic period, and is thus not a measure of future growth expectations. As manufacturers expect normalization, our numbers refer to 2019, the last pre-COVID year, when RPK growth expectations were 4.3% (Airbus) and 4.6% (Boeing), or an average of 4.45%. The 2024 global forecast by Boeing/Airbus, which is now available, is less clear on future growth rates. Since the exact growth rate has no

relevance for our argument, we now refer more generally to Airbus (2024) and Boeing (2024), and have removed reference to the average we calculated.

• "(…) policies (…) need to consider such complexities of growth, distribution, and energy-intensity." Could the authors specify what they mean by "distribution"?
We have rephrased the sentence to read "...growth, geographical distribution, and energy-intensity"

• "(…) industry expectations point to continued growth, from a current value of US$44 billion (…)" What is the "value" referred to here? Is this annual revenue, profit, value of aircraft, ..?
The figure refers to this sector's global business jet market size. It does include aircraft manufacturers, operators, charter services, fractional ownership, leasing, financing, and maintenance and support services. The text has been changed to read "from a current global business jet market size of US$44 billion…"

Energy Intensity and Distribution
• "There are 72 PA models in use worldwide (…)"
This is a very strong claim. The authors were able to identify 72 models. Unless the authors can show convincingly that no other models are currently in use worldwide, a more humble formulation might be in order.
The sentence has been rephrased: "Our analysis considers 72 aircraft models marketed as business aircraft."

• "(…) as PA travel at above 40,000 feet (ADS-B Exchange 2024)."
Clearly, not all PA travel at this altitude. This includes some of the most popular turboprop-driven models the authors included in their scope. This becomes even more clear from the average speed the authors note in the next paragraph: "only" 575kph. The statement and the associated reference on flight altitude should therefore be re-formulated.
We agree, and have now calculated the share of the flight time that takes place at above 30,000 to 40,000 feet for the global fleet of PA. Results show that 45% of flight time is spent above 30,000 feet, and 21% above 40,000 feet. This has been integrated in the paper.

Figure 1
• "There is very limited private air transport in all of Africa, with the exception of South Africa and Nigeria."
While this seems plausible, the method employed by the authors hardly allows for a definitive statement of this nature. After all, I expect the ADS-B Exchange data coverage to be lacking in large parts of Africa. This highlights the importance of checking the quality/coverage of ADSB Exchange data against other sources (see my earlier comments).
ADS-B Exchange data appears to be reliable, even in remote regions, and our methodology accounts for lost signals. There may be regions within which aircraft are not tracked at all, which is now also discussed in the Methodology. We have rephrased the sentence, which now reads: "There appears to be very limited private air transport in all of Africa, with the exception of South Africa and Nigeria."

• "In comparison to population distributions, PS is concentrated in affluent countries."
It seems to me that PS would be concentrated in affluent countries regardless of "population distribution". Perhaps the authors could clarify this statement.
The sentence has been shortened and now reads: "Private aviation is concentrated in affluent countries."

Table 2, Table 5, Figure 7
I must strongly discourage the authors from using bubble charts to compare a single variable. Since circle area does not scale linearly, an immediate visual comparison is almost impossible. This readability issue has been replicated in recent studies (cf. https://doi.org/10.1109/TPC.2020.3032053, section "Perception of Graph Readability"):
A bar chart will perfectly convey the author's data in these tables/figures.
Bubble charts in Figure 5 and Figure 7 have been replaced with bars, and bubbles have been removed from Table 2.

Methods
• "For air traffic control and monitoring, aircrafts are required to switch on the Automatic Dependent Surveillance – Broadcst(ADS-B) transponder during flight (FAA 2023)."
The reference (FAA 2023) does not exist. I can only infer that the authors mean to cite an authoritative reference like 14 CFR 91.225 (https://www.ecfr.gov/current/title-14/section-91.225). However, this would only apply to US-registered aircraft and/or those foreign-registered aircraft operating in US airspace.
We apologize for this omission. The FAA serves as an example of regional regulation, and we have added a reference to ICAO for the Asia/Pacific region.

• "ADS-B Exchange (…) a platform that provides comprehensive and unfiltered traffic data for every aircraft on a 60 second basis."

See my other comments about this data source.
We hope that we have sufficiently addressed the critique of ADS-B.

• "For this project, the entire database for private aircraft was retrieved (…)"
On what basis is the determination of "private" made? The authors mention this later on in the text. The reader would benefit from a definition at this point.
The definition has been moved forward. The sentence now reads: "For this project, the entire database for private aircraft – defined by manufacturers as business aircraft - was retrieved for the period 2019 and 2023, totalling 1.8 TB of data related to a total of 18,655,789 legs (individual flights)."

• "The flight data does not consider a share of flights using third-party flight ID. Under the Federal Aviation Administration's ADS-B Privacy program, aircraft registered in the US and flying in US managed flight information regions can apply for Privacy ICAO aircraft addresses (PIA). These are temporary ICAO aircraft addresses not assigned to the owner in the Civil Aircraft Registry (CAR) (FAA 2024)."
The inclusion of this information is greatly appreciated. It is particularly helpful to readers unfamiliar with aircraft registration procedures. I strongly suggest the authors include a paragraph discussing future challenges resulting from newly introduced legislation. This is particularly important since other researchers may be more limited in their tracking of aircraft in the future. The authors should think about mentioning this change more prominently. It seems that other researchers "may never again get such good data".
Thank you. We have added this, the section now reads: "This may become more difficult in the future, as the use of Privacy ICAO Addresses (PIA) is growing and will potentially lead to a declining quality of ADS-B data for emission assessments."

• "All fuel use considered refers to aircraft being in flight (…)"
Where do the sources from which the authors have extracted fuel consumption data state this explicitly? It seems plausible that this number may be an average across taxi, takeoff, climb, cruise, descent, landing, taxi (for an average trip length).
Values refer to flight times, as brokers sell aircraft with a view to the expected fuel economy. Please see our discussion in the revised version of the paper, which provides more detail on these issues.

• "and was deemed accurate."
Were any discrepancies found? If so, how many?
No discrepancies were found, the section has also been re-written for clarity.

• "By tracking the position of each aircraft over time, flight legs, distances, and flight times can be calculated. From the position of the jet over time the flight legs, flown distance, and flight times are calculated."
I assume the authors forgot to de-duplicate this sentence?
We apologise for the omission. The second sentence has been removed.

• "The focus on CO2 ignores non-CO2 effects at flight altitude (Lee et al. 2021), as well as scope 3 emissions (Gössling et al. 2024)."
I would recommend the authors re-consider the utility of mentioning different scope emissions in this context. They are estimating the carbon emissions associated with burning a certain amount of jet fuel. This is alone is neither scope 1 nor 2, but only a part of the emissions scope of an entity.
To avoid confusion, the second part of the sentence has been removed.

• "When the signal is lost for more than 5m"
Presumably the "m" stands for "minutes"?
Yes, we have now spelled m out as "minutes".

Air Transport Patterns
• "Further insights can be derived from the analysis of spatial patterns, such as the importance of global events, or the travel patterns of individuals."
I am wondering what insights this is providing. The authors do not specify this in the text. It is well known that high-level gatherings such as the World Economic Forum of the COP climate conferences attract a large number of private aircraft. While the maps provided for these events are visually appealing, I am missing the insight the authors are claiming.
We consider patterns relevant, and this is the first paper to confirm PA attendance. Please note that reviewer 2 considers this part of the analysis to be relevant - this may be a matter of viewpoints.

• "Total emissions from events are higher (…)"
Since the authors are looking only at emissions from private aircraft, this is to be expected. What are the authors trying to convey with this statement?
Since it would be incorrect to state that PA-related emissions are equivalent to direct emissions, there needs to be a qualifier. If there is a misunderstanding regarding this issue, please let us know.

• "The analysis of the spatial movement patterns of individual air travellers reveals considerable differences in flight numbers, emissions, min-max, and average distances (Figure 6, 7). These require further investigation, as very short flights (13 km to 72 km) suggest that aircraft are moved for parking and pick-up/delivery patterns, business and leisure flights (Figure 8)."
Again, I fail to see what could be accomplished by "investigating" positioning flights in the context of large events. If the objective of the authors is to compute carbon emissions, they already have sufficient data.
As stated, there may be different opinions regarding "relevant" data. The investigation of patterns is part of the analyses we present in this paper. We believe that the issue of very short flights is of potential interest in the context of 'wastefulness', as take-offs are the most energy-intense part of the LTO cycle. Certainly empty flight shares, as well as private air transport patterns (parking or pick-up/delivery) also have relevance in this context.

• "A considerable, but undeterminable share of flights is made empty."
These are known are positioning flights. While they certainly play a role in private air transport, I am wondering how the authors can both claim that their number is "considerate", but also "undeterminable".
We have described the phenomenon as "considerable, but undeterminable", because our analyses suggest that positioning flights occur regularly. Yet, it is not possible to calculate the exact number. We have rephrased: "An indeterminable share of flights is made empty."

• Figure 7: "(…) based on Forbes (2024)"
Like the reference (FAA 2023) mentioned earlier, this reference also does not seem to exist. Further, "Global celebrities' private air travel" seems to me to be an insufficient figure caption. Who counts as a celebrity? Is Elon Musk a celebrity, or does he count as a corporate traveller? Presumably, the authors used the definition of Forbes – but the missing reference did not allow me to check that.
We have removed the word celebrities, and clarified the context as well as added a reference.

• Figure 8: "206 (11.6%) went to Switzerland and 134 (7.6%) to Scotland, indicating second home ownership. Another 54 flights were made to Florida, USA."
Was the assertion of second-home-ownership made arbitrarily? Why was this not deemed to be the case for Florida?
Patterns have been under investigation by a TV station, which found second home ownership to be the reason for flights to Switzerland and Scotland, and an annual horse/riding event to be the reason for flights to Florida. We cannot cite an investigative journalist's report as a reference, hence the formulation "indicating". We do not qualify Florida, given that the family in question may also own a second home in Florida.

Travel Motives
• "Arrivals are also concentrated on weekends, suggesting that travel motives are leisure-dominated."
Why are weekend arrivals indicative of leisure travel? Surely this would only be the case if both the arrival and departure are on the same weekend?
As figure 9 shows, indeed departures peak on Sundays on the same weekends. Data for Nice shows, for example, that 34 out of 52 weekends (65%) fall under this pattern.

• "Data also reveals that travel motives overlap. (…) For example, 172 of the 595 aircraft trail numbers appearing at the World Economic Forum (WEF) in Davos also served the Cannes Film Festival, and 65 identical tail numbers were identified at both the WEF and COP28. (…) This data suggests that there is a co-attendance of these events and an amalgam of travel motivations across political, economic, and cultural dimensions that is also reflective of global power structures."
For these claims to hold, the authors MUST show that (the majority) of private aircraft that were found to attend both events are in fact owned by single individuals. It seems to me rather plausible that private aircraft owned by companies such as Jet Aviation (https://www.jetaviation.com) would attend both events – but not necessarily with the same passengers. Also, fractional ownership of private aircraft is a popular legal ownership model. The authors themselves mention different ownership models earlier in their manuscript.
For instance, the owners.csv file the authors provide on their GitHub repository does not list a single aircraft owned by a private individual. It only lists corporations.
I must stress the importance of this point. The claim of the authors make a vague claim about global power structures ("an amalgam of travel motivations (…) that is also reflective of global power structures.") based on the fact that some of the same aircraft are used to fly to different events.
If the authors are able to show that the same individuals use these same aircraft to attend different events, I would appreciate some clarification on what it means for our understanding of "global power structures".
The reviewer is correct that all private aircraft are registered with corporations, possibly because the cost is tax deductible. It is also correct that there is fractional ownership as well as charter traffic. Even where aircraft are owned by individuals, they may have been rented or given to business relations or others. Hence, we have rephrased the section:

“Data also reveals that private aircraft serve the same events. The events studied (Figures 3-5) have political, economic, cultural, and sports foci, yet are frequented by the same aircraft (Figure 10). For example, 172 of the 595 aircraft trail numbers appearing at the World Economic Forum (WEF) in Davos also served the Cannes Film Festival, and 65 identical tail numbers were identified at both the WEF and COP28. Of the 404 aircraft at COP28, 96 also appeared at the FIFA World Cup. It is not possible to say whether this means that events are attended by the same individuals, though it would be of interest to further investigate travel motivations across political, economic, and cultural dimensions.”

Conclusions

• “Given limited evidence of emission-intensity gains (…)” – The authors have provided no such evidence.

While the authors may argue that efficiency gains have not been able to keep up with increasing demand, the original claim (“limited evidence of emission-intensity”) is false and misleading. While it is difficult to compare aircraft in the list directly, a brief look at two Gulfstream aircraft:

Gulfstream V, 1997, 500gph
Gulfstream G500, 2015, 430gph

Shows a 14% decrease in fuel burn between 1997 and 2015. This seems to be at the very least comparable to similar efficiency gains in cars during the same period.

This part of the sentence has been removed, please also consider the revised Conclusions that we hope now have a better structure.

• “To properly assess the system of private aviation, it would also be necessary to consider taxiing, or helicopters that are used to reach final destinations.”

This seems of secondary importance to me. Much more important would be a more sophisticated approach to fuel consumption calculations. Or the distance actually flown, as opposed to great-circle distances.

Our methodology is focused on flight time to derive fuel consumption. We have also calculated the difference between great circle and flown distances, which is 10.1%.

Development of Maps

While the attempt to describe the mapping methodology in detail is appreciated, the current section shows a lack of geographic understanding:

1. WGS84 is NOT a projection. Rather, it is a Geographic Coordinate System. Only a Projected Coordinate System has a projection. However, the authors never disclose the projection they use in their maps. The absence of the poles (the South Pole, at the very least) suggests their projection is a Mercator-like projection. They authors may be forgiven for this misunderstanding, since this seems to be a popular point of
confusion: https://gis.stackexchange.com/q/73576, https://gis.stackexchange.com/q/149749. Also, the popular GeoPandas open-source GIS package for Python incorrectly uses the term “WGS84 latitude-longitude projection” on one of their documentation pages (https://geopandas.org/en/stable/docs/user_guide/projections.html).
2. WGS84 is also NOT based on an ellipsoidal earth model. It IS one.
3. “This system is widely used for GPS” – GPS ONLY provides WGS84 coordinates. Decoding the GPS satellite signal ONLY provides WGS84 coordinates. Of course, these can be converted to another coordinate system.

Thank you for these corrections and observations. We have rephrased the respective section, which now reads:
“Maps visualize air transport based on the geographic coordinate system WGS84 (World Geodetic System 1984) that defines latitude, longitude, and altitude, and using a Mercator projection.”

4. What is an “imperfect sphere”?

We refer to a ‘sphere’ in the revised version of the text.

5. “ADS-B transponder data for departure and arrival points are transferred to the map, representing great circle distances, i.e. the shortest path between two points on the surface of a sphere.” – This sentence is not clear to me. Do the authors mean to imply that the (flight) distance between two points was calculated based on the great circle distance? Also, the authors just a few sentences ago mention that they are not assuming the earth to be a perfect sphere. Now they use the approximation of the sphere for calculating great-circle distances?

This section of the paper describes the development of maps. The sentence has been re-formulated for clarity. It now reads:
“Maps are generated based on ADS-B transponder data for departure and arrival points representing great circle distances, i.e. the shortest path between two points on the surface of a sphere.” We have calculated great circles, but added a calculation of the differences to real distances flown (10.1% greater).

6. "It needs to be considered that any two-dimensional map introduces visual distortion, as the length of lines indicating flight distances is not proportional to actual distances." – This sentence is simply nonsensical. Do the authors mean to imply that they: 1) calculated distances based on the great-circle distance, but 2) were unable to show these great circle distances on the map? It is obviously possible to draw the great circle distance on any projection – it may just turn out not to be a straight line (cf. https://transportgeography.org/contents/chapter1/transportation-and-space/great-circle-distance/). This section and the maps in the manuscript require a complete re-writing, ideally after the authors have consulted with a colleague with a background in GIS.
We have rephrased for clarity:
"The projection distorts distance by increasingly stretching distances between points as they move away from the equator towards the poles, leading to distance exaggeration of high-latitude regions."

Reviewer #3 (Remarks to the Author):
The presented paper 'Private aviation makes growing contribution to climate change' submitted by Stefan Gössling, Andreas Humpe and Jorge Cardoso Leitão for publication in 'Communications Earth & Environment' estimates CO2 emissions from private aviation (PA) from 2019 to 2023 and analyzes the results with regard to geospatial patterns, global events, celebrities private air travel, company flight patterns, and annual as well as seasonal developments. The authors apply a simple method to estimate CO2 emissions based on a comprehensive data base resulting from combining ADS-B data with fuel consumption data from marketing material for 72 identified PA aircraft. The authors show PA's significant contribution to aviation CO2 emissions in general as well as a significant annual growth over the investigated time period. Moreover, the results show a high concentration of PA in certain regions, a strong relation to global events such as FIFA world cup, high impact from individual celebrities' private travel and strong seasonal effects.
The study's focus on PA as a sector of aviation provides new insights leading to original findings regarding global events, company flight patterns and seasonal effects. In general, the manuscript is well-written, easy to follow and the figures underline the content of the manuscript. Most of the taken assumptions are well explained and seem reasonable. The underlying data base is comprehensive and perfectly suited for the analysis. Furthermore, I highly appreciate the open source availability of all data bases and software code increasing the studies. However, the applied method is associated with significant simplifications, which does not represent the current state of emissions modelling in aviation climate assessment. Furthermore, reference to previously published research in this context (refer e.g. Sun et al. 2023, Joseph & Mumbower 2022) is missing as well as an explanation on how the findings of this work advance previous work as, for instance, conducted in Sun et al. (2023). Sun et al. (2023) also deal with an extensive assessment of CO2 emissions from business and private aviation applying more sophisticated methods.
All in all, I can recommend to accept this manuscript for publication after a comprehensive revision including reference to previous work in this context as well as the points mentioned below. Nevertheless, this paper contains several valuable contributions to emission quantification for private aviation, which has not yet been studied comprehensively in the current state of literature.
Thank you for the positive and constructive comments. Please consider the following comments in response.

Major comments:
• Climate change vs. CO2 emissions: The study states to address PA's contribution to climate change, but concentrates on CO2 emissions only. As demonstrated in many previous studies (e.g. Lee et al. 2021), the climate impact of aviation is not only influenced by CO2 emissions but also significantly by non-CO2 emissions. In contrast to CO2 climate effects, non-CO2 emissions vary significantly with location and time of emission as well as meteorological boundary conditions. A simple scaling with a factor between 3 and 4 (as introduced in lines 237-239) represents a strong simplification of these processes and requires evidence for private aviation aircraft and their specific operating conditions (high altitudes, medium latitudes, short distances). The scope of this study is restricted to CO2 emissions only and omits other species such as nitrogen oxides (NOx), water vapor (H2O) and aerosols. Therefore, I am of the opinion that the restricted scope of the study does not match the research objective of targeting the contribution of PA to climate change as major climate forcing effects are excluded from the analysis. I am convinced that the quality of the manuscript will improve significantly, if non-CO2 emissions and their climate effects are additionally considered in the analysis.
Thank you. We have omitted non-CO2 effects for the very reasons highlighted by the reviewer: non-CO2 effects vary depending on altitude, latitude, atmospheric/stratospheric conditions, and other factors (Teoh et al. 2024). For this reason, any inclusion of non-CO2 effects is difficult, and would be likely criticised. For all aviation, Lee et al. (2021) concluded that non-CO2 radiative forcings correspond to a factor three over CO2. How this translates to private aviation is however unclear, and we believe that for these reasons, it is more appropriate to focus on CO2 in this paper, and to highlight the potentially large contribution from non-CO2 not considered.

• Modelling methods: The modelling method for assessing CO2 emissions resulting from PA is rather derivative and does not represent the current state of research regarding emissions modelling. For instance, Teoh et al. (2024) or Sun et al. (2023) present high-fidelity modelling techniques for larg traffic

samples of ADS-B data. Current state of emission quantification methods typically considers variations in fuel consumptions according to detailed trajectory simulations. Assuming a constant fuel consumption (per flight hour) marks a significant simplification excluding effects from different aircraft masses (load factor, but also including fuel for fuel effects for long-range missions), different flight altitudes, different flight speeds as well as different phases of the flight (i.e. take-off, cruise and descent). Furthermore, I assume that marketing materials provide an optimistic estimate of fuel consumption so that actual values could be strongly underestimated. I am aware of the fact that more detailed flight performance data for PA aircraft is difficult to access, but there are approaches in literature that aim to address this lack of data availability (e.g. OpenAP model as applied in Sun et al., 2022)
Since reviewer one made similar comments, we engaged in a comparison of the different methods employed (see Table 1), concluding that these are more complex, but not necessarily more reliable. Specifically, Sun et al. (2022) use OpenSky data, which has been shown by Quadros et al. (2022) to have the least reliable data, and an "OpenAP model based on a Gulfstream G650" that is extended to 250 private jets. As far as we can judge their approach, it is not validated against real fuel use data. Teoh et al. (2024) state that their data set was obtained from Spire Aviation, "ahead of other ADS-B providers (such as Flightradar24, FlightAware and the OpenSky network) because of the availability of satellite coverage and price affordability." The reliability of their data is not discussed beyond the sentence: "The raw ADS-B telemetry may contain limitations where multiple unique flights can share the same identifier and/or have missing flight segments". In comparison, beyond the exclusion of the same identifiers, our data controls for missing flight segments. In conclusion, our Methodology may represent "optimistic fuel use estimates", but it allows us to define a lower boundary for emissions from PA. Please consider the revised Methodology.

Minor comments:
• Title: From my point of view the title "Private aviation makes growing contribution to climate change" does not meet the content of the study as it is restricted to CO2 emission quantifications.
Even though we focus on CO2, this would still seem to justify the title. We discuss the implications of non-CO2 emissions, but we do not quantify these, because a very small share of flights seems responsible for a major share of radiative forcings (Teoh et al. 2024b). We have however added a calculation of the share of time flown by PA in the stratosphere. We hope that these efforts to quantify the climate impact of PA does qualify for the title.

• Abstract: I suggest the abstract to be rewritten as it does not conclude the major outcomes of this study regarding the growing contribution to climate changes. Also, I recommend to provide more details regarding the research objective to be addressed as well as the emissions modelling approach.
Thank you. We have revised the abstract, and hope that it now contains all relevant elements.

• Lines 92-94: Is there evidence for higher flight altitudes in PA? It might make sense to introduce another figure to highlight the distribution of emissions in PA in comparison to commercial aviation? Is there further evidence for a disproportionate increase as indicated in line 93? I am wondering if emission quantities decrease for higher altitudes and therefore potentially compensate higher climate sensitivity in those regions.
A comparison is difficult, but we have calculated the flight time spent by the global fleet of PA in our study at above 30,000 and 40,000 feet, which is specifically relevant for the North Atlantic flight corridor, where much PA takes place (Figure 2). This is now part of the discussion. Regarding growth, we have added two business references to add an industry perspective of expected developments. We cannot answer the question "I am wondering if emission quantities decrease for higher altitudes and therefore potentially compensate higher climate sensitivity in those regions" because this would require a spatial analysis beyond the scope of this paper.

• Lines 101 – 107, Table 1, lines 319-320, lines 397-399, Figure 1 (Method): Do you consider track distances or great circle distances in your analysis? It is possible to derive the detailed track data from ADS-B points; thus, it would be good to represent this information in the data analysis and figures instead of simplified great circle connections.
The analysis is based on flight time. Maps are created for illustrative purposes, and refer to great circle distances using departure/arrival airports. To assess the difference, we have calculated flown distances based on datapoints, finding a 10.1% difference that is now mentioned in the paper.

• Line 126: How are affluent countries defined? It would be great to incorporate a related KPI to Table 2.
We have rephrased the sentence, as the definition of affluence is indeed difficult considering the case of Brazil and Mexico. The sentence now reads: "PA use is concentrated, with six countries accounting for more than 80% of aircraft"

• Figure 7: Are the results presented based on Forbes (2024) only or do you also consider your data in this analysis?
These are our own calculations, we only used Forbes to identify a suitable sample of individuals - we have replaced the reference with Yard (2022).

• Line 263-264: Could you provide some evidence for why you expect PA to replace cars.

The evidence is in the current flight patterns, with a large share of very short flights (18.9% are shorter than 200 km). We have rephrased the sentence to make this clearer: “Findings also confirm that PA are used routinely, and in many instances appear to replace cars for time gains or convenience, as evident from the high share of very short flights.” Please note that the 18.9% are listed only a few sentences earlier in the text.

• Abbreviation PIA is not introduced in the main part of the paper.
The abbreviation is now spelled out in the main body of the text.

• Figure numbering is not consistent from my point of view.
The numbering of the Figures should now be consistent; the numbering starts from 1 in the Methodology.

Added References:
Junzi Sun, Xavier Olive, and Martin Strohmeier (2023): Environmental Footprint of Private and Business Jets. Engineering Proceedings, 28 (13). https://doi.org/10.3390/engproc2022028013.
Joseph B. Sobieralski, and Stace Mumbower (2022): Jet-setting during COVID-19: Environmental implications of the pandemic induced private aviation boom, Transportation Research Interdisciplinary Perspectives, 13. https://doi.org/10.1016/j.trip.2022.100575.
Thank you. Both references are now included and discussed in the paper. As a general issue with Sobieralski and Mumbower (2022), we note that a Corrigendum had to be published (https://www.sciencedirect.com/science/article/pii/S2590198222002111). We also note that Sobieralski and Mumbower (2022) cite CO2-equivalent emissions, though they do not refer to radiative forcing as a measure to compare long-lived with short-lived greenhouse gases; their reference is to methane and nitrous oxides, which are not normally discussed as equivalent emissions (cf. Lee et al. 2021). We thus consider this paper as difficult for comparison, and have only integrated their relative comparison to PA, i.e. the share of private aviation in all aviation.

Reviewer #4 (Remarks to the Author):

The work proposed by the authors is significant and interesting. It provides a comprehensive analysis of the environmental impact of private aviation. It uses ADS-B Exchange data to quantify emissions from private aviation over a five-year period (2019-2023). The paper highlights the significant contribution of private aviation to CO2 emissions, the geographical concentration of private flights, and the growth trends in private aviation. It also explores the implications for climate policy and social justice. The analysis of the air transport patterns with respect to major events is a significant contribution that should be more underlined in the abstract and maybe the title.
Thank you. We have outlined this and other contributions of the paper more clearly in the abstract.

The paper is well-written and generally easy to follow. Overall the figures and tables are clear and relevant except two figures that are mentioned in the detailed comments which require modification. Overall the references are up-to-date and relevant. However, there are a few recent key publications missing directly linked to the problem addressed or that bring significant context to the overall topic (cf. detailed comments in attached file).
Also, no concrete policy recommendations are proposed which is in contradiction with the conclusions on the necessity to have simultaneously an efficient climate policy and social justice.
For these reasons, I recommend to accept the publication with major revisions.
Thank you. Please see the following responses addressing all concerns in detail.

General overview
The work proposed by the authors is significant and interesting. It provides a comprehensive analysis of the environmental impact of private aviation. It uses ADS-B Exchange data to quantify emissions from private aviation over a five-year period (2019-2023). The paper highlights the significant contribution of private aviation to CO2 emissions, the geographical concentration of private flights, and the growth trends in private aviation. It also explores the implications for climate policy and social justice. The analysis of the air transport patterns with respect to major events is a significant contribution that should be more underlined in the abstract and maybe the title.
Thank you. We have now included reference to major events in the abstract.

The paper is well-written and generally easy to follow. Overall the figures and tables are clear and relevant except two figures that are mentioned in the detailed comments which require modification. Overall the references are up-to-date and relevant. However, there are a few recent key publications missing directly linked to the problem addressed or that bring significant context to the overall topic (cf. detailed comments).
Thank you. Please see our following detailed responses.

Also, no concrete policy recommendations are proposed which is in contradiction with the conclusions on the necessity to have simultaneously an efficient climate policy and social justice.

We have considered the references provided by the reviewer and included concrete policy recommendations.

For these reasons, I recommend to accept the publication with major revisions.
Thank you for the opportunity to revise this paper.

Detailed comments
Title and abstract
The title is clear and concise, effectively summarizing the main focus of the paper. The abstract provides a good summary of the study's objectives, methods, key findings, and implications. It highlights the significant CO2 emissions from private aviation and the concentration of these activities in the USA. The abstract effectively sets the stage for the detailed analysis in the main body of the paper.
Thank you.

Main
The main section highlights the growing contribution of global aviation to CO2 emissions and the need to understand the specific role of private aviation. It successfully outlines the research objectives and the scope of the study.
However, key articles are missing in the literature review which address the same problem on the same scope or for commercial aviation:
Quadros, F. D., Snellen, M., Sun, J., & Dedoussi, I. C. (2022). Global civil aviation emissions estimates for 2017–2020 using ADS-B data. Journal of Aircraft, 59(6), 1394-1405.
Sun, J., Olive, X., & Strohmeier, M. (2022). Environmental footprint of private and business jets. Engineering Proceedings, 28(1), 13.
It is important to compare methods as well as results with the ones proposed. This is a major lack of the actual version of the paper.
We have now integrated these papers, including a comparison of the methods used, as well as the results.

While Bergero et al. 2023; Dray et al. 2022; Grewe et al. 2021 focuses on technological levers, the following article provides a literature review of these levers in addition to an opening towards demand/supply side management and systemic changes in the context of the Paris agreement climate objectives which would be more in line with the approach proposed by the authors:
Planès, T., Delbecq, S., Pommier-Budinger, V., & Bénard, E. (2021). Simulation and evaluation of sustainable climate trajectories for aviation. Journal of Environmental Management, 295, 113079.
Sacchi, R., Becattini, V., Gabrielli, P., Cox, B., Dirnaichner, A., Bauer, C., & Mazzotti, M. (2023). How to make climate-neutral aviation fly. Nature Communications, 14(1), 3989.
Delbecq, S., Fontane, J., Gourdain, N., Planès, T., & Simatos, F. (2023). Sustainable aviation in the context of the Paris Agreement: A review of prospective scenarios and their technological mitigation levers. Progress in Aerospace Sciences, 141, 100920.
We are grateful for the recommendation of these articles, which are included in the revised discussion of demand/supply side management.

Energy intensity and distribution The section presents comprehensive data on the fuel consumption of 72 private aircraft models and their respective CO2 emissions. The data is well-organized in tables and supported by clear figures. The analysis of energy intensity is thorough, showing a wide range of fuel consumption rates among different aircraft models. The comparison with average human CO2 emissions per year is particularly impactful. The explanation of how altitude impacts warming effects and the overall relevance of private aviation to climate change is clear but I would suggest to add this more recent reference on mitigation aspect:
Lee, D. S., Allen, M. R., Cumpsty, N., Owen, B., Shine, K. P., & Skowron, A. (2023). Uncertainties in mitigating aviation non-CO 2 emissions for climate and air quality using hydrocarbon fuels. Environmental Science: Atmospheres, 3(12), 1693-1740.
Thank you. We have added Lee et al. (2023).

Also, the sentence "as PA travel at above 40,000 feet (ADS-B Exchange 2024)" is wrong since for instance the ceiling of a PC-12 is at 30, 000 feet. I would suggest to add "most" to the sentence.
We have added "most" to the sentence.

Air transport patterns
The paper provides a detailed map and analysis of the geographical distribution of private flights. The focus on the USA and other affluent regions is well-justified and clearly presented. The discussion on the impact of global events (e.g., World Economic Forum, Super Bowl, COP28) on private aviation traffic is insightful. However, it misses patterns od CO2 emissions. For example, it would be nice to have at least one of the figures with the CO2 emissions that correspond to the thickness of lines.
We agree, but have chosen not to include CO2 emissions in the maps. The main reason is that maps would contain too much information, they are arguably difficult to read as they are (see following comment on Figure 6). Here, we are also concerned with arrival (origin) patterns, i.e. the calculation of CO2 emissions associated with events is depicted in Figure 5. As lines add up, they already represent an approximation of emissions (the

number of flights from a given airport to the event site). We hope that this “indirect” information is a sufficient indicator of carbon relevance.

In addition, Figure 6 is unreadable and has to be modified. Overall, the flight pattern figures could be prettier using alternative rendering libraries.
Figure 6 has been modified; we hope it is now more readable.

Travel motives
The analysis of travel motives distinguishes between leisure and business travel, showing a clear seasonal trend in destinations like Ibiza and Nice. The concentration of flights on weekends during peak seasons suggests leisure-dominated travel. The data showing cross-visitation of events by the same private aircraft highlights the multifaceted travel motives of private jet users. The connection between political, economic, and cultural events is well-documented and is well illustrated in Figure 10.
Thank you.

Growth trends
The paper presents robust data on the growth trends in private aviation, including the number of jets, distances flown, and emissions over the period 2019-2023. The analysis of these trends is thorough and clearly presented. The discussion on the impact of the COVID-19 pandemic on flight patterns and emissions is well-integrated into the analysis. The explanation of the stagnation in total distance flown between 2022 and 2023 is interesting. The projections of continued growth in private aviation and the implications for future emissions are well-founded and supported by data. However, one main concern here is that the period available. It could be interesting to mention studies that looked at periods before COVID-19 and compare the trends.
We have provided a comparative section of earlier studies in our response to reviewer 1, and and added this to the discussion. Our paper covers the longest period of PA data that has ever been published. Unfortunately, there is no data for PA published for the time before 2019. Our data suggests a 46% increase in emissions in the period 2019-2023, and we have added two industry references that also support the expected growth trend. We hope this addresses the comment.

Conclusions
The conclusions succinctly summarize the key findings of the study, emphasizing the significant contribution of private aviation to global CO2 emissions and the likely continued growth of this sector. The section discusses the policy implications of the findings, highlighting the need for more effective measures to address the emissions from private aviation. The discussion on social justice issues related to the energy-intensive consumption patterns of affluent groups is particularly compelling. The suggestion for future research areas, including a more comprehensive assessment of non-CO2 effects and downstream emissions, is well-placed and relevant but could benefit of an additional reference: Teoh, R., Engberg, Z., Schumann, U., Voigt, C., Shapiro, M., Rohs, S., & Stettler, M. E. (2024). Global aviation contrail climate effects from 2019 to 2021. Atmospheric Chemistry and Physics, 24(10), 6071-6093.
Thank you. We have added the reference.

Methods
The explanation of the data collection process, including the use of ADS-B Exchange data, is detailed and clear. The paper effectively describes the variables included in the dataset and the rationale for their use. The methodology for calculating CO2 emissions from flight data is well-documented. There are however main assumptions never discussed such as the load factor or the variation of fuel consumption depending on the operating range. The discussion of limitations related to data completeness and potential biases is honest and thorough.
Thank you. Please consider the added discussion on aircraft performance in the revised version.

Response to reviewers: COMMSENV-24-1205A

Reviewer #3 (Remarks to the Author):

Revised manuscript review:

The quality of the manuscript has increased significantly in course of the revision process. I highly appreciate the consideration of uncertainties in the methodology section which clearly improves the paper. From my point of view, the paper can be accepted for publication. Nevertheless, the following remarks are remaining from my side:
- Page 3: 'Considering altitude warming effects, the relevance of PA for climate change is even greater (Lee et al. 2021; Lee et al. 2023). Private aircraft spend 45.4% of the total flight time at >30,000 and 21.4% at >40,000 feet, making PA emissions specifically relevant in the highly frequented North Atlantic (Figure 2).'
From my perspective, it is not clear why the flight level distribution shows that PA emissions are highly relevant in the North Atlantic. I assume, that rephrasing the second part of the sentence will clarify the context. Also, I am confused in how far this is related to the relevance of PA for climate change. Why do you expect the relevance to be even greater? From my point of view, this is only the case if the non-CO2 effects of PA are disproportionate in comparison to other sectors of aviation. The paper is not providing any data to draw this conclusion as non-CO2 effects vary with altitude and lateral position as well as time. A more detailed investigation is required from my point of view to support this point.
We agree and have rephrased. The sentence now reads:
"Private aircraft spend 45.4% of the total flight time at >30,000 and 21.4% at >40,000 feet, suggesting that a share of emissions enters sensitive layers of the atmosphere with relevance for non-CO_2 radiative forcing (Lee et al. 2021; Lee et al. 2023)."

- Page 3, Table 1: Great circle distances. Real distances are 10.1% longer.
I suggest to rephrase "Real distance are on average 10.1% longer", as I assume the relative difference is larger for shorter distances and smaller for longer flight distances.
We have rephrased the sentence to "Real distances are on average 10.1% longer".

- Abstract & Conclusion: The study provides a first understanding of global private aviation's role in climate change. Total direct emissions of 15.6 Mt CO2 in 2023 amount to 1.7% to 1.8% of commercial aviation's CO2 emissions. The sector's contribution to climate change is considerably larger if non-CO2 warming is considered (Lee et al. 2021; Teoh et al. 2024b).
Again, I am not sure if this conclusion can be drawn from the results presented in this paper. There is no evidence in the data for higher non-CO2 effects of PA compared to commercial aviation as these effects are non-linear depending on location and time of emission which is not sufficiently covered in this paper. Furthermore, I still think, that the paper only covers the CO2 part of the climate impact, which requires clarification in title, abstract and conclusion from my side.
We agree. The sentence has been removed, and replaced with the statement "Non-CO_2 effects from PA require further investigation (Lee et al. 2021; Teoh et al. 2024b)."

- Page 12 (Method): The focus on CO2 ignores non-CO2 effects at flight altitude, and thus represents a significant underrepresentation of the sector's contribution to radiative forcing (Lee et al. 2021; Teoh et al. 2024b). To assess this contribution, we use ADS-B Exchange data for an analysis of the flight time spent at altitudes >30,000 and >40,000 feet, finding that 21.4% of flight hours are spent at >30,000 feet, and 45.4% at <40,000 feet. This is not proportional to emissions at these altitudes, as larger aircraft models are more likely to fly at these altitudes. The data is available at https://private-jets.fra1.digitaloceanspaces.com/leg/v2/all/year={year}/data.csv.
This contradicts the information on page 3, where the authors state that 21.4% of the flight time is above 40,000ft and 45.4% are above 30,000ft. A clarification is needed here.
We apologize for the mistake. 45.4% are spent above 30,000 feet, and 21.4% above 40,000 feet.
Thank you for spotting this.

Reviewer #4 (Remarks to the Author):

Thank you authors for the revised manuscript.

The majority of my comments have been addressed satisfactorily.

There are two remaining issues for me.

First, the authors mention that a comparison of the methodology proposed and that of the literature has been achieved and that it has been summarized in a table. I do not see that "Table 1"?
We apologize for the confusion. We originally developed a table as an overview for the reviewers that was to be part of the Response to reviewers, but later removed the table realizing that no tables or figures are allowed in the response. Reference to the table should have been removed; all information that was in the table had been transferred to the text.

Then, I think the flight patterns figures do not meet the quality and does not provide the insights required for such journal. I suggest again using alternative libraries such as plotly (https://plotly.com/python/scatter-plots-on-maps/). Also, I am still convinced that a figure of the patterns of CO2 emissions would be of interest (maybe even mandatory if you look at the paper title) to answer the question "what is the distribution of private aviation emissions with respect to countries/continent/macro routes?".
All figures included in the submission are low-resolution. High resolution figures are uploaded with the final version of the text.
As for patterns of emissions, we have analyzed patterns by country, finding very small differences to jet registrations. As it is unclear whether these differences are a result of larger aircraft flown in some countries, longer distances per aircraft because of higher charter shares, this opens up for speculation. We have not added this information for this reason. We believe the research question does adequately describe what is covered in the paper, and hope that the reviewer agrees:

“[…], the paper investigates the energy-intensity of private aviation, its global scale and distribution, the role of events in attracting private aviation, patterns of individual aircraft use, as well as travel motives and growth trends. “

Reviewer 2

General Comments
The changes the authors have made to their manuscript are greatly appreciated. Overall, I am satisfied with the modifications the authors have made to their manuscript. It now reflects a higher degree of epistemic humility, in line with the methods underlying the manuscript. As a whole, it also feels less polemic, focusing instead on the "insights" which can be derived from tracking private aircraft. I can recommend the article for publication after major changes, which I list below in detail.

Comments on the Rebuttal Letter
• "ADS-B is a commercial platform, tied to community-led receivers, which impacts the quality of data."
I must stress again that ADS-B was not a commercial platform for a significant period of the time that the authors are investigating. Like many other community members, I myself have stopped feeding data to the service after it was sold by the original owner. From anecdotal evidence alone it would seem plausible that some level of service degradation would be the result of this event. If the authors did not find any such change to data quality – all the better. But they should make at least passing mention of this fact.
We believe that a discussion of the history of ADS-B is perhaps misplaced in this paper. We cannot refer to anecdotal evidence pointing to service degradation, as this reviewer will understand. We have rephrased the sentence:
"The ADS-B data was retrieved from ADS-B Exchange (https://www.adsbexchange.com), a platform that offers comprehensive and unfiltered traffic data for every aircraft on a 60 second basis". The quality of the data is discussed in the section following this sentence, as per submitted revision.

• "We believe that the issue of very short flights is of potential interest in the context of 'wastefulness', as take-oOs are the most energy-intense part of the LTO cycle. Certainly empty flight shares, as well as private air transport patterns (parking or pick-up/delivery) also have relevance in this context."
While I comment on this below, I will mention it again in this context: The text would benefit from some suggestions on policies or regulations the authors deem appropriate. The authors deem empty flights (to pick up paying passengers) wasteful – this seems to be a very specific issue, almost detached from the remainder of the manuscript. If they choose to retain this issue, the reader might benefit from some concrete suggestions on how to avoid these.
We investigate PA patterns in this paper. Aviation regulation is a complex field in itself, and it will require multiple interlinked policies to bring down emissions from PA. It is beyond the scope of this paper to discuss these in depth, and we do not wish to point to individual measures without knowledge how these might impact the sector's emissions. This is why we chose to generically state "it will be necessary to regulate the sector".

Abstract
• "global roll"
is presumably a typo?
Thank you. Yes, this is a typo and was corrected.

• "(…) are linked to 72 aircraft models and their thrustspecific fuel consumption in gallons per hour."
Thank you for clarifying that you did indeed refer to thrust-specific fuel consumption. However, I am now confused. The authors later on state, that:
"Table 1 shows the number of private aircraft by model, including fuel consumption in gph, as provided by aircraft brokers for these models."
and
"Fuel consumption values are calculated for standard operating profiles, i.e. the Landing and Take-OO (LTO) cycle that considers taxiing, takeoO, climb, cruise, descent, and landing. Brokers use these values so that customers – often charter companies – can compare the fuel eOiciency of diOerent aircraft models."
It seems therefore that the authors used average fuel consumption, not thrust-specific fuel consumption. This is further supported by the equation:
"leg emission kg CO2=consumption gallonh*liters per gallonLgallon*kg per liter of jet

fuel kgL*CO2 emissions per kg CO2kg*leg time [h]"
Did the authors incorrectly used "thrust-specific" in the abstract?
Thrust-specific refers to the efficiency of an aircraft to produce thrust, while average fuel consumption refers to the overall efficiency per distance flown. One is related to the other, but here we should indeed have referred to average fuel consumption. This has been corrected.

Main
• "only 2-4% fly internationally in a year"
Gössling and Humpe in 2020 found that 11% fly in a year. Focusing on international flights in this context is irrelevant. The authors should use the more appropriate number.
We have removed the percentages. The sentence now reads:
"Air transport is an energy-intense activity, in which only a small share of the world population is involved."

• "Global mitigation eOorts are hampered by growth (…)"
The clarity of this paragraph could be improved if the type of mitigation were mentioned explicitly (climate change).
We have added "climate change" to the sentence.

• "(…) and policies focused on energy content in consumption (…)"
Would "energy intensity" not be a more appropriate term in this context, in line with the use of terminology in the rest of the manuscript?
We have changed the phrasing to "energy intensity".

• "Private air transport illustrates the policy conundrum of addressing the role of the aOluent."
What conundrum? If the authors are using this term to describe a diOicult question – the framing of the sentence is not clear. Surely the authors would agree that the regulation even of commercial aviation in general is a legal challenge due to the limits of national jurisdiction as pertaining to what is primarily an international undertaking. Why therefore "addressing the role of the aOluent" presents a particular issue for policymakers does not follow from the text.
We have rephrased to make the sentence clearer it now reads:
"Private air transport illustrates the policy conundrum of addressing the role of the affluent, as policymakers are reluctant to focus on the wealthy and powerful (Kenner 2019)."
We otherwise believe that regulation is a matter of political will more than legal challenges: Larsson, J., Elofsson, A., Sterner, T., & Åkerman, J. (2019). International and national climate policies for aviation: a review. *Climate Policy*, *19*(6), 787-799.

Energy intensity and distribution
• "Real distances are 10.1% longer."
While this addition (here and elsewhere in the manuscript) is appreciated, the authors should add the qualifier "on average". Otherwise, readers might be lead to think of this diOerence as a systematic oOset, rather than the statistical result that it is.
We have added "on average" throughout.

Air transport patterns
• "Further insights can be derived from the analysis of spatial patterns (…) or the travel patterns of individuals."
Since the authors in this version of the manuscript rightly no longer make strong claims to have any verifiable insight into the travel patterns of individuals, this sentence should removed.
We have removed the sentence.

Conclusions
• "(…) support services such as helicopters used to reach final destinations, or downstream emissions."
Could the authors clarify what they mean by "downstream" emissions in this context? Would this be emissions that arise, for instance, from the lavish parties hosted at Cannes? It seems that should be outside the scope of this publication – or inquiries into transport emissions in general. That is, unless the authors wish to delve deeper into the issues of double-counting of emissions, which remains an area of mathematical inquiry in the field of life-cycle assessment.
We have removed "or downstream emissions".

• "(…) and its relevance for climate policy and social justice."
Could the authors elaborate on their use of the term social justice, which is left undefined throughout the manuscript. On a related note, the authors do not propose any particular type of legislation or regulation for the private air transport sector – perhaps they might hint at established proposals, which takes their definition of "social justice" into account.
"Social justice" has been removed from the manuscript.

Methods
• "We generally find that earlier ADS-B Exchange data to be more noisy, as transponders may not have worked as reliably."
This seems an unlikely conclusion considering the short time-period (in relation to the average lifetime of present-day aircraft avionics systems) covered. Instead, a more plausible explanation might be found in changes to the open-source software distributed by volunteers of the ADS-B Exchange network.
We have rephrased the text, which now reads:
"We generally find earlier ADS-B Exchange data to be noisier, potentially because of changes to the open-source software distributed by volunteers of the ADS-B Exchange network."

• "(…) an horizontally scaled blob storage (…)"
The "an" is likely a typo – and the concept of blob storage could be elucidated on, or dropped altogether.
Reference to the storage form has been removed.

• "To assess the potential range of fuel consumption values, we consider the ranges specified by brokers. Fuel consumption values are calculated for standard operating profiles, i.e. the Landing and Take-OO (LTO) cycle (…). Ranges provide an indication of the relevance of other factors, such as pilot flight styles. Over the sample of aircraft models for which such data is available (n=18), we find a variation in fuel consumption values within 10%, calculated as the standard deviation from average consumption values (the data is available at (…)"
Unfortunately, I do not follow the description in this paragraph. The linked CSV file lists only one number for fuel consumption – the average provided by the brokers. I take it from the author's description that this number is computed such that it approximates the fuel consumption across a landing-takeoO-cycle. What does the "sample of aircraft models for which such data is available (n=18)" refer to? What data is available – does this data include fuel consumption as a function of diOerent pilot flying styles? Did the authors make this sample of aircraft available also?
We have rephrased the text for clarity; essentially we compare min-max consumption ranges with the averaged values we use for our calculations, finding that the SD is 10.1%. The new text now reads:
"To assess the potential range of fuel consumption values, we consider the ranges specified by brokers for n=18 aircraft. Average fuel consumption values are calculated for standard operating profiles, i.e. the Landing and Take-Off (LTO) cycle that considers taxiing, takeoff, climb, cruise, descent, and landing. Brokers use these values so that customers – often charter companies – can compare the fuel efficiency of different aircraft models. As fuel is one of the major operational cost factors, reliable fuel economy values have relevance for purchase decisions. Ranges provide an indication of the relevance of other factors. Over the sample of the 18 aircraft models we find a variation in fuel consumption values of 10.1%, calculated as the standard deviation from the average consumption values available at https://private-jets.fra1.digitaloceanspaces.com/model/db/data.csv."

• Table 1: Uncertainties
If the authors are including PIA (~1%) of aircraft as a potential cause for the underestimation of emissions, the question naturally arises why they did not consider two additional sources of uncertainty potentially leading to overestimation of emissions: First, the use of private aircraft by air ambulance services or for governmentoperated public-interest missions. Operations of this nature are likely to exceed 1% of private air traOic emissions. Second, the present and future use of sustainable aviation fuel (SAF) by operators of private aircraft. After all, the Honeywell report the authors cite in their manuscript already states that "12% of respondents are already using sustainable aviation fuel (SAF) blends to power their aircraft (…)". With life-cycle emissions of established SAF processes (HEFA processing, as performed for the Lufthansa group) ~80% lower than for fossil-derived jet fuel, this is likely to exceed 1% of private air traOic emissions – especially in light of the ReFuelEU legislation already in

place.
As a note, the link to the Honeywell report has changed since the authors included in in their references (a dash has been introduced, breaking the link currently provided in the manuscript):
https://aerospace.honeywell.com/content/dam/aerobt/en/documents/landingpages/brochures/2023_BusinessAviationReport.pdf
We agree that some private aircraft may be used for ambulance or government services. We have made a note on this in the uncertainties section, adding a row to the table, but we do not think it is possible to speculate on the extent of such services.
As for biofuels, it is unclear what a stated claim of "12% of respondents already using SAF" may imply. Is this a reliable estimate? Which share of fuels is replaced? The latter will ultimately depends on fuel providers, who may not have biofuel quotas that can be easily requested by customers. For 1% of private aviation emissions to be "carbon neutral", as the reviewer suggests, the 12% of respondents would have to roughly use a 10% biofuel quota that is at the upper end of lifecycle CO_2 avoidance. This seems unlikely. We consequently believe that the error is <1%, which we have included in the table. Please also note that the amount of biofuels available in the EU is already lower than legislated quotas and fuel providers in the EU pay fines for this reason (a cost lower than the cost of biofuels). It is also evident that there will be no syn-fuel (PtL) production at the scale necessary to meet ReFuel mandates, as the technology is not working and even if it worked could not be upscaled at the necessary speed to meet 2030 quotas. Hence, the future potential of SAF, including synfuels, is highly uncertain. The link has been replaced.

Development of maps
In my last review I mentioned:
"However, the authors never disclose the projection they use in their maps. The absence of the poles (the South Pole, at the very least) suggests their projection is a Mercator-like projection."
Based on this comment, the authors have now added the description:
"Maps visualize air transport based on the geographic coordinate system WGS84 (World Geodetic System 1984) that defines latitude, longitude, and altitude, and using a Mercator projection."
While this clarification is appreciated, a closer inspection of the distortion towards the poles seems to indicate that the employed projection is not in fact Mercator(-like), but more likely Robinson(-like) (with its "bent" lines of longitude, see for instance the shape of Greenland or the Canadian Arctic island). I would greatly appreciate clarification on this issue.
I would like to add that I my previous comment did not mean to suggest the projection be mentioned explicitly. However, now that the authors have added it to the manuscript, they should make sure they do not mis-represent this choice. Even if they chose to remove it in the next revision, I am now interested in clarification of the chosen projection.
We have removed the projection type, which was provided by the graphic designer.

In my last review I further mentioned:
"'It needs to be considered that any two-dimensional map introduces visual distortion, as the length of lines indicating flight distances is not proportional to actual distances.' – This sentence is simply nonsensical."
Based on this comment, the authors have now added the description:
"The projection distorts distance by increasingly stretching distances between points as they move away from the equator towards the poles, leading to distance exaggeration of high-latitude regions."
While this clarification is appreciated, it completely misses my original point of criticism. I will try to be clearer in this review. The authors state:
"(…) data for departure and arrival points representing great circle distances, i.e. the shortest path between two points on the surface of a sphere."
When the authors describe routes, they talk about great circle distances – but their maps DO NOT show great circle distances. This is because their mapping software – in the configuration used – was seemingly unable to plot those correctly on the projection they have chosen. The following images illustrate my point:
Here, as an example, I have chosen to highlight a route which is visible in "Figure 3: Company flight patterns, 2019-2023": Seattle to Keflavik. On the left, I have highlighted the route as it appears in the figure. On the right is the route as it SHOULD appear, if it is plotted according to the great circle distance between the two airports.
The authors must either convincingly motivate their choice of "straight lines on a Mercator (or Robinson?) projection map" (which ARE NOT the shortest distances

between two points), or simply re-plot the maps – which I request they do! After all, the authors in other parts of the manuscript refer specifically to geographic areas aOected by flight patterns:
"(…) making PA emissions specifically relevant in the highly frequented North Atlantic"
And this alone requires the actual great-circle distances being plotted – not the straight lines they have plotted thus far.

We apologize for the misunderstanding. We wrote: "Maps are generated based on ADS-B transponder data for departure and arrival points representing great circle distances, i.e. the shortest path between two points on the surface of a sphere." This was meant to be an explanation for the *creation* of the maps, i.e. referring to the input to the software, but it was not to imply that this is what maps show. The following sentence in the section was meant to clarify this: "The projection distorts distance by increasingly stretching distances between points as they move away from the equator towards the poles, leading to visual distance exaggeration of high-latitude regions."
We have now removed reference to great circles. The sentence reads:
"Maps are generated based on ADS-B transponder data for departure and arrival points. The projection distorts distance by increasingly stretching distances between points as they move away from the equator towards the poles, leading to visual distance exaggeration of high-latitude regions."
Maps serve as illustrations. We have used different formats and wish to stay with the ones used for reasons of legibility. We have removed reference to the North Atlantic flight corridor.

Response to reviewers: COMMSENV-24-1205B

Reviewer #2 (Remarks to the Author):

I appreciate the patience of the authors and the diligence with which they have gone through my comments. I believe that their last revision has - again - greatly improved the clarity of their manuscript. After my last point below is addressed, I will be happy to recommend their article for publication without further changes:

The authors in response to my own last comment about their maps mention that "Maps serve as illustrations." This, as they would surely agree, is a truism that has no bearing on my comment. Naturally maps serve an illustrative purpose.

The real question is about the distortion that maps introduce. It might well be that maps greatly distort reality in order to better convey a specific message. Subway maps are perhaps the most well-known and well-motivated such example. However, here the authors have no reason NOT to CORRECTLY render great-circle distances on a map that is clearly using an isogonal projection.

Since the authors are submitting to Nature Comms. Earth and Environment, a reasonable level of accuracy on maps is to be expected of all submissions. I must insist they provide a map which CORRECTLY renders great circle distances. Foruntately, a master's students with basic knowledge of Python-based plotting libraries such as Plotly (helpfully suggested by Reviewer #4) will be able to re-render the entire set of maps in a single afternoon.

All maps have been redesigned rendering great circle distances, as demanded by the reviewer.