nature portfolio

Peer Review File

Drivers of global tourism carbon emissions

Corresponding Author: Dr Ya-Yen Sun

This file contains all reviewer reports 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:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
I applaud this highly ambitious and comprehensive work, which has the potential to set a new standard for modelling the global impact of tourism in terms of greenhouse gas emissions. Using the GLORIA database allows a much more profound understanding than that achieved by previous papers. However, the authors should explain their methodology in further detail, especially how they separated and carried out the resident-based and destination-based analysis. In addition, it is crucial that they acknowledge and discuss the limitations and potential inaccuracies of global modelling of carbon emissions in a specific sector, related to the difficulty of attributing emissions to tourism and other sectors (how they dealt with system boundaries!), the difficulty to estimate emissions from aviation, data inaccuracies, etc. Also, they do not clearly state why the analysis of the paper, submitted in 2024, stops in 2019 or 2020 (the text is inconsistent regarding the study's time frame). The paper is well-written, but the supplementary files require language editing.

Reviewer #2

(Remarks to the Author)
Please see attached document for my comments; thank you in advance for addressing them.

Reviewer #3

(Remarks to the Author)
1. The Introduction fails to motivate the study. In the present form, it resembles a mini-review of literature, rather than discussing any policy-level problem. Why this study is necessary? What policy-level problem is this study addressing? How is the study expected to provide any solution to that problem? How does the choice of sample complement that problem? Are the results and policies generalizable? The introduction is silent in all these aspects. The mere choice of new variables, new methods, or a new context is not a contribution of a study.

Try to find out the policy-level problem persisting in the chosen countries from the third-party research reports, as academic literature will not be able to provide you with the specific policy issue..

2. What is the aim of the review of literature? The authors have merely listed out the studies without even creating a debate among them. The research gap cannot be substantiated without that debate and thoughtful contradictions.
4. The authors can provide more recent references
https://doi.org/10.1016/j.gr.2023.03.017
https://doi.org/10.1007/s11356-022-23044-2
https://doi.org/10.1016/j.renene.2022.12.085
https://doi.org/10.1016/j.jenvman.2023.119679
https://doi.org/10.1016/j.resourpol.2022.102848
https://doi.org/10.1016/j.resourpol.2022.103091
https://doi.org/10.1016/j.resourpol.2023.103547
https://doi.org/10.1016/j.gr.2023.03.017
3. How did the authors derive the empirical model? There should be a thorough theoretical underpinning behind the model. This section should be based on the authors' logic, and no citation/reference should appear here. The empirical model will

follow this section.

4. Authors have merely reported the results without even discussing the economic intuitions behind the results. Are these results supporting or refuting the existing policies in the chosen context? Are the results directed toward any new policy initiatives? The discussion of results should open up the threads of policy discussion, which is entirely absent in this case. A mere comparison of the results with the literature doesn't ensure the novelty of the results unless they give out something new on the theory/policy front.

5. Conclusion reiterates the results, which is entirely undesirable. The authors should summarize the results within a maximum of 3 sentences. Moreover, the policies are completely vague, and it seems that the authors already had them in mind before starting the paper. The policies should be directly derived from the discussion of the results and should not go beyond the results.

6. The language used in the paper is way below the publishable level

Reviewer #4

(Remarks to the Author)
This is a sound piece of research that answers the interesting question, how the world's tourism sector and it's carbon emissions rebounded after the pandemic. The methodology and utilised data bases are adequate and the completed work supports the conclusions.
Working and climate mitigation and adaptation research myself, I would, as probably many other readers also, like to see a link between the issue of the climate impact of tourism to the issue of climate impact on tourism. This expectation is also founded in many regulatory settings to inform investors in any industry, also known as the double materiality in CSRD e.g. ("outside in" and "inside out"). Of course, you cannot add an entire analysis on that, but remarking that tourism is also a very weather/climate dependent industry clearly is missing. You could refer e.g. to https://www.nature.com/articles/s41558-023-01759-5
or other recent papers in the field, in this case covering the special case of winter tourism, where the impact from global warming on snow scarcity risk is evident. But there is also a vast literature on how different climatic conditions will alter the regional composition of overnight stays. This could be mentioned in the introduction, or, more demanding, it of course would also be interesting to get an estimate of the relative share of emissions of different tourism types (Beach tourism, Ski tourism etc.)
You mention national assessments of carbon intensities, you might want to add Austria
https://doi.org/10.1016/j.jort.2020.100331

I recommend that this paper be published, maybe with these minor ammendments to include links to an interesting different strand of tourism/climate literature.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The authors have made a considerable effort to enhance the manuscript. They have adequately addressed my comments and, as far as I can judge, those of the other reviewers. Therefore, I recommend the publication of the manuscript.

(Remarks on code availability)

Reviewer #2

(Remarks to the Author)
I appreciate that the authors have made sincere efforts to address my comments. Unfortunately, additional important issues have arisen, and the manuscript is not ready for publication without significant additional revision.

1) Thank you for revising the description of the methods for estimating tourism expenditure.
However, the revised description is concise (I assume to stay within word limits), but it is too concise to the point that it would still be difficult to for other researchers to replicate.
Therefore, please provide a clear, expanded description of the steps in the SI and consider including illustrative diagrams, tables, and/or spreadsheets. For instance, which 32 sectors were chosen? For comparison with other works, the description of the development of just e.g. the labor accounts for the Exiobase MRIO were 10 pages long (Simas, M., K. Stadler, and R. Wood. 2018. EXIOBASE 3: SI_labor Supporting Information for labor accounts. Journal of Industrial Ecology: 10. DOI: 10.1111/jiec.12715)

2-4)Thank you for addressing my comments regarding current versus constant dollars. There are remaining issues regarding

the prices:
2) Regarding the statement: "To account for inflation over time, constant-price tourism expenditure (base year 2019) was computed for the periods of 2009-2020 using the USA Consumer Price Index, obtained from the World Bank."
2a) Why was base year 2019 chosen here, not 2009 as elsewhere?
2b) Why was the USA Consumer Price Index used to represent global constant prices here, instead of more globally-appropriate metrics such as Purchasing Power Parity (previously suggested)?
2c) Was the USA Consumer Price Index used throughout the analysis? The approach is not stated elsewhere in the manuscript.

3) There are still some statements which are ambiguous regarding current and constant dollars. Below are some instances, please check throughout the manuscript for others:
3a) The paragraph beginning "The COVID-19 pandemic is the only event that significantly reduced tourism's carbon footprint" has ambiguous references, and the years are being referred to for the changes are unclear.
3b) Is this sentence comparing kg CO2-e per US current dollars? "The sector's carbon intensity improved from 1.03 to 0.92 kg CO2-e per US$". Note that in the US, there was a 6% rate of inflation from 2019 to 2021, which would affect this improvement if current dollars are used.

4) Minor point: Most values were listed as 2009 constant dollars, which is an improvement. It's acceptable, but somewhat of an odd choice, as readers can better relate to more recent prices.

5-6) IMPORTANT - thank you for addressing my point about inclusion of non-CO2 forcing from aviation. However, in making the methods and intermediate results more transparent in Supplementary Information 2, other issues are raised:

5) Estimates of climate impact of aviation seem very high.
Supplementary Information 2 states: "tourism air transport contributed 1.1 Gt CO2 in 2019" and "The radiative forcing from non-CO2 is equivalent to 3.4 Gt CO2-e".

Note that in the SI as well as Table 5 of Lee et al (2021), the 2018 global civil aviation emissions in terms of GWP100 are estimated to be:
CO2: 1.033 Gt CO2e
non-CO2: 0.764 Gt CO2e
Total: 1.797 Gt CO2e

The 2019 CO2 estimate for aviation tourism in this paper (1.1 Gt CO2), therefore, is greater than the total global CO2 estimate for the year 2018 for all civil aviation (1.033 Gt CO2).

Further, the estimate of 3.4 Gt CO2e is very inaccurate, in comparison with the estimated 0.764 Gt CO2e. This is due to the approach of misconstruing 2.06 times the radiative forcing as 2.06 times the GWP100. Each non-CO2 forcer has a different lifespan and radiative efficiency; the GWP100 scaling across these forcers is not linearly proportional.

6) Greater data transparency is needed.
6a) Since the transparent nature of the data underlying the aviation calculations raised questions, it occurs to me that more transparency is needed for underlying data and results throughout the study, which would enable other scholars to compare with your estimates. Doing so will offer more credibility to your analysis and reduce doubts.

6b) Relatedly, while the drivers of global tourism impact are assessed via SDA in this study, a thorough breakdown of the contribution to the impact are not presented in the text or SI; this hampers readers' ability to understand which aspects of tourism are causing the impacts and make comparisons with other works that may study specific aspects of tourism.

Please note that I do appreciate that statements such as this one begin to address this, but the results are currently far too aggregated: "This consumption is associated with a tourism carbon footprint of 5.3 Gt CO2-e in 2019, including direct emissions (2.1 Gt) from tourism businesses, indirect emissions (2.2 Gt) from suppliers, and emissions from private vehicle use (0.9 Gt CO2-e)."

There are many categories of impact assessed which sum to the total, and these granular results should be made explicit. It should be straightforward to create tables and figures which display this information. (See for instance Figure 2 in: Lenzen, M. et al. 2021. Implementing the material footprint to measure progress towards Sustainable Development Goals 8 and 12. Nature Sustainability: 1–10).

Smaller comments:

Please check for typos:
"structure decomposition analysis" -> "Structural decomposition analysis"
"GLRIA" -> "GLORIA"

(Remarks on code availability)
Limited code and associated files are provided, enough to remake the figures in the manuscript.

There is not enough code to reproduce the results. They are not expected to provide all the databases (eg. GLORIA etc.), but there should be code for how they compiled the tourism data and ran the model.

Version 2:

Reviewer comments:

Reviewer #2

(Remarks to the Author)
Thanks to the authors for thoroughly addressing my comments; I feel that the manuscript is now ready for publication.

The additional supplementary information are especially helpful. Also, I apologize for not acknowledging the pie charts included in the supplemental information from the prior revision.

Regarding my 5th comment on the climate impact of aviation and non-CO2 climate forcers, while I'm glad the incorrect calculation was removed, please note that it is possible to convert short-lived climate forcers into GWP100 (or GWP of any time horizon) as was done in the SI of Lee et al. 2021, it's just that radiative forcing of non-CO2 forcers are not linearly proportional to GWP. See for instance:

Fuglestvedt, J.S., K.P. Shine, T. Berntsen, J. Cook, D.S. Lee, A. Stenke, R.B. Skeie, G.J.M. Velders, and I.A. Waitz. 2010. Transport impacts on atmosphere and climate: Metrics. Atmospheric Environment 44(37). Transport Impacts on Atmosphere and Climate: The ATTICA Assessment Report: 4648–4677.

Borella, A., O. Boucher, K.P. Shine, M. Stettler, K. Tanaka, R. Teoh, and N. Bellouin. 2024. The importance of an informed choice of CO2-equivalence metrics for contrail avoidance. Atmospheric Chemistry and Physics 24(16): 9401–9417.

(Remarks on code availability)
It would be preferable to host the code e.g. in Github rather than make them available upon request.

Dear Editor and four reviewers,

We would like to express our great appreciation for the detailed and constructive comments you have provided. These remarks allow us to expand and reflect on perspectives that are critical to this study. Major changes to the revised manuscript include:

- **Comparison of results based on constant-price tourism expenditure**: We re-calculate tourism expenditures ($), intensities (kg/$), and the decomposition analysis based on the constant price tourism expenditure (base year 2009).
- **Inclusion of the contrail cirrus impacts from aviation**: The non-CO_2 radiative forcing (RF) of aviation emissions—including O3, H_2O, contrails, SO_4, soot, and induced cirrus—is approximated and included in the results. This assists the study in presenting a more comprehensive picture of the climate impact of tourism consumption.
- **Provision of Monte Carlo simulation to understand the sensitivity of the emissions results**: Monte Carlo simulation is implemented to provide the 99% confidence level of global tourism emissions results.
- **Incorporation of new discussions on tourism growth threshold and the climate impact change on tourism demand**: We expanded the Conclusion section to elaborate on our view of what constitutes a fair and just design of a tourism growth threshold and to highlight that tourism emissions may undermine the sector's own sustainable development due to intensified climate impact in altering regional tourism demand.
- **Expansion of Method and Supplementary Information sections**: Detailed information is added to address queries regarding the analytical framework, data, method assumptions, and uncertainties.

You can find below our detailed responses (marked in blue) and the new text added to the manuscript (marked in green). We hope you find that these changes adequately address your comments. Thank you again for providing us with high-quality feedback to improve this manuscript.

Reviewer #1

I applaud this highly ambitious and comprehensive work, which has the potential to set a new standard for modelling the global impact of tourism in terms of greenhouse gas emissions. Using the GLORIA database allows a much more profound understanding than that achieved by previous papers. However, the authors should explain their methodology in further detail, especially how they separated and carried out the resident-based and destination-based analysis. In addition, it is crucial that they acknowledge and discuss the limitations and potential inaccuracies of global modelling of carbon emissions in a specific sector, related to the difficulty of attributing emissions to tourism and other sectors (how they dealt with system boundaries!), the difficulty to estimate emissions from aviation, data inaccuracies, etc. Also, they do not clearly state why the analysis of the paper, submitted in 2024, stops in 2019 or 2020 (the text is inconsistent regarding the study's time frame). The paper is well-written, but the supplementary files require language editing.

Thank you very much for the suggestions. Please find below the information regarding major changes made to the manuscript.

1. We provided detailed information on the definitions of resident-based and destination-based accounting, and the analysis procedure (Supplementary Method Section 1). Resident-based accounting calculates the emissions generated by residents' domestic and outbound travel. Typically, higher-income countries have a larger resident-based footprint. Alternatively, destination-based accounting presents emissions produced to support all tourism activities (domestic and inbound tourism) within a given economic territory. Countries with high destination-based emissions are popular destinations with a high volume of inbound visits. By using both accounting methods, our study showcases the differences in emissions from the consumer versus destination perspective, illustrating the inequality inherent in the global tourism footprint.

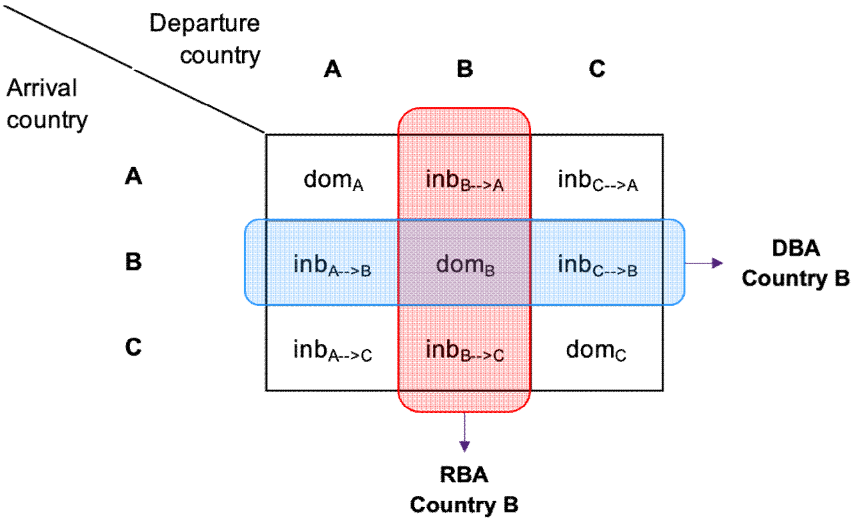
New text:

"**Supplementary Method Section 1**

We employ two accounting perspectives for assessing carbon footprint: the residence-based accounting (RBA) principle and the destination-based accounting (DBA) principle. Distinguishing between these two perspectives is crucial for assigning carbon responsibility, whether from the viewpoint of origin countries (RBA) or destination countries (DBA). This distinction provides essential information to advise mitigation strategies, addressing both travel behaviours at points of departure and technological improvements at destinations.

The graph below illustrates the distinction between the RBA and DBA perspectives. Assume the rows represent arrival countries and the columns represent departure countries. The RBA emissions is obtained by summing the values across the rows for each column. This means RBA emissions equal the emissions of domestic tourism plus the emissions of outbound tourism. In contrast, the DBA perspective is derived by summing the emissions across the columns for each row. This represents the summation of emissions from domestic tourism and inbound tourism.

For example, the RBA carbon footprint of Country B includes the carbon footprint from domestic tourism activities (dom_B) of Country B, and the carbon footprint associated with residents of Country B traveling abroad to Country A ($inb_{B \to A}$) and Country C ($inb_{B \to C}$). The DBA carbon footprint of Country B is the summation of domestic tourism emissions (dom_B) and inbound tourism emissions for tourists from Country A ($inb_{A \to B}$) and Country C ($inb_{C \to B}$) to Country B."



2. We have added a section in Method to discuss the limitations of multi-regional input-output analysis and the system boundary issues in modelling sector-specific emissions.

   New text:

   "Uncertainties

   Two levels of uncertainty arise from modelling global tourism carbon emissions. The first is based on the assumptions used in the MRIO model. This model assumes that emissions coefficients and production structures are stable for a given year, leading to constant multipliers [39]. In other words, economies of scale, short-run price effects, and supply constraints do not affect production coefficients. Under these assumptions, tourism expenditure and emissions are presumed to have a linear relationship. However, this may not accurately reflect the operation of tourism sectors, which often experience strong seasonality, price fluctuations, and varying utilization rates [51,52].

   The second source of uncertainty arises from the data and parameters adopted in the model. The GLORIA database Release 057 serves as the source of GHG emissions data for this study. This data aligns with the EDGAR 7.0 dataset, which provides GHG emissions data updated only through 2019. Consequently, GHG emissions data beyond 2019 are estimated values [53]. This may introduce uncertainty into the 2020 emissions results.

   In addition, GLORIA's updated emissions satellite uses two emissions data sources: the EDGAR database (emissions by activities) and the OECD/Eurostat databases (emissions by industries). Proxies and assumptions were employed to derive the activity-by-industry emissions estimates needed by GLORIA. While the adjustment procedures provide reliable estimates for most sectors, road transport remains ambiguous. The current method can only divide road transport emissions into private vehicles (allocated to households) and allocate the remainder to road transport, postal, and courier services, but not to other sectors [53].

Data quality is crucial for global tourism emissions modelling, with tourism expenditure and input-output tables being the key parameters. We introduce a three-grade system of "very good," "good," and "fair" to represent the reliability of parameters and emissions results in our study.

"Very good" applies to countries that produce their own tourism satellite accounts and national input-output tables. Tourism satellite accounts provide detailed spending breakdowns by sector, allowing for an accurate match of consumption (tourism expenditure) to the MRIO sectors. Additionally, having a national input-output table ensures that local economic information is directly embedded into GLORIA, accurately representing the economic structure of an economy, which is essential for deriving emissions multipliers.

The second grade, "good," includes countries where either the official tourism satellite account or the national input-output table is missing. In such cases, a disaggregation procedure is required to develop a comprehensive tourism spending profile, or trade data is used to estimate the economic multipliers of a given economy.

"Fair" applies to countries lacking both official tourism satellite accounts and input-output tables. In these instances, a higher level of uncertainty in the results is expected, as these two key parameters are based on estimation.

Our model currently includes 65 countries with TSA and IO tables, classified as 'very good,' covering 92% of global tourism expenditure (see Supplementary Method Table 1). The 'good' group comprises 79 countries, while the 'fair' group includes 31 countries—most of which are small countries with a limited scale of tourism activities.

Modelling aviation emissions remains a key challenge in mapping out the global tourism carbon footprint. This study relies on Forward Keys data to assign aviation emissions to individual countries based on global air booking and ticket sales. Our analysis shows that tourism air transport contributed 1.05 Gt CO2 in 2019, including direct emission (passenger transport) and indirect emissions (freight transport due to supply chain activities). While our results are slightly larger than existing references [54,55], it is unclear what is summarized under "aviation" and whether freight aviation emissions are included in these reports.

Overall, the high coverage rate of 92% global tourism expenditure data based on 65 TSA data enables us to model global tourism emissions with a high level of reliability. A Monte Carlo simulation indicated that tourism carbon emissions in 2019 were between 5.1 and 5.5 Gt CO2-e, with a 99% likelihood range (Supplementary Method Section 2)."

3. The database covers tourism expenditure from 2009 to 2020. We have updated the manuscript and appendix throughout to ensure consistency in the timeline. The analysis stops at 2020 because most countries take about three years or longer to publish their latest tourism satellite accounts. At the time of preparing this manuscript, most countries had not yet published their 2021-2023 data. We plan to continue updating this global database annually, allowing us to incorporate the latest tourism satellite accounts and tourism expenditure data as they become available in future years.
4. The supplementary file has been expanded and edited for English.

Reviewer #2 (Remarks to the Author):

Overall: This manuscript addresses the important issue of international tourism impacts by creating a novel tourism satellite extension to the GLORIA MRIO model. There are several key changes required prior to publication though: contrail cirrus impacts from aviation need to be incorporated in the climate impact, the monetary estimates need to be converted into constant currency for comparison over time, the description of the methods needs improvement for reproducibility and the equity discussion needs to reflect the perspectives of low-income countries.

These are very constructive comments and are greatly appreciated. For the revision, we added the contrail cirrus impacts from aviation, calculated all results using constant-price tourism expenditure, and strengthened the equality discussion. The methods section was rewritten to provide further information on the analysis procedure, and a Monte Carlo simulation was added to provide a sensitivity analysis of the emissions results.

Conceptual comments:

Methods, Tourism expenditure: This is a critical step to convey clearly; the description in the second paragraph is too concise and somewhat ambiguous, making the analysis difficult to reproduce. Please rewrite the paragraph to clarify these points.

Paragraphs are rewritten to better explain the method and analysis process.

- You refer to “the aggregated data” and “total tourism expenditure”, but it’s not obvious which datasets (UNWTO and/or WTTC) that refers to.

  For the 110 countries that do not have a tourism satellite account, inbound tourism expenditure is sourced from the UNWTO, and domestic tourism expenditure is provided by the WTTC. In this manuscript, the aggregated data (or total tourism expenditure) refers to the national tourism expenditure for each of these 110 countries.

- Also, is this data available at the country level or global level? Relatedly, is household consumption enabling disaggregation into sectors or enabling the disaggregation of the global RoW expenditures across countries? If the former, then presumably each sector’s share of the total household consumption is used to disaggregate tourism expenditure, so it’s not obvious as described why *economy-wide* economic downturns during COVID would influence those shares (unless the data reveals that downturns affected consumption of various sectors unequally).

  Tourism expenditure data is available at the country level. To disaggregate tourism expenditure into sectors, the following procedure is used. We first choose 32 goods and services (11 groups) in GLORIA that tourists may purchase. Domestic household and government consumption data across these 32 goods and services are then used to disaggregate domestic tourism expenditure into sectors. Total household and government consumption (domestic + exports) across these 32 goods and services is chosen to disaggregate inbound tourism expenditure—this proxy considers export values consumed by overseas households, in this case, inbound tourists.

During the economy-wide downturns during COVID-19, the shares of these 32 goods and services fluctuated, partly due to changing tourism patterns. For example, the accommodation share was reduced during COVID-19 because domestic tourism day trips replaced inbound overnight trips.

- Further, if TSA-based average shares (global? regional?) are used for transportation expenditures, are the transportation sectors excluded from the disaggregation step using household consumption?

  We used household consumption data (described above) to allocate a proportion of tourism expenditure to transport sectors.

- Lastly, do you model the transportation expense differently for inbound vs domestic tourism, assuming that air travel is more prevalent for transnational tourism? How does your description of transportation expenses here align with your description of transportation emissions in the following section, which uses a different approach?

  Aviation emissions (direct effects) are calculated using the Forward Keys data.

  Two procedures are used for non-aviation transport modelling. First, for countries with TSA data, their transport expenses are fed into GLORIA to calculate related emissions. For countries that do not have TSA data, domestic tourism transport expenses are modelled based on the ratio from the 33 goods and services in the country's "domestic household and government spending." Inbound tourism transport expenses are then modelled based on "total household and government spending (domestic + imports)." This allows different allocation proxies to be adopted for these two visitor segments.

Methods, emissions:

- The GLORIA database Release 057 notes that it aligns its GHG emissions with EDGAR 7.0 (https://edgar.jrc.ec.europa.eu/dataset_ghg70). Some of that data is only updated through 2019, with a "Fast Track" approach used to extend it through 2021. This data limitation should be mentioned since your time series extends through 2020.

  This limitation is mentioned in Method.

- Which GWP time horizon do you adopt?

  100-year time horizons Global Warming Potentials (GWP)

- Lee et al. (2021)1 has shown the substantial climate impact of contrail cirrus from civilian aviation. This is not captured in GLORIA's GHG emissions, and therefore is a missing climate impact. You note that aviation is a major contributor to the tourism footprint, and therefore this is likely a significant omission. There is a growing body of research on contrail cirrus impact estimation, and the IPCC assessment reports discuss it. Further, the Rocky Mountain Institute (RMI) has convened an airline industry task force to tackle contrail cirrus emissions from an operations perspective.

Thank you for this important insight. In Lee et al.'s study, the non-CO2 radiative forcing (RF) of aviation emissions (O3, H2O, contrails, SO4, soot, and induced cirrus) in 2020 is 2.06 times greater than the CO2 RF. As you mentioned, this represents a significant add-on effect on climate warming and cannot be overlooked.

We have calculated the non-CO2 RF and the results are discussed below.

New text:

"**Supplementary Information 2. The non-CO_2 radiative forcing effect of air transport**

The non-CO2 radiative forcing (RF) of aviation [1,2] is not captured in GLORIA's GHG emissions coefficients. Lee et al. [2] calculate non-CO2 radiative forcings (RF) from aviation emissions (O3, H2O, contrails, SO4, soot, and induced cirrus) for the year 2020 at 2.06 times (1.55-3.36, 90% likelihood range) the CO2 RF. To demonstrate and include the magnitude of the impact of non-CO2 in comparison to CO2, we express the RF as a CO2-equivalent approximation.

Our analysis shows that tourism air transport contributed 1.1 Gt CO2 in 2019, or 1.9% of global emissions from long-lived GHG (Supplementary Method Table 5). The radiative forcing from non-CO2 is equivalent to 3.4 Gt CO2-e (2.8~4.9 Gt, 90% likelihood range), or 5.8% of global anthropogenic warming. This increases the overall total contribution of tourism consumption to global warming to 7.5 Gt CO2-e, or 12.7%.

Supplementary Table 1. Air transport emissions and tourism emissions for including non-CO2 radiative forcing.

2019	Low range	Medium range	High range
Air transport emissions if including non-CO_2 RF (Gt CO_2-e)	2.8	3.4	4.9
Total tourism emissions (Gt CO_2-e)	6.9	7.5	9.0
Global GHG (Gt CO_2-e)	59.1	59.1	59.1
Air transport share (%)	4.8%	5.8%	8.2%
Tourism share (%)	11.7%	12.7%	15.2%

- I do appreciate your efforts to use the ForwardKeys database for robustness.

Results:

It does not seem that the dollar values have been adjusted for comparison over time. While the GLORIA MRIO database is indeed in current dollars, that is fine as it does not affect the resulting annual emissions snapshots. Comparing either the tourism expenditures ($) or intensities (kg/$) across years requires conversion into something like constant 2015 US$ or purchaser power parity (ppp) constant 2017 international $. Therefore, any and all statements like "Tourism has outpaced growth of the global economy, rising from US$3.5 trillion in 2009 to US$6.0 trillion in 2019, or an annual expenditure growth rate of 5.5% (SI Figure 1)" or "The sector's carbon intensity improved from 0.88 to 0.80 kg CO2-e per US$" are inaccurate and must by recalculated.

Relatedly, I'm concerned that the per capita tourism expenditure effect included in your SDA is also incorrect.

Thank you for this great insight. We have re-calculated tourism expenditures ($), intensities (kg/$) and the decomposition analysis based on the constant price tourism expenditure (baseline year 2009). Results are presented in both current and constant prices throughout the manuscript.

Discussion and Conclusion:

The discussion of equity neglects the reality that many low-income countries which receive high-income tourists rely on those tourists' spending as a core part of their economy. (It may be possible to demonstrate this with the data assembled). I feel that the policy suggestions offered are too simplistic for the complex situation. Please refer to appeals made by stakeholders and leaders from low-income countries themselves on these issues. Many such countries are strong advocates of limiting global GHG emissions during international negotiations, but may have more nuanced opinions regarding international tourism policies.

We agree and appreciate your observations. We do not support a simple universal reduction of tourism volume across countries (e.g., all countries cut back their tourism demand by 5%) as this procedure does not represent a fair and just mitigation approach.

The IPCC (2014) suggested that a "fair contribution" in emissions mitigation needs to acknowledge four components: equality, responsibility, capability, and cost-effectiveness. Such a process considers cumulative emissions produced, the cost and capability to support technology uptake, and the responsibility of high-income countries to support other developing countries.

Our study shows that tourism emissions are largely emitted by high-income countries (the top twenty countries account for 75% of global tourism emissions) and to service high-income travellers. Because of this carbon inequality, we support the view that volume control in tourism needs to consider historical and cumulative tourism emissions, the capacity of individual countries, and the responsibility to support low-income and small island destinations. As you mentioned, this is a complex process, and having a consensus on what constitutes a "fair contribution" to reduce tourism emissions will be the starting point for an effective tourism mitigation scheme—this is reflected in our concluding statement. We have included this viewpoint in the discussion.

IPCC. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge, United Kingdom and New York, NY, USA., 2014).

New text:

"Accelerating tourism demand growth clearly presents an impossible emissions challenge in the absence of much greater technology and supply chain efficiencies. This echoes the degrowth research findings that technology improvements that could cancel out demand growth would be extremely unrealistic 30. Defining 'tourism volume thresholds' to manage demand growth is ultimately required to curb rising tourism emissions.

A simple universal reduction of tourism volume across countries (e.g., all countries reduce their tourism demand by 5%) however is not an ideal approach as this procedure does not represent a fair and just mitigation approach. The IPCC 31 suggests that a "fair contribution" in emissions mitigation needs to acknowledge four components: equality, responsibility, capability, and cost-effectiveness. Based on this, we support the view that tourism demand volume controls must consider historical and cumulative tourism emissions, while also being cognizant of the varied financial and technical capacities of individual countries to mitigate, and responsibilities to support low-income and small island economies."

Last paragraph

"Our findings provide concrete evidence that focusing alone on technology and efficiency gains is insufficient for achieving net-zero milestones. Strong measures to reduce travel demand are urgently required. The urgency of such measures is particularly acute among high-emitting countries and in relation to long-haul air travel. The definition and implementation of tourism volume thresholds will be inevitable under the current emissions trajectory if tourism is to be aligned with global net-zero goals".

Smaller comments:

Introduction:

1st paragraph: The timeframe associated with the pre-COVID global tourism statistics is ambiguous, and a scholarly or governmental source would be preferable to an industry association (WTTC).

We have inserted the year "2019" to the sentence and replace the WTTC source with the UN World Tourism Organization reference for that sentence.

4th paragraph: Please improve the punctuation and structure of the sentence listing the five drivers. Also, please emphasize the research questions by moving to the top of the paragraph.

The paragraph is rewritten. Research questions are now placed on the top of the paragraph, followed by the introduction of five drivers.

The last paragraph mentions "tourism consumption profiles of 114 countries", but carbon footprints are estimated for 174 countries. Is 114 is a typo?

We continue to update tourism satellite account and tourism expenditure data during the review period. This allows us to include new countries with recently published tourism satellite accounts and to reflect changes in tourism expenditure updated by individual statistical offices in the past few months. Currently, the model covers 65 countries with tourism satellite accounts and 110 countries with general tourism expenditure data. In total, the model covers tourism carbon emissions from 175 countries. The numbers have been updated in the manuscript.

Please mention ICAO CORSIA, as it is the official mechanism to reduce the emissions from international flights.

CORSIA is mentioned in the introduction.

Methods, Tourism expenditure: The grammar in first paragraph needs improvement. Also, it states TSAs are available for 60 countries, whereas in data availability section it states 61 countries.
Sorry about the typo. Currently, we have 65 countries with TSA data. We have updated the number of countries in the manuscript and also rewritten the first paragraph.

Reviewer #3 (Remarks to the Author):

The Introduction fails to motivate the study. In the present form, it resembles a mini-review of literature, rather than discussing any policy-level problem. Why this study is necessary? What policy-level problem is this study addressing? How is the study expected to provide any solution to that problem? How does the choice of sample complement that problem? Are the results and policies generalizable? The introduction is silent in all these aspects. The mere choice of new variables, new methods, or a new context is not a contribution of a study.

The study aims to tackle a critical policy challenge: managing the rapid growth of tourism-related carbon emissions. Tourism is a major economic sector, contributing 10% of global GDP and employment. It consumes substantial energy to meet the demands of over 20 billion personal trips annually. Despite international pledges for net-zero emissions by 2050 (supported by organizations such as the UN World Tourism Organization, UN Environmental Programme, World Travel and Tourism Council, and International Civil Aviation Organization), both public and private sectors struggle to mitigate these emissions, as evidenced in numerous studies. The reasons why we consider this study to be necessary are outlined in the Introduction.

Try to find out the policy-level problem persisting in the chosen countries from the third-party research reports, as academic literature will not be able to provide you with the specific policy issue.

We highlight the significant challenge posed by the tension between robust tourism demand and rising emissions trajectories. We propose that the first step to break this deadlock is to understand the drivers and inhibitors of tourism emissions and map out changes in emissions across countries and regions. Our findings provide crucial evidence to guide future policy interventions. These points are outlined in the Introduction.

What is the aim of the review of literature? The authors have merely listed out the studies without even creating a debate among them. The research gap cannot be substantiated without that debate and thoughtful contradictions.
See responses immediately above.

The authors can provide more recent references
https://doi.org/10.1016/j.gr.2023.03.017
https://doi.org/10.1007/s11356-022-23044-2
https://doi.org/10.1016/j.renene.2022.12.085
https://doi.org/10.1016/j.jenvman.2023.119679
https://doi.org/10.1016/j.resourpol.2022.102848
https://doi.org/10.1016/j.resourpol.2022.103091
https://doi.org/10.1016/j.resourpol.2023.103547
https://doi.org/10.1016/j.gr.2023.03.017

We use the most recent references available.

How did the authors derive the empirical model? There should be a thorough theoretical underpinning behind the model. This section should be based on the authors' logic, and no citation/reference should appear here. The empirical model will follow this section.

This paper identifies and analyses five key drivers: two focusing on demand and three on technology. This analysis framework responds to statements from the IPCC that behavioural changes are critically needed *alongside* technological advancements for meaningful and profound decarbonization. Any analysis of emissions must therefore consider consumption patterns and lifestyle choices. In this model, we examine average consumption per trip and population growth, illustrating how these demand factors influence tourism emissions. This study provides the first global evidence on how human travel demand contributes to global greenhouse gas emissions over time.

Authors have merely reported the results without even discussing the economic intuitions behind the results. Are these results supporting or refuting the existing policies in the chosen context? Are the results directed toward any new policy initiatives? The discussion of results should open up the threads of policy discussion, which is entirely absent in this case. A mere comparison of the results with the literature doesn't ensure the novelty of the results unless they give out something new on the theory/policy front.

International tourism bodies like UNWTO, WTTC, and ICAO emphasize leveraging technology as the primary means to achieve net-zero goals in tourism. Our study provides comprehensive evidence that technology alone cannot achieve these milestones. In addition to technological advancements, proactive strategies are needed to address the sustained high growth in unsustainable tourism demand. We propose setting tourism growth thresholds by country to curb unchecked tourism development, particularly in the top 20 countries with by far the highest tourism emissions.

Conclusion reiterates the results, which is entirely undesirable. The authors should summarize the results within a maximum of 3 sentences. Moreover, the policies are completely vague, and it seems that the authors already had them in mind before starting the paper. The policies should be directly derived from the discussion of the results and should not go beyond the results.

The results directly inform the conclusions drawn. The criteria for defining demand growth thresholds have not been established in academic literature or policy. Nonetheless our results confirm beyond doubt that such thresholds – as challenging as they are - represent a critical step toward aligning tourism emissions with global net-zero ambitions. Comprehensively addressing complex global or national policy implications lies beyond the scope of this study. Our intention is to present global tourism emissions patterns as the essential foundation required to inform urgent policy development.

The language used in the paper is way below the publishable level

The revised paper has been comprehensively edited prior to resubmission. We made several editorial corrections but found nothing to suggest that the submission copy of the paper was below publishable level.

Reviewer #4 (Remarks to the Author):

This is a sound piece of research that answers the interesting question, how the world's tourism sector and it's carbon emissions rebounded after the pandemic. The methodology and utilised data bases are adequate and the completed work supports the conclusions.

Working and climate mitigation and adaptation research myself, I would, as probably many other readers also, like to see a link between the issue of the climate impact of tourism to the issue of climate impact on tourism. This expectation is also founded in many regulatory settings to inform investors in any industry, also known as the double materiality in CSRD e.g. ("outside in" and "inside out"). Of course, you cannot add an entire analysis on that, but remarking that tourism is also a very weather/climate dependent industry clearly is missing. You could refer e.g. to https://www.nature.com/articles/s41558-023-01759-5
or other recent papers in the field, in this case covering the special case of winter tourism, where the impact from global warming on snow scarcity risk is evident.

But there is also a vast literature on how different climatic conditions will alter the regional composition of overnight stays. This could be mentioned in the introduction, or, more demanding, it of course would also be interesting to get an estimate of the relative share of emissions of different tourism types (Beach tourism, Ski tourism etc.)

Thank you for this great insight and your suggestions. We like the idea of presenting emissions results by different activity types (beach tourism, ski tourism, etc.). However, the current tourism satellite accounts and general tourism expenditure data do not provide detailed spending profiles by segments. This prevents us from modelling emissions by activity type.

Based on your suggestion, we have added new discussions regarding the climate impact on tourism. We first emphasize how climate change has impacted tourism demand, using the examples of ski tourism and fire exposure risk. We then discuss the various climate change vulnerabilities faced by individual countries, with poorer countries being affected the most. Linking back to the carbon inequality pattern observed in this study, it is clear that tourism emissions are largely produced by high-income countries and serve high-income travellers. At the same time, tourism consumption contributes to climate change, further devastating poor regions by inhibiting tourism demand. The uncapped tourism emissions, in fact, contribute to the vicious cycle of climate injustice.

New text:

"Sustained high growth emissions undermine the future viability of global tourism. Destinations are witnessing the accelerating impact of climate change which is altering patterns of tourism demand. Reduced snow volume at ski resorts, increasing fire risks and heatwave exposure are vivid examples of these climate impacts 35,36. Global destinations face varying levels of climate change vulnerability. Africa, the Middle East, South Asia, and Small Island Developing States are among the most affected, with projections indicating tourism demand will be negatively influenced due to climate change 37,38. Given that tourism emissions are primarily emitted by high-income countries and that their climate impact contributes to suppressing tourism demand among poorer regions, curbing tourism emissions is therefore not only essential for ensuring the future viability of global tourism, but also for addressing deeply embedded climate injustices.”

You mention national assessments of carbon intensities, you might want to add Austria https://doi.org/10.1016/j.jort.2020.100331

The example of Austria is added to the manuscript.

I recommend that this paper be published, maybe with these minor ammendments to include links to an interesting different strand of tourism/climate literature.

Dear reviewers,

Thank you very much for your time in reviewing and commenting the revised manuscript. Please find below our detailed responses (marked in blue). We hope you find that these changes adequately address your comments.

Reviewer #1 (Remarks to the Author):
The authors have made a considerable effort to enhance the manuscript. They have adequately addressed my comments and, as far as I can judge, those of the other reviewers. Therefore, I recommend the publication of the manuscript.
Thank you. We appreciate your time in reviewing our revision.

Reviewer #2 (Remarks to the Author):
I appreciate that the authors have made sincere efforts to address my comments. Unfortunately, additional important issues have arisen, and the manuscript is not ready for publication without significant additional revision.

1) Thank you for revising the description of the methods for estimating tourism expenditure. However, the revised description is concise (I assume to stay within word limits), but it is too concise to the point that it would still be difficult to for other researchers to replicate.
Therefore, please provide a clear, expanded description of the steps in the SI and consider including illustrative diagrams, tables, and/or spreadsheets. For instance, which 32 sectors were chosen? For comparison with other works, the description of the development of just e.g. the labor accounts for the Exiobase MRIO were 10 pages long (Simas, M., K. Stadler, and R. Wood. 2018. EXIOBASE 3: SI_labor Supporting Information for labor accounts. Journal of Industrial Ecology: 10. DOI: 10.1111/jiec.12715)

Thank you for your suggestion. Due to the word limit in the main article, we have made every effort to address all comments from the four reviewers in the first round. As mentioned in our previous 'response to reviewer comments' letter, several new paragraphs were added to the main text, leaving limited space for further additions.

To address your comment, we have developed two supplementary files—one for the methodology and another for additional results (Supplementary Information_Method and Supplementary Information_Result). Specifically, we added an extensive section (Supplementary Method 6) that details the process of compiling tourism expenditures across 175 countries and the formula used to allocate and map expenditures to the GLORIA sectors. This section also includes the individual data sources for each of the 62 TSA tables, as well as information for the 32 sectors in the GLORIA database.

2-4)Thank you for addressing my comments regarding current versus constant dollars. There are remaining issues regarding the prices:
2) Regarding the statement: "To account for inflation over time, constant-price tourism expenditure (base year 2019) was computed for the periods of 2009-2020 using the USA Consumer Price Index, obtained from the World Bank."
2a) Why was base year 2019 chosen here, not 2009 as elsewhere?
2b) Why was the USA Consumer Price Index used to represent global constant prices here, instead of more globally-appropriate metrics such as Purchasing Power Parity (previously suggested)?
2c) Was the USA Consumer Price Index used throughout the analysis? The approach is not stated elsewhere in the manuscript.

All spending figures reported in the manuscript are in constant prices (base year 2009), unless specified otherwise. We apologize for the typo in the sentence and have revised the manuscript to ensure this information is clear throughout.

We adopt the following adjustment procedure to convert tourism expenditure from current prices to constant prices: First, tourism expenditure in local currencies is converted to U.S. dollars using the average market exchange rate for each year from 2009 to 2020, and then it is deflated using the U.S. Consumer Price Index.

This "convert-first, then deflate" approach is preferred by most researchers (Lan et al., 2016). The main condition for adopting this procedure is that the sectoral output composition between countries should be similar (Pardey et al., 1992). Tourism satisfies this condition as its production of tourism services mainly consists of transportation, accommodation, food, recreational activities, and retailing. Every destination uses these components and similar production structure to construct "tourism".

From a feasibility perspective, this approach is further supported by the availability of high-quality currency converters and deflators. Exchange rates against a common currency (the U.S. dollar) are available for all countries from 2009 to 2020. The availability of the U.S. Consumer Price Index across 44 categories, including those specific to food away from home, motor fuel, and transport services, allows for sector-specific adjustments. This helps minimize the noise that would occur from applying a single consumer price index across all expenditures. We did not employ the 'deflate-first, then convert' procedure because several countries lack consumer price index data from the World Bank database. The literature suggests that similar results are achieved whether the 'convert-first, then deflate' or 'deflate-first, then convert' approach is used (Fitzsimons et al., 1999).

There are scholarly discussions about which converter to use: market exchange rates or purchasing power parity (PPP). In this paper, we chose market exchange rates for the following reasons:

1. **Tourism expenditure is directly influenced by exchange rates.**
   Exchange rates are a key factor influencing the magnitude of foreign receipts flowing into a destination country via inbound tourism (Shi et al., 2023; Xue et al., 2018). As exchange rates are more volatile than PPP, they capture the reality that international tourists face—when the exchange rate fluctuates, tourists consider how much local currency they can obtain and what to spend given their fixed travel budget. A 5% depreciation of the local currency against the U.S. dollar means inbound tourists will have 5% more local currency to spend in the destination country. Using market exchange rates allows for more accurate comparisons of tourism expenditure over time.

2. **The project focuses on financial flow of tourism expenditure.**
   IMF supports the use of market exchange rates when financial flows are the major subject to be compared (Callen, 2018). In this project, we aim to measure the total tourism expenditure that occurs in a given year based on a common currency. It is not our intent to compare the differences in purchasing power given a fixed income (e.g., US$10,000) across countries. In addition, PPP is estimated using hundreds of items, including housing, construction, medical care, education, goods and services, in which many are tourism irrelevant (OECD-EUROSTAT, 2012). The financial transactions of tourism spending in a common currency are better reflected using market exchange rates than in PPP.

3. **Tourism services and goods are traded internationally.**
   One main utility of PPP is to compare the production and consumption of non-traded goods. Tourism is one of the few exceptions where all its services are traded internationally. For example, hotel room services in Japan can be consumed by visitors from Germany, Canada, and Thailand, meaning that Japan effectively exports hotel services to these countries, similar to how it exports computers, cars, and rice. Because of its traded nature, market exchange rates provide better information on total tourism consumption across countries.

The following text is added to Method.

To account for inflation over time, constant-price tourism expenditure (base year 2009) for the period 2009–2020 was calculated by first converting local currencies to US dollars and then adjusting for inflation using the USA Consumer Price Index across 44 categories, obtained from the US Bureau of Labor Statistics [48].

This “convert-first, then deflate” approach is preferred by most researchers [49]. The main condition for adopting this procedure is that the sectoral output composition between countries should be similar [50]. Tourism satisfies this condition as its production of tourism services mainly consists of transportation, accommodation, food, recreational activities, and retailing. Every destination uses these components and similar production structure to construct “tourism”.

From a feasibility perspective, this approach is further supported by the availability of high-quality currency converters and deflators. Exchange rates against a common currency (the U.S. dollar) are available for all countries from 2009 to 2020. The availability of the U.S. Consumer Price Index across 44 categories, including those specific to food away from home, motor fuel, and transport services, allows for sector-specific adjustments. This helps minimize the noise that would occur from applying a single consumer price index across all expenditures. We did not employ the 'deflate-first, then convert' procedure because several countries lack consumer price index data from the World Bank database. The literature suggests that similar results are achieved whether the 'convert-first, then deflate' or 'deflate-first, then convert' approach is used [51].

3) There are still some statements which are ambiguous regarding current and constant dollars. Below are some instances, please check throughout the manuscript for others:

We have double-checked the main text and added additional wording ('constant price 2009') throughout to ensure clarity.

3a) The paragraph beginning "The COVID-19 pandemic is the only event that significantly reduced tourism’s carbon footprint" has ambiguous references, and the years are being referred to for the changes are unclear.

Thanks for pointing it out. The reference year is year 2009 (Table 1). We have changed the first two sentence to give a better information on the reference year.

“The COVID-19 pandemic is the only event that significantly reduced tourism’s carbon footprint, producing a smaller environmental impact than the base year 2009 (Table 1). In 2020, limitations in international travel and reductions in domestic tourism led to a decline in global tourism emissions from 5.2 Gt in 2019 to 2.2 Gt in one year.”

3b) Is this sentence comparing kg CO2-e per US current dollars? "The sector’s carbon intensity improved from 1.03 to 0.92 kg CO2-e per US$". Note that in the US, there was a 6% rate of inflation from 2019 to 2021, which would affect this improvement if current dollars are used.

The comparison is based on constant dollars (base year 2009) between year 2009 and year 2019.

4) Minor point: Most values were listed as 2009 constant dollars, which is an improvement. It's acceptable, but somewhat of an odd choice, as readers can better relate to more recent prices.

Thank you for the suggestion. We choose 2009 as the base year because it is the starting point of our panel data (2009-2020). It also provides a nice reference point of a decade between 2009-2019 before the COVID-19. We also feel this is a good baseline year as it can be compared and benchmarked against the Lenzen et al. (2018) study who estimated global tourism emission from 2009 to 2013.

5-6) IMPORTANT - thank you for addressing my point about inclusion of non-CO2 forcing from aviation. However, in making the methods and intermediate results more transparent in Supplementary Information 2, other issues are raised:

5) Estimates of climate impact of aviation seem very high.
Supplementary Information 2 states: "tourism air transport contributed 1.1 Gt CO2 in 2019" and "The radiative forcing from non-CO2 is equivalent to 3.4 Gt CO2-e".

Note that in the SI as well as Table 5 of Lee et al (2021), the 2018 global civil aviation emissions in terms of GWP100 are estimated to be:
CO2: 1.033 Gt CO2e
non-CO2: 0.764 Gt CO2e
Total: 1.797 Gt CO2e

The 2019 CO2 estimate for aviation tourism in this paper (1.1 Gt CO2), therefore, is greater than the total global CO2 estimate for the year 2018 for all civil aviation (1.033 Gt CO2).

Further, the estimate of 3.4 Gt CO2e is very inaccurate, in comparison with the estimated 0.764 Gt CO2e. This is due to the approach of misconstruing 2.06 times the radiative forcing as 2.06 times the GWP100. Each non-CO2 forcer has a different lifespan and radiative efficiency; the GWP100 scaling across these forcers is not linearly proportional.

The original comment by the reviewer was this:

c) Lee et al. (2021) has shown the substantial climate impact of contrail cirrus from civilian aviation. This is not captured in GLORIA's GHG emissions, and therefore is a missing climate impact. You note that aviation is a major contributor to the tourism footprint, and therefore this is likely a significant omission. There is a growing body of research on contrail cirrus impact estimation, and the IPCC assessment reports discuss it. Further, the Rocky Mountain Institute (RMI) has convened an airline industry task force to tackle contrail cirrus emissions from an operations perspective.

We interpreted this to mean that we should include non-CO_2 impacts in the calculation, but any such inclusion can only be done by way of approximation, as in particular water and NOx-related warming at flight altitude is short-lived, and not comparable to the long-lived GHG considered in GLORIA. For this reason, we sought to compare the radiative forcing from short-lived emissions to the radiative forcing from CO_2, based on the assessment of effective radiative forcing in Lee et al. (2021).

As the reviewer now highlights, the comparison is ambiguous. For example, GWP is a measure of comparison originally devised for long-lived GHG, which is why Lee et al. (2021) develop radiative forcing and effective radiative forcing as metrics to assess the impact of aviation for the years 2000-2018 as the <u>immediate</u> impact of all emissions on the Earth's energy balance in a given year. They conclude that "For 2018 the net aviation ERF is +100.9 milliwatts (mW) m^{-2} (5–95% likelihood range of (55, 145)) with major contributions from contrail cirrus (57.4 mW m^{-2}), CO_2 (34.3 mW m^{-2}), and NO_x (17.5 mW m^{-2}). Non-CO_2 terms sum to yield a net positive (warming) ERF that accounts for more than half (66%) of the aviation net ERF in 2018."

To adequately assess tourism's impact, CO_2 and non-CO_2 effects would have to be compared on the basis of changes in forcings (mW per m^2). This cannot be done on the basis of GHG assessments as contained in GLORIA, nor can it be done for short-lived emissions from aviation, as forcings depend on flight routes. The impact related to freight also would have to be deducted. We sought to go around the issue by providing an estimate of non-CO_2 effects expressed as CO_2, the metric on which this paper is focused. This indeed can only be an approximation and is prone to misintepretation, also because non-CO_2 warming is then expressed as CO_2-e, which we use to refer to long-lived GHG, and because the non-CO_2 approximation is very large in comparison to the more accurately derived values for other GHG.

Given these complexities, we wish to return to the original version of the paper that avoided these issues that are also highlighted in reviewers' comments. We have for this reason removed the calculations (Supplementary Information 2). In the text, we have reinforced the importance of non-CO_2 warming by adding two references:

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.

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.

6) Greater data transparency is needed.
6a) Since the transparent nature of the data underlying the aviation calculations raised questions, it occurs to me that more transparency is needed for underlying data and results throughout the study, which would enable other scholars to compare with your estimates. Doing so will offer more credibility to your analysis and reduce doubts.

6b) Relatedly, while the drivers of global tourism impact are assessed via SDA in this study, a thorough breakdown of the contribution to the impact are not presented in the text or SI; this hampers readers' ability to understand which aspects of tourism are causing the impacts and make comparisons with other works that may study specific aspects of tourism.

Please note that I do appreciate that statements such as this one begin to address this, but the results are currently far too aggregated: "This consumption is associated with a tourism carbon footprint of 5.3 Gt CO_2-e in 2019, including direct emissions (2.1 Gt) from tourism businesses, indirect emissions (2.2 Gt) from suppliers, and emissions from private vehicle use (0.9 Gt CO_2-e)."

There are many categories of impact assessed which sum to the total, and these granular results should be made explicit. It should be straightforward to create tables and figures which display this information. (See for instance Figure 2 in: Lenzen, M. et al. 2021. Implementing the material footprint to measure progress towards Sustainable Development Goals 8 and 12. Nature Sustainability: 1–10).

This is a good suggestion. In this revision, we have provided additional information on the results, including:

1. Supplementary Information_Result: A supplementary file that includes further details on the results.
2. Source Data: An Excel file containing all data points for each of the four figures in the main text, along with the decomposition results by country.

We have structured the supplementary information in such a way that each table or figure in the main text is supported by multiple supplementary tables/figures, offering detailed information to help readers easily locate relevant data. Please see the table below for an overview of the information presented in the main text and the supplementary files.

Main text	Supplementary Information _ Result
Global tourism expenditure and carbon footprint (Table 1)	▪ SI 1. Tourism expenditure and carbon footprint by sectors ▪ SI 2. Carbon intensity by sectors
DBA and RBA tourism emissions by country (Figure 1)	▪ SI 3. The resident-based accounting emissions for top 20 countries, 2009, 2019, 2020 ▪ SI 4. The destination-based accounting emissions for top 20 countries, 2009, 2019, 2020 ▪ SI 5. Tourism carbon footprint per capita from top 20 countries, 2009, 2019, 2020

Global and country decomposition results (Figures 2 and 3)	▪ Source data: Decomposition results by countries
Per capita emissions by GDP (Figure 4)	▪ SI 6. Outbound travel by country's income status ▪ SI 7. Tourism carbon footprint per capita globally

We note that a detailed breakdown of tourism expenditure and carbon emissions is provided in SI 1. Pie charts are used to compare changes in expenditure and emissions for 2009, 2019, and 2020 by major categories at the global level. This allows individual components to be identified in relation to the totals presented in the main article. Additionally, the breakdown of direct and indirect emissions by sector is provided in SI Table 1.

We agree that identifying drivers through decomposition analysis is a central focus of this paper. In the main article, we presented the global tourism decomposition results in Figure 2, and for the top ten countries in Figure 3. A new table, detailing the decomposition results for individual countries between 2009 and 2019, has been added to the data source file. This table provides information on the drivers and inhibitors of tourism emissions over the past decade at the country level.

Smaller comments:

Please check for typos:
"structure decomposition analysis" -> "Structural decomposition analysis"
"GLRIA" -> "GLORIA"

Thank you and typos are corrected.

Reviewer #2 (Remarks on code availability):

Limited code and associated files are provided, enough to remake the figures in the manuscript. There is not enough code to reproduce the results. They are not expected to provide all the databases (eg. GLORIA etc.), but there should be code for how they compiled the tourism data and ran the model.

For countries that report TSA, tourism data is manually processed and compiled into TSA 39 sector classification system. For those without TSA data, their tourism expenditure (domestic and inbound tourism expenditure) is allocated and mapped to the GLORIDA database using formula detailed in Supplementary Method 6. The code will be provided upon request.

Additional references

Callen, T. (2018). Purchasing Power Parity: Weights Matter. *Finance and Development Magazine*.

Fitzsimons, E., Hogan, V., & Neary, J. (1999). Explaining the Volume of North-South Trade in Ireland: A Gravity Model Approach. *The Economic and Social Review, 36*(4), 381-401.

Lan, J., Malik, A., Lenzen, M., McBain, D., & Kanemoto, K. (2016). A structural decomposition analysis of global energy footprints. *Applied Energy, 163*, 436-451. https://doi.org/10.1016/j.apenergy.2015.10.178

Lenzen, M., Sun, Y.-Y., Faturay, F., Ting, Y.-P., Geschke, A., & Malik, A. (2018). The carbon footprint of global tourism. *Nature Climate Change, 8*(6), 522-528. https://doi.org/https://doi.org/10.1038/s41558-018-0141-x

OECD-EUROSTAT. (2012). *Eurostat-OECD Methodological Manual on Purchasing Power Parities*. Publications Office of the European Union.

Pardey, P. G., Roseboom, J., & Craig, B. J. (1992). A Yardstick for International Comparisons: An Application to National Agricultural Research Expenditures. *Economic Development and Cultural Change, 40*(2), 333-349.

Shi, W., Gong, Y., Wang, L., & Nikolova, N. (2023). Heterogeneity of inbound tourism driven by exchange rate fluctuations: implications for tourism business recovery and resilience in Australia. *Current Issues in Tourism, 26*(3), 450-467. https://doi.org/10.1080/13683500.2021.2023478

Xue, G., Chang, H.-L., & Chi-Wei, S. (2018). Does exchange rate always affect the number of inbound tourists significantly in China? *Theoretical & Applied Economics, 25*(1), 55-72.

Dear reviewer,

Thank you very much for your time in reviewing and commenting the revised manuscript. Please find below our responses (marked in green). We hope you find that these changes adequately address your comments.

Reviewer #2 (Remarks to the Author):

Thanks to the authors for thoroughly addressing my comments; I feel that the manuscript is now ready for publication.

The additional supplementary information are especially helpful. Also, I apologize for not acknowledging the pie charts included in the supplemental information from the prior revision.

Regarding my 5th comment on the climate impact of aviation and non-CO2 climate forcers, while I'm glad the incorrect calculation was removed, please note that it is possible to convert short-lived climate forcers into GWP100 (or GWP of any time horizon) as was done in the SI of Lee et al. 2021, it's just that radiative forcing of non-CO2 forcers are not linearly proportional to GWP. See for instance:

Fuglestvedt, J.S., K.P. Shine, T. Berntsen, J. Cook, D.S. Lee, A. Stenke, R.B. Skeie, G.J.M. Velders, and I.A. Waitz. 2010. Transport impacts on atmosphere and climate: Metrics. Atmospheric Environment 44(37). Transport Impacts on Atmosphere and Climate: The ATTICA Assessment Report: 4648–4677.

Borella, A., O. Boucher, K.P. Shine, M. Stettler, K. Tanaka, R. Teoh, and N. Bellouin. 2024. The importance of an informed choice of CO2-equivalence metrics for contrail avoidance. Atmospheric Chemistry and Physics 24(16): 9401–9417.

We acknowledge the high uncertainties involved in estimating these effects, as highlighted in Borella (2024) and further explained in detail in our previous "Reply to Reviewer Comments" submitted on September 16, 2024. Please allow us to iterate our view on this.

As the reviewer highlights, the calculation is complex and ambiguous. For example, GWP is a measure of comparison originally devised for long-lived GHG, which is why Lee et al. (2021) develop radiative forcing and effective radiative forcing as metrics to assess the impact of aviation for the years 2000-2018 as the immediate impact of all emissions on the Earth's energy balance in a given year. They conclude that "For 2018 the net aviation ERF is +100.9 milliwatts (mW) m^{-2} (5–95% likelihood range of (55, 145)) with major contributions from contrail cirrus (57.4 mW m^{-2}), CO_2 (34.3 mW m^{-2}), and NO_x (17.5 mW m^{-2}). Non-CO_2 terms sum to yield a net positive (warming) ERF that accounts for more than half (66%) of the aviation net ERF in 2018."

To adequately assess tourism's impact, CO_2 and non-CO_2 effects would have to be compared on the basis of changes in forcings (mW per m^2). This cannot be done on the basis of GHG assessments as contained in GLORIA, nor can it be done for short-lived emissions from aviation, as forcings depend on flight routes. The impact related to freight also would have to be deducted. We sought to go around the issue by providing an estimate of non-CO_2 effects expressed as CO_2, the metric on which this paper is focused. This indeed can only be an approximation and is prone to misintepretation, also because non-CO_2 warming is then expressed as CO_2-e, which we use to refer to long-lived GHG, and because the non-CO_2 approximation is very large in comparison to the more accurately derived values for other GHG.

We aim to provide reliable and valid estimates of global tourism carbon emissions for long-lived GHGs over the past decade. We acknowledge the importance of non-CO_2 warming in aviation emissions in the main article, though it is not included in our current estimates.

It would be preferable to host the code e.g. in Github rather than make them available upon request.

The programming code has been made available on GitHub as requested.

Overall:

This manuscript addresses the important issue of international tourism impacts by creating a novel tourism satellite extension to the GLORIA MRIO model. There are several key changes required prior to publication though: contrail cirrus impacts from aviation need to be incorporated in the climate impact, the monetary estimates need to be converted into constant currency for comparison over time, the description of the methods needs improvement for reproducibility and the equity discussion needs to reflect the perspectives of low-income countries.

Conceptual comments:

Methods, Tourism expenditure: This is a critical step to convey clearly; the description in the second paragraph is too concise and somewhat ambiguous, making the analysis difficult to reproduce. Please rewrite the paragraph to clarify these points.

- You refer to “the aggregated data” and “total tourism expenditure”, but it’s not obvious which datasets (UNWTO and/or WTTC) that refers to.
- Also, is this data available at the country level or global level? Relatedly, is household consumption enabling disaggregation into sectors or enabling the disaggregation of the global RoW expenditures across countries? If the former, then presumably each sector’s share of the total household consumption is used to disaggregate tourism expenditure, so it’s not obvious as described why *economy-wide* economic downturns during COVID would influence those shares (unless the data reveals that downturns affected consumption of various sectors unequally).
- Further, if TSA-based average shares (global? regional?) are used for transportation expenditures, are the transportation sectors excluded from the disaggregation step using household consumption?
- Lastly, do you model the transportation expense differently for inbound vs domestic tourism, assuming that air travel is more prevalent for transnational tourism? How does your description of transportation expenses here align with your description of transportation emissions in the following section, which uses a different approach?

Methods, emissions:

a) The GLORIA database Release 057 notes that it aligns its GHG emissions with EDGAR 7.0 (https://edgar.jrc.ec.europa.eu/dataset_ghg70). Some of that data is only updated through 2019, with a “Fast Track” approach used to extend it through 2021. This data limitation should be mentioned since your time series extends through 2020.
b) Which GWP time horizon do you adopt?
c) Lee et al. (2021)[1] has shown the substantial climate impact of contrail cirrus from civilian aviation. This is not captured in GLORIA’s GHG emissions, and therefore is a missing climate impact. You note that aviation is a major contributor to the tourism footprint, and therefore this is likely a significant omission. There is a growing body of research on contrail cirrus impact estimation, and the IPCC assessment reports discuss it. Further, the Rocky Mountain Institute (RMI) has convened an airline industry task force to tackle contrail cirrus emissions from an operations perspective.

---

[1] Lee, D. S., Fahey, D. W., Forster, P. M., Newton, P. J., Wit, R. C. N., Lim, L. L., Owen, B., & Sausen, R. (2009). Aviation and global climate change in the 21st century. Atmospheric Environment, 43(22), 3520–3537. https://doi.org/10.1016/j.atmosenv.2009.04.024

d) I do appreciate your efforts to use the ForwardKeys database for robustness.

Results:

It does not seem that the dollar values have been adjusted for comparison over time. While the GLORIA MRIO database is indeed in current dollars, that is fine as it does not affect the resulting annual emissions snapshots. Comparing either the tourism expenditures ($) or intensities (kg/$) across years requires conversion into something like constant 2015 US$ or purchaser power parity (ppp) constant 2017 international $. Therefore, any and all statements like “Tourism has outpaced growth of the global economy, rising from US$3.5 trillion in 2009 to US$6.0 trillion in 2019, or an annual expenditure growth rate of 5.5% (SI Figure 1)” or “The sector’s carbon intensity improved from 0.88 to 0.80 kg CO2-e per US$” are inaccurate and must by recalculated.

Relatedly, I’m concerned that the per capita tourism expenditure effect included in your SDA is also incorrect.

Discussion and Conclusion:

The discussion of equity neglects the reality that many low-income countries which receive high-income tourists rely on those tourists’ spending as a core part of their economy. (It may be possible to demonstrate this with the data assembled). I feel that the policy suggestions offered are too simplistic for the complex situation. Please refer to appeals made by stakeholders and leaders from low-income countries themselves on these issues. Many such countries are strong advocates of limiting global GHG emissions during international negotiations, but may have more nuanced opinions regarding international tourism policies.

Smaller comments:

Introduction:

1st paragraph: The timeframe associated with the pre-COVID global tourism statistics is ambiguous, and a scholarly or governmental source would be preferable to an industry association (WTTC).

4th paragraph: Please improve the punctuation and structure of the sentence listing the five drivers. Also, please emphasize the research questions by moving to the top of the paragraph.

The last paragraph mentions “tourism consumption profiles of 114 countries”, but carbon footprints are estimated for 174 countries. Is 114 is a typo?

Please mention ICAO CORSIA, as it is the official mechanism to reduce the emissions from international flights.

Methods, Tourism expenditure: The grammar in first paragraph needs improvement. Also, it states TSAs are available for 60 countries, whereas in data availability section it states 61 countries.