nature portfolio

Peer Review File

Climate-optimized flight planning can effectively reduce the environmental footprint of aviation in Europe at low operational costs

Corresponding Author: Dr Abolfazl Simorgh

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:

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Dear Dr Simorgh,

Your manuscript titled "Pathways to Sustainable Aviation: Aligning Flight Plans with Climate Goals" 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.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to
• address these criticisms (that is, either to incorporate the suggestions or provide a compelling argument why the point made by the reviewer is not valid or relevant to the editorial threshold as outlined below)
AND
• meet our editorial thresholds as outlined below,

then we would be happy to look at a revised manuscript.

In the following, we list our minimum requirements for publication

• Provide novel and fully supported insight into the effectiveness of climate-friendly flight planning to mitigate the climate impact.

• Consider reducing the scope of your study to Europe and outlining your data and methodology in detail, including random search methods, quantifying the climate impact of re-routed flights, the size of the warming and colling, and adding sensitivity analysis.

• Expand your discussion to account for your data and model limitations and discuss operational and economic implications and potential barriers.

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,

Sadia Ilyas, PhD
External Editor
Communications Earth & Environment

Martina Grecequet, PhD
Associate Editor
Communications Earth & Environment

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https://www.nature.com/documents/nr-reporting-summary.zip

For your information, you can find some guidance regarding format requirements summarized on the following checklist: (https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf) and formatting guide (https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Comments to "Pathways to Sustainable Aviation:
Aligning Flight Plans with Climate Goals"

Major comments:

This article primarily examines the potential of climate-friendly flight planning as operational measures to alleviate the aviation industry's climate impacts. The analysis comprehensively takes into account the impact of aircraft carbon dioxide and various non-carbon dioxide emissions, including nitrogen oxide emissions and contrail clouds. The findings reveal that the effectiveness of climate-friendly flight planning in mitigating climate impacts is closely linked to meteorological conditions, time, and seasons. Proper route adjustments can effectively mitigate climate impacts, and flight route adjustments can be minimized to maintain operational feasibility. Moreover, flight plans are most effective in reducing the impact of condensation contrails on the climate. Reducing other non-carbon dioxide impacts often leads to higher costs and necessitates significant route modifications. The article's conclusion offers aviation policymakers a clearer understanding of the potential climate benefits and associated impacts achievable through flight plans. However, the article has limitations, including insufficient consideration of non-carbon dioxide climate impact factors and a less detailed analysis of the impact of nitrogen oxides on the climate. The most perplexing aspect of the article is quantifying the climate impact of rerouted flights over the next 20 years and whether this impact should be projected relative to future aircraft emissions. Specifically, how are aircraft emissions after route adjustments to be subtracted from projected emissions? The article does not provide an explanation for these data.

Specific comments:
1. Aviation emissions have an impact on climate. The emissions from aircraft not only affect the climate, but also include carbon dioxide, nitrogen oxides, water vapor, and condensation wake, as well as hydrocarbons, especially methane. This article did not discuss the climate impact of methane.
2. Nitrogen oxides are a part of aviation emissions. However, not all nitrogen oxides have an impact on the climate, and nitrous oxide in nitrogen oxides is the greenhouse gas with the greatest impact on the climate. Therefore, is it more targeted to specifically discuss nitrous oxide?
3. The aerosols in the condensation wake of an aircraft generate negative effective forcing radiation, which can alter the impact of the condensation wake on the climate. The aerosols in the condensation wake of an aircraft generate negative effective forcing radiation, which can alter the impact of the condensation wake on the climate. It is recommended that the author take this into consideration during the writing process.
4. The abstract merely highlights the beneficial impact of climate-friendly flight plans on mitigating aviation emissions, without corroborating this with specific data. Thus, might it be possible to incorporate data from the findings and discussion section to more vividly illustrate the potential of such flight plans in reducing aviation emissions?
5.Page 1，“These objectives aim to limit climate warming to well below 2◦ above preindustrial levels and to pursue efforts to restrict the temperature rise at 1.5◦” It is suggested that the author replaced “2◦” and “1.5◦” degrees" with “2◦C” and “1.5◦C” to improve the accuracy of written expression.
6. Page 5，“Figure 3-a illustrates the daily potential for climate impact mitigation, highlighting that the climate-optimized routing option associated with a higher additional cost and unrestricted rerouting achieves the largest mitigation potential. Generally, reduction in climate impact varies between 0-53% for a 0.2% extra cost and 2-68% for a 2.0% extra cost (considering both rerouting limits). ” Part of the lines in Figure 3 are obscured by text, making it difficult to directly observe the climate impact range with an additional cost increase of 0.2% and 2.0%. It is suggested that the author annotate the maximum and minimum values of climate impact in the graph, and adjust the range of text in Figure 3 to facilitate clear observation of relevant information by readers.
7. Page 6，The left half of Figure 2 depicts the climate relief potential of flights departing at midnight. It seems that there is no line representing January in the figure. Did the author forget to draw it, or did the data for January overlap with other months and cannot be displayed?

Reviewer #2 (Remarks to the Author):

The paper is thorough and well-structured, presenting a thorough analysis of how climate-friendly flight planning can mitigate the aviation sector's climate impact. However, I have some major concerns that need to be revisited before it is ready to be published.

The study relies on various data sources and models, each with inherent uncertainties. A more detailed sensitivity analysis addressing these uncertainties, particularly in meteorological data and emission indices, would strengthen the findings.

The analysis primarily focuses on European flight routes, which may not be representative of global aviation patterns. Extrapolating the findings to a global scale without considering regional variations could limit the generalisability of the results.

The optimisation part of the study is robust and innovative, offering a significant contribution to climate-friendly flight planning. However, it would benefit from a more detailed explanation of the constraints and assumptions used in the model. Further, the authors should elaborate on the computational performance of this model.

The authors should explain their choice of Augmented Random Search in more detail. Why is this method better than others? What are the benefits of using it?

The practical feasibility of implementing the optimised flight trajectories on a large scale has not been deeply explored. Including more realistic operational constraints would strengthen the study's practical relevance. Additionally, a more detailed analysis of the operational and economic implications, as well as potential barriers to implementation, would be beneficial.

The optimisation results are highly sensitive to specific weather scenarios and initial flight conditions. While the study addresses this by using ensemble weather scenarios, further exploration of how these sensitivities impact different types of flights (e.g., short-haul vs. long-haul) would be beneficial.

The solution-picking algorithm selects one routing option per flight based on aggregated climate effects and cost constraints. However, the methodology for determining the allowable cost increase and the proportion of rerouted flights is not fully transparent. A more detailed explanation of these criteria would enhance understanding and reproducibility.

The choice of weighting parameters for operating costs and climate impacts is somewhat arbitrary and might not reflect real-world priorities. A sensitivity analysis of these parameters would provide insights into how different priorities affect the optimisation results.

While the paper accounts for uncertainties, it could benefit from a more explicit discussion of the limitations of current models and tools in predicting long-term climate impacts. This would provide a clearer context for the results.

Reviewer #3 (Remarks to the Author):

The authors conduct an end-to-end analysis of how much adjustments to flight trajectories (e.g., rerouting, deviations from flight plans) with the objective of reducing aviation climate impacts can do in terms of, e.g., reduced CO2 and non-CO2 (e.g., NOx) impacts. The overall idea is well-motivated, and the paper is well-written. However, I have two significant concerns regarding the scope, and some of the initial input claims made by the author. I detail these comments below:

(1.) In the first introductory section, the authors present a very well-written, well-motivated, and thorough background of sustainable aviation initiatives. However, the scope and purpose of the article are a bit mis-aligned with the data presented. In particular, the authors portray the upcoming analysis as applicable to the entire international aviation system, but for their actual analysis/experimental set up, they focus only on European market segments. Even within Europe they focus only on a further subset of 150 flights. It is not clear at all what is the generalizability of the authors' claims, particularly because not only are there difference in the supply (e.g., flight schedules, fleet mixes, etc.) and demand (e.g., passenger travel behaviors, demand patterns), there are also different regulations/policies governing flights on a region-by-region level (sometimes even at an FIR-by-FIR level). I would suggest the authors either significantly reduce the scope, and clarify at the very beginning that they are only examining European flights, or expand their data analysis/experimental setup.

(2.) Figure 1 is a good overall perspective of the sustainable aviation ecosystem that the authors are operating within. However, it is not clear how the authors derive some of the claims made in the figure. In particular, the "influence on the radiation balance" is an extremely critical element when evaluating sustainable aviation impacts. It is not clear to me how the authors decided on the size of the warming / cooling impacts. It is also not clear how the "uncertainty levels" are determined. If Figure 1 is more notional / conjectured by the authors, it must be stated clearly. If Figure 1 is based on numerical data, it would be great to cite the source. As is, Figure 1 seems to be extremely authoritative in saying, e.g., contrail's cooling impact is significantly less than its warming impacts, and that the uncertainty levels between warming and cooling impacts can be compared (given the blurriness level). At best, this is a bit confusing, at worst, it is misleading.

(3.) Some minor comments:

- There are many typos throughout the paper that the authors should double-check (e.g., "two-thirds" is misspelled in the caption for Figure 1); In the subtitle for Figure 7(a), the word "humidity" is misspelled

- This may be a stylistic difference (I will defer to the journal copy editors), but some of the figure captions (e.g., on Figure 7) are extremely long. This to me breaks up the flow of the paper, and is distracting -- I would encourage the authors to integrate the explanations of the figures naturally into the appropriate places within the main text of the paper.

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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 Dr Simorgh,

Your manuscript titled "Toward Sustainable Aviation: Climate-Optimized Flight Planning in the European Airspace" 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 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,

Sadia Ilyas, PhD
Editorial Board Member

Communications Earth & Environment

Martina Grecequet, PhD
Senior Editor,
Communications Earth & Environment
@CommsEarth

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

No further comments

Reviewer #2 (Remarks to the Author):

The authors have adequately addressed all my concerns.

Reviewer #3 (Remarks to the Author):

The authors have thoroughly addressed all of my concerns.

Response to reviewers regarding the paper entitled:

"Toward Sustainable Aviation: Climate-Optimized Flight Planning in the European Airspace"

We greatly appreciate the editor and the reviewers for the complimentary and constructive suggestions on our paper entitled "Toward Sustainable Aviation: Climate-Optimized Flight Planning in the European Airspace". The manuscript has been modified following the reviewers' comments and resubmitted for consideration for publication. Please find attached a point-by-point response to the reviewer's concerns. We hope that you find the responses satisfactory and that the manuscript is now acceptable for publication.

For the sake of clarity, the following criteria have been adopted throughout this document:

- Reviewer's comments
- Authors' responses
- Words changed or added to the paper after revision
- ~~Words removed~~

Reviewer 1

This article primarily examines the potential of climate-friendly flight planning as operational measures to alleviate the aviation industry's climate impacts. The analysis comprehensively takes into account the impact of aircraft carbon dioxide and various non-carbon dioxide emissions, including nitrogen oxide emissions and contrail clouds. The findings reveal that the effectiveness of climate-friendly flight planning in mitigating climate impacts is closely linked to meteorological conditions, time, and seasons. Proper route adjustments can effectively mitigate climate impacts, and flight route adjustments can be minimized to maintain operational feasibility. Moreover, flight plans are most effective in reducing the impact of condensation contrails on the climate. Reducing other non-carbon dioxide impacts often leads to higher costs and necessitates significant route modifications. The article's conclusion offers aviation policymakers a clearer understanding of the potential climate benefits and associated impacts achievable through flight plans. However, the article has limitations, including insufficient consideration of non-carbon dioxide climate impact factors and a less detailed analysis of the impact of nitrogen oxides on the climate. The most perplexing aspect of the article is quantifying the climate impact of rerouted flights over the next 20 years and whether this impact should be projected relative to future aircraft emissions. Specifically, how are aircraft emissions after route adjustments to be subtracted from projected emissions? The article does not provide an

explanation for these data.

The authors would like to thank the reviewer for their valuable comments and suggestions, which have improved the quality of the paper.

Regarding the comment, "**The most perplexing aspect of the article is quantifying the climate impact of rerouted flights over the next 20 years ...**,", we note that the scope of this study is not to quantify the climate impact of flights over the next 20 years. In fact, the study aims to assess the mitigation potential achievable through flight planning, which needs to be evaluated based on an appropriate climate metric. The selected metric is the Average Temperature Response with a 20-year time horizon (ATR20). Several climate metrics exist in the literature, each addressing different climate-related questions [1]. For climate-optimized flight planning, a temperature-based climate metric is most beneficial because it is commonly used (e.g., in the Paris Agreement) and easily understood by non-experts. Since climate-optimized flight planning aims to mitigate the climate effects of non-CO_2 emissions (such as contrails and NO_x-induced effects), we require a metric that places significant emphasis on these species. For this purpose, ATR20 is one of the most appropriate metrics (in line with the literature [2–4]). ATR20 quantifies climate effects based on temperature change, and the 20-year time horizon is sufficient to capture the atmospheric lifetime and climate impacts of non-CO_2 species. A longer time horizon, such as 100 years, could understate the importance of non-CO_2 effects by averaging their impacts over a century, thus diluting the critical short-term climate response that is currently of great concern in aviation. Another key advantage of ATR20 is its low sensitivity to variations in background emissions scenarios [2]. Background emissions refer to the broader global emissions context, including contributions from sectors beyond aviation. This low sensitivity is particularly beneficial for climate-optimized flight planning, as it should ideally be effective without precise knowledge of how emissions from other sectors or regions will evolve. The robustness of ATR20 means that its outcomes are less influenced by uncertainties in future emissions scenarios (e.g., variations in future global emissions pathways), enabling a more reliable decision-making [2].

Regarding your concern about the "**insufficient consideration of non-CO_2 climate impact factors and a less detailed analysis of the impact of nitrogen oxides (NO_x) on the climate**," we have addressed this in our responses to the first two specific comments (i.e., comments 1 and 2).

- ***Comment 1***: Aviation emissions have an impact on climate. The emissions from aircraft not only affect the climate, but also include carbon dioxide, nitrogen oxides, water vapor, and condensation wake, as well as hydrocarbons, especially methane. This article did not discuss the climate impact of methane.

- ***Comment 2***: Nitrogen oxides are a part of aviation emissions. However, not all nitrogen oxides have an impact on the climate, and nitrous oxide in nitrogen oxides is the greenhouse gas with the greatest impact on the climate. Therefore, is it more targeted to specifically discuss nitrous oxide?

  Response: Thank you for raising these points, which we agree need clarification in the paper. We address both comments here, as we believe they are related.

  We acknowledge the multiple pathways through which NO_x emissions ($NO_x = NO + NO_2$) contribute to climate change, and these have been accounted for in the analysis performed in this study (i.e., NO_x-induced perturbations in the atmospheric concentrations of ozone (O_3) and methane (CH_4)). The aCCF for NO_x emissions captures the short-term increase in ozone production, the long-term destruction of methane, and changes in primary mode ozone (referring to the reduction in ozone production) resulting from the decreased atmospheric concentration of methane. However, the reduction in stratospheric water vapor due to methane oxidation has not been considered in the development of aCCFs, having a relatively small climate impact compared to other NO_x-induced effects.

Based on the reviewer's comments, we have differentiated between NO_x impacts on ozone and methane in the revised manuscript. In particular, Figure 4 in the main paper now illustrates the NO_x-induced effects on ozone and methane, rather than showing the overall impact of NO_x emissions.

Changed Figure: Figure 4.

Additionally, the following explanations have been provided to clarify the NO_x-induced climate effects considered in this study.

Introduction:
We account for the climate effects of CO_2 emissions and the most relevant non-CO_2 forcing agents, including NO_x emissions-induced effects (i.e., changes in the atmospheric concentrations of ozone and methane), water vapor emissions, and aviation-induced cloudiness.

Section Methods, Aircraft emissions and climate impact estimation model:
The aCCFs provide climate sensitivity information for NO_x-induced effects, persistent contrails, H_2O emissions, and CO_2 emissions. The aCCF for NO_x emissions captures the short-term increase in ozone production, the long-term destruction of methane, and changes in primary mode ozone (referring to the reduction in ozone production) resulting from the decreased atmospheric concentration of methane. However, the reduction in stratospheric water vapor due to methane oxidation has not been considered in the development of aCCFs, having a relatively small climate impact compared to other NO_x-induced effects [5].

- ***Comment 3***: The aerosols in the condensation wake of an aircraft generate negative effective forcing radiation, which can alter the impact of the condensation wake on the climate. It is recommended that the author take this into consideration during the writing process.

  Response: If we have correctly understood, the reviewer is asking to discuss the climate effects induced by aerosol emissions in the paper. Since aerosol effects were not considered in the analysis conducted in this study, we agree that it is important to discuss their effects and provide justification for their exclusion.

  The following text has been added to the discussion section of the paper.
  ... . The analysis of non-CO_2 climate impacts and mitigation potential presented in this study did not account for the direct effects of aerosol emissions or their indirect impact on natural clouds (both low-level and cirrus clouds). Sulfate aerosols scatter incoming shortwave radiation, leading to a cooling effect, while soot aerosols absorb shortwave radiation, causing a warming effect. According to state-of-the-art research on aviation-induced climate impacts, the net direct effect of aerosol is cooling, although it is relatively small compared to that of NO_x emissions and contrails (see [6]). However, the aerosol-cloud effect remains highly uncertain, making it a topic of extensive ongoing research [7]. Currently, no models compatible with flight planning account for these aerosol-induced effects, which is the primary reason they were excluded from this study. ...

- ***Comment 4***: The abstract merely highlights the beneficial impact of climate-friendly flight plans on mitigating aviation emissions, without corroborating this with specific data. Thus, might it be possible to incorporate data from the findings and discussion section to more vividly illustrate the potential of such flight plans in reducing aviation emissions?

  Response: Thanks for the suggestion. We have incorporated specific data and key findings from the results and discussion sections into the abstract.

  Overall, for a subset of European flights, a reduction in climate impacts of 12.5% and 21.3% is achievable with an increase in operational costs of 0.2% and 2.0%, respectively.

The findings suggest that flight planning is most effective at mitigating the climate impact of contrails (accounting for over 80% of the net mitigation potential), whereas reducing other non-CO_2 impacts, including NO_x-induced effects, tends to be costlier and necessitates extensive rerouting.

Added Figure: Figure S19 (Contribution of each forcing agent to the net achieved mitigation potential).

- ***Comment 5***: Page 1, "These objectives aim to limit climate warming to well below 2$\circ$ above preindustrial levels and to pursue efforts to restrict the temperature rise at 1.5$\circ$" It is suggested that the author replace "2$\circ$" and "1.5$\circ$" degrees" with "2$\circ$C" and "1.5$\circ$C" to improve the accuracy of written expression.

  Response: We appreciate your precise look. We have addressed it in the revised manuscript.

- ***Comment 6***: Page 5, "Figure 3-a illustrates the daily potential for climate impact mitigation, highlighting that the climate-optimized routing option associated with a higher additional cost and unrestricted rerouting achieves the largest mitigation potential. Generally, reduction in climate impact varies between 0-53% for a 0.2% extra cost and 2-68% for a 2.0% extra cost (considering both rerouting limits). "Part of the lines in Figure 3 are obscured by text, making it difficult to directly observe the climate impact range with an additional cost increase of 0.2% and 2.0%. It is suggested that the author annotate the maximum and minimum values of climate impact in the graph and adjust the range of text in Figure 3 to facilitate clear observation of relevant information by readers.

  Response: Thank you for your suggestion. In the revised version of the manuscript, we have annotated the minimum and maximum values of the mitigation potentials in the figure. Please note that the values previously reported for mitigation potential in the text were based on the minimum and maximum values considering the ten ensemble estimates. In the revised version, we report the ranges based on a 98% confidence interval to align with what is shown in Figure 3 (where the shaded areas represent 98% confidence interval). Additionally, the same figure, with shaded areas representing the minimum and maximum values across all ensemble members and annotations of the corresponding minimum and maximum values, has now been included in the supplementary materials.

  Changed Figure: Figure 3(a).
  Added Figure: Figure S9 (in Supplementary Material).

  Generally, reduction in climate impact varies between 0-48% for a 0.2% extra cost and 2-61% for a 2.0% extra cost (considering both rerouting limits).

- ***Comment 7***: Page 6, The left half of Figure 2 depicts the climate relief potential of flights departing at midnight. It seems that there is no line representing January in the figure. Did the author forget to draw it, or did the data for January overlap with other months and cannot be displayed?

  Response: Thank you for your careful observation. The Pareto curves for January and February overlap for nighttime flights. In the revised version of the manuscript, we have added a zoomed-in view of that subplot to enable a clearer distinction between the two curves.

  Changed Figure: Figure 2.

Reviewer 2

The paper is thorough and well-structured, presenting a thorough analysis of how climate-friendly flight planning can mitigate the aviation sector's climate impact. However, I have some major concerns that need to be revisited before it is ready to be published.

- ***Comment 1***: The study relies on various data sources and models, each with inherent uncertainties. A more detailed sensitivity analysis addressing these uncertainties, particularly in meteorological data and emission indices, would strengthen the findings.

  Response: Thank you for your suggestion. The primary models used in this research include those for aircraft dynamics, flight performance variables, emissions estimation, climate effects of non-CO_2 species, and the flight planning tool. The main source of uncertainty considered in this study is meteorological data, which can introduce variability into the outputs of these models. In response to your comment, we have conducted a more detailed sensitivity analysis (in addition to those included in the sensitivity analysis section), exploring the variability in the relevant meteorological variables and their effects on the calculated non-CO_2 climate impacts, aircraft performance variables, and emissions, briefly discussed in the following.

  To model aircraft dynamics, we employed the full 3DoF point mass model, commonly used in ATM studies, along with the BADA 4.2, which is regarded as one of the most reliable (available) models for representing aerodynamic and propulsive performance. For calculating emissions, we utilized the Boeing Fuel Flow Method II, the most widely adopted approach for estimating NO_x emissions. These models rely on meteorological variables (e.g., wind and temperature), thus sensitive to the quality of weather data. Regarding the climate effects, we employed state-of-the-art algorithmic climate change functions (aCCFs) (the only available modeling approach compatible with flight planning) to provide information on the climate sensitivity of the most relevant non-CO_2 species. These functions are highly dependent on meteorological conditions, making them sensitive to the quality of the weather data. Therefore, the effectiveness of climate-optimized flight planning can be highly affected by the uncertainty in the meteorological conditions. In this study, we used the ERA5 reanalysis data product, containing ten ensemble members, to conduct a sensitivity analysis on how meteorological uncertainty impacts optimization results.

  The figures and sensitivity analysis reported in the paper are based on the average and 98% confidence interval (as shaded areas) of the performance variables calculated considering the ten ensemble weather scenarios. A more detailed sensitivity analysis, based on the reviewer's comment, has been provided in Figures (S10-S15). In particular, Figure (S12) shows the average (solid line) and min-max ranges (shaded areas) of the required weather variables, averaged over grid points covering all flights at 250 hPa, for all days in 2022. Additionally, Figure (S10) presents the geographical distribution of the standard deviation of the normalized weather variables for a specific day. It can be seen that the variability in meteorological variables is generally low, except for humidity and outgoing longwave radiation. Consequently, the highest uncertainty is expected for the climate effects of contrails (see Figures (S11, S14, and S15)), while aircraft performance variables (e.g., fuel flow and flight time), emissions, and other non-CO_2 species are almost deterministic, as illustrated in Figures (S13 and S14). We note that, for the scope of this study, the reanalysis data was used. However, for flight planning, we rely on forecast data, typically with a larger ensemble size (e.g., 50 members), which may show greater variability in the meteorological variables required for calculating aircraft performance variables, emissions, and the climate effects of non-CO_2 species.

  The sensitivity of the flight planning tool will be discussed in response to Comment 3.

Added Figure: Figure S10 (Geographical distribution of variability across ensemble realizations of the required meteorological variables for a specific day).
Added Figure: Figure S11 (Geographical distribution of variability across the resulting ensemble climate-sensitivity maps (i.e., aCCFs) for a specific day).
Added Figure: Figure S12 (Mean and variability of the required meteorological variables throughout 2022).
Added Figure: Figure S13 (Sensitivity analysis of flight performance variables to the meteorological uncertainties characterized using the ERA5 reanalysis data).
Added Figure: Figure S14 (Sensitivity analysis of the climate effects of non-CO_2 species to the meteorological uncertainty characterized using the ERA5 reanalysis data).
Added Figure: Figure S15 (Sensitivity analysis of the climate effects of daytime and nighttime contrails to the meteorological uncertainty characterized using the ERA5 reanalysis data).

These added figures are referenced in the main text when discussing sensitivity to meteorological uncertainty (Section Sensitivity Analysis, ERA5 10-ensemble member).
A more detailed sensitivity analysis, exploring the variability in relevant meteorological variables and their effects on the calculated non-CO_2 climate impacts, aircraft performance variables, and emissions, is provided in the supplementary materials (Figures S10-S15).

- ***Comment 2***: The analysis primarily focuses on European flight routes, which may not be representative of global aviation patterns. Extrapolating the findings to a global scale without considering regional variations could limit the generalisability of the results.

  Response: Thank you for this comment. We agree that the findings are focused on European flights and believe we have not made any claims regarding the validity of the analysis in other regions. If this was unclear in the manuscript, we apologize. This point has been clarified in the revised manuscript.

  Title
  ~~Pathways to Sustainable Aviation: Aligning Flight Plans with Climate Goals~~
  Toward Sustainable Aviation: Climate-Optimized Flight Planning in the European Airspace

  Abstract
  Overall, for a subset of European flights, a reduction in climate impacts of 12.5% and 21.3% is achievable with an increase in operational costs of 0.2% and 2.0%, respectively.

  Discussion
  The potential of flight planning to mitigate climate effects explored in this study was focused on European flights due to the validity scope of aCCFs. Updated versions of aCCFs are under development, which will enable assessing the validity of this study's conclusions in other regions.

- ***Comment 3***: The optimisation part of the study is robust and innovative, offering a significant contribution to climate-friendly flight planning. However, it would benefit from a more detailed explanation of the constraints and assumptions used in the model. Further, the authors should elaborate on the computational performance of this model.

  Response: In the supplementary materials of the revised manuscript (Section Insights into the Flight Planning Approach), we have provided additional details on the optimization method, including assumptions (e.g., phases of flight, airspace graph structure, and discrete flight level and Mach changes) and constraints (e.g., dynamical constraints and flight envelope). These details are also referenced in the main text (Section Method, Robust Aircraft Trajectory Optimization). Furthermore, we have included an analysis of the sensitivity of the optimization algorithm's convergence performance, along with insights into the computational time required (See Figures S17 and S18).

Added Figure: Figure S17 (Convergence performance assessment of the flight planning method across 50 different runs).
Added Figure: Figure S18 (Computational performance of the flight planning method for 10 days of optimizations, with two departure times per day and 4 routing options for each flight).

Added Section to Supplementary "Insight into the Flight Planning Approach":
Modelling flight planning problem primarily involves the aircraft's dynamical model, flight planning objectives, and the relevant physical and operational constraints, briefly discussed in the following.

Airspace Structure and Flight Plan Definition
The optimization performed in this study focuses on structured airspace, requiring consideration of specific constraints within this operational context (e.g., the air traffic service (ATS) route network). In the following, we briefly present our proposed modeling of the airspace structure and flight plan.

We model the airspace as a directed acyclic graph $G = (V, E)$, where V represents the navigation waypoints, and E consists of the airway edges connecting these waypoints. The flight trajectory is assumed to begin at the end of the Standard Instrument Departure (SID) procedure (climb phase) and end at the beginning of the Standard Instrument Arrival (STAR) procedure at the destination airport (descent phase). For the route graph, we extract a subgraph from the complete airspace structure of June 2018. This subgraph consists of paths, each no longer than 105% of the length of the shortest ground distance path.

We define the flight plan, as a tuple $F := (R, \overline{\mathrm{FL}}, \overline{\mathrm{M}}, C, D, d_D)$, where the lateral path, R, is a sequence of waypoints $R := (r_0, r_1, \cdots, r_{n_r})$, the vertical cruise profile, $\overline{\mathrm{FL}}$, is defined as an ordered sequence of tuples (r_k, FL_k), and the Mach schedule, $\overline{\mathrm{M}} := (\mathrm{M}_0, \mathrm{M}_1, \cdots, \mathrm{M}_{n_r})$, specifies the target Mach number. Additionally, the climb and descent profiles, C and $D : \mathbb{R} \to \mathbb{R}$, are represented by continuous, piecewise-differentiable functions that map altitude to the target airspeed for the climb and descent phases, respectively. During the cruise phase, flight level changes are made in increments or decrements of 2,000 feet, while Mach profile adjustments are performed in steps of 0.01. Furthermore, for the practicality of the optimized trajectory (e.g., maintaining passenger comfort), rapid changes are restricted.

The objective is to determine an optimal flight plan, i.e., F^o, such that a given objective function, including flight planning objectives (e.g., operational cost and climate effects), gets minimized while respecting a set of constraints (e.g., aircraft dynamics and flight envelope) to ensure feasibility from physical and operational perspectives.

Aircraft Dynamical Model and Flight Envelope
For a given flight plan, to obtain the required flight performance variables needed to evaluate the defined objective function (e.g., fuel consumption, flight time, and climate effects for Eq. (4)), trajectory integration needs to be performed based on the aircraft dynamics. For this study, the aircraft dynamical model is represented

using the three-degrees-of-freedom (3DoF) point-mass model, which is commonly employed in ATM studies:

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix}\phi\\ \lambda\\ h\\ v_{tas}\\ m\end{bmatrix}=\begin{bmatrix}\big(v_{tas}\cos(\gamma)\cos(\chi)+w_y\big)\big(R_M(\phi)+h\big)^{-1}\\ \big(v_{tas}\cos(\gamma)\sin(\chi)+w_x\big)\Big(\big(R_N(\phi)+h\big)\cos(\phi)\Big)^{-1}\\ v_{tas}\sin(\gamma)\\ \big(\mathrm{T}(C_T)-D(C_L)\big)m^{-1}-g\sin(\gamma)\\ -f_c(C_T)\end{bmatrix}\quad \begin{array}{l}\text{Latitude, Longitude}: \phi,\lambda\\ \text{Altitude, True airspeed}: h, v_{tas}\\ \text{Mass, Fuel flow}: m, f_c\\ \text{Thrust \& Drag forces}: \mathrm{T}, \mathrm{D}\\ \text{Thrust \& Lift coefficients}: C_T, C_L\\ \text{Components of wind}: w_x, w_y\\ \text{Heading \& Path angles}: \chi,\gamma\end{array} \tag{1}$$

where $C_L(\gamma) = (2mg\cos(\gamma))/(\rho v_{tas}^2 S)$, g is the gravitational acceleration, S is the wetted wing surface, ρ is the air density, R_M and R_N are the radii of curvature of the meridian's ellipse and the radius of curvature in the prime vertical, respectively. The aerodynamic and propulsive performance are modeled utilizing BADA4.2. The following set of constraints are considered for the flight envelope:

$$\begin{aligned} v_{CAS,stall} &\leq v_{CAS}(v) \leq v_{CAS,\max}\\ C_{T,\min} &\leq C_T \leq C_{T,\max}\\ M(v_{tas}) &\leq M_{\max}\\ C_L &\leq C_{L,\max}\\ h &\leq h_{\max}\end{aligned} \tag{2}$$

where M is the Mach number and v_{CAS} is the calibrated airspeed. For more details on the optimization approach, interested readers are referred to [8].

Added to Methods, Robust Aircraft Trajectory Optimization:
The convergence and computational performance of the optimization approach are shown in Figures S17 and S18.

- ***Comment 4***: The authors should explain their choice of Augmented Random Search in more detail. Why is this method better than others? What are the benefits of using it?

  Response: The optimization of aircraft trajectories within the structured airspace involves a combination of both discrete and continuous decision variables, resulting in a mixed-integer nonlinear programming problem, which is mathematically complex and computationally intensive. To efficiently address the proposed flight planning problem, the optimization is represented in an equivalent form, which enables searching in the space of probability distributions defined over flight plans rather than directly searching for the optimal flight plan, thus yielding a continuous search space. To facilitate this search, the probability distribution is parameterized, leading to a stochastic optimization problem, which is more amenable to solution methods typically employed in reinforcement learning (RL) algorithms. To solve the resulting stochastic optimization problem, we utilize the Augmented Random Search (ARS) algorithm, known for its simplicity in implementation and its sample efficiency (see [9] for a discussion comparing ARS with other RL algorithms). Particularly for the flight planning in this study, we are interested in the algorithm's scalability, which allows iterative advancement of the solution by evaluating multiple search directions in parallel.

  In the revised version of the manuscript, we have discussed the suitability of ARS and highlighted how it can be parallelized to provide near real-time solutions to the highly complex robust flight planning problem considered in this study.

Included in the Methods, Robust Aircraft Trajectory Optimization:

... . To facilitate search, the probability distribution is parameterized with a vector of parameter θ. For a given θ, flight plans can be randomly sampled (see [8]). To solve the resulting stochastic optimization problem, we utilize the Augmented Random Search (ARS) algorithm, known for its simplicity in implementation and its sample efficiency (see [9]). In this study, we specifically leverage its scalability, allowing for iterative solution advancement by evaluating multiple search directions in parallel (see Supplementary Materials, Section "Augmented Random Search" for a detailed discussion on the scalability of ARS).

Included in the section "Insights into the Flight Planning Approach" in the supplementary materials:

Augmented Random Search

The proposed flight planning problem within the structured airspace involves a combination of both discrete and continuous decision variables, resulting in a mixed-integer nonlinear programming problem, which is mathematically complex and computationally intensive [10]. To efficiently address the proposed flight planning problem, the optimization is represented in an equivalent form, which enables searching in the space of probability distributions defined over flight plans (i.e., $\min_{p(F)} \mathbb{E}_{p(F)}\{J(F)\}$) rather than directly searching for the optimal flight plan (i.e., $\min_F J(F)$), thus yielding a continuous search space. To facilitate this search, the probability distribution is parameterized by a vector of parameters, θ. From θ, flight plans can be sampled randomly (see [8]), leading to the following stochastic optimization problem:

$$\min_{\theta} \mathbb{E}[J(\theta)] \tag{3}$$

To solve the resulting stochastic optimization problem, we utilize the Augmented Random Search (ARS) algorithm for its sample efficiency and, most notably for the purpose of this study, its scalability properties. In ARS, the algorithm generates multiple perturbations δ_i $(i = 1, \cdots, N)$ around the current policy parameters θ (or decision variables). For each perturbation, two policy evaluations $\theta + \nu\delta_i$ and $\theta - \nu\delta_i$ are performed independently to obtain the corresponding rewards r_i^+ and r_i^-. Since these evaluations are independent of each other, they can be distributed across multiple GPU cores to evaluate several perturbed policies in a parallel fashion (i.e., $2N$ parallel evaluations). After obtaining the rewards for all perturbations, the algorithm aggregates the results to determine the update direction for the decision variables. The update rule is:

$$\theta_{k+1} = \theta_k + \frac{\alpha}{N\sigma_r} \sum_{i=1}^{N} \left(r_i^+ - r_i^-\right) \delta_i$$

where:

- θ_k is the current policy parameter vector.
- θ_{k+1} is the updated policy parameter vector after iteration k.
- α is the step size (learning rate).
- N is the number of perturbations.
- σ_r is the standard deviation of the rewards r_i^+ and r_i^-.
- r_i^+ and r_i^- are the rewards obtained from the positive and negative perturbations, respectively.
- δ_i is the perturbation vector sampled from a standard normal distribution.

By implementing the flight planning method on GPUs, multiple flight plans across various scenarios are run in parallel, enabling the robust climate-optimized flight plan to be delivered within seconds. It is important to note that, for each search direction, evaluating the performance associated with each flight plan requires performing N_{EPS} trajectory integrations, one for each ensemble member. Consequently, a total of $2N \times N_{EPS}$ parallel simulations are executed. The computational efficiency of the robust flight planning method enabled the large-scale analysis conducted in this study.

- ***Comment 5***: The practical feasibility of implementing the optimized flight trajectories on a large scale has not been deeply explored. Including more realistic operational constraints would strengthen the study's practical relevance. Additionally, a more detailed analysis of the operational and economic implications, as well as potential barriers to implementation, would be beneficial.

  Response: Thank you for raising this point. The primary aim of this study, as an initial attempt at a large-scale analysis of climate-optimized flight planning, was to provide qualitative insights into specific aspects of this measure. In particular, we sought to address the following questions: Which non-CO_2 species can be most effectively mitigated through flight planning? Is it possible to reduce climate impacts with a limited number of trajectory re-plannings and a slight increase in cost? Is climate-optimized flight planning consistently effective across different days, months, and seasons? What changes in flight profiles can be expected? What are the differences between daytime and nighttime flights? And, is there a possibility of identifying big-hit scenarios based on weather forecasts prior to flight planning?

  We acknowledge the reviewer's concern that further analysis is necessary to address the practicality and economic aspects of implementing such routing options in real-world scenarios (e.g., considerations within the context of air traffic flow management). This is the focus of our ongoing research; the assessment and resolution of operational manageability of climate-optimized routes (from strategic and pre-tactical perspectives) have been explored in [11, 12], though restricted to limited scenarios (e.g., real traffic over several days), requiring advancing our methodologies to be extended to large-scale analysis, and the study in [13] addresses contrails avoidance within a commercial flight planning system, FLIGHTKEYS.

  In the revised manuscript, we have clarified the scope and discussed the reviewer's concern regarding the need to analyze the results from a more operational perspective.

  Discussion
  Climate-optimized flight planning based on the constant traffic scenario involving 150 flights aimed to provide qualitative insights into specific aspects of this measure. In particular, we sought to address the following questions: Which non-CO_2 species can be most effectively mitigated through flight planning? Is it possible to reduce climate impacts with a limited number of trajectory re-plannings and a slight increase in cost? Is climate-optimized flight planning consistently effective across different days, months, and seasons? What changes in flight profiles can be expected? What are the differences between daytime and nighttime flights? And, is there a possibility of identifying big-hit scenarios based on weather forecasts prior to flight planning?

  The considered traffic scenario was shown to capture larger traffic patterns when results are reported on a per-flight basis. However, for a more realistic estimation of mitigation potential and an assessment of operational feasibility, it is necessary to consider complete daily traffic scenarios and conduct a comprehensive analysis from the air traffic management perspective rather than focusing solely on individual flights. In particular, when aircraft trajectories are optimized independently, traffic patterns may shift significantly to avoid or, in some cases, intentionally fly through climate-sensitive areas, potentially affecting ATM performance in terms of sector demand, ATC workload, and complexity [12]. If needed, appropriate modifications should be applied to flight plans in order to maintain traffic stability while preserving climate optimality as closely as possible to the independently optimized trajectories. Such an approach would yield more realistic insights into the potential for climate impact mitigation, which remains the focus of ongoing research.

- ***Comment 6***: The optimization results are highly sensitive to specific weather scenarios and initial flight conditions. While the study addresses this by using ensemble weather scenarios, further exploration of how these sensitivities impact different types of flights (e.g., short-haul vs. long-haul) would be beneficial.

  Response: As discussed in response to comment 1, the uncertainty in the results is primarily due to the high variability among the ensemble members of relative humidity, leading to considerable uncertainty in identifying areas where persistent contrails form, their climate effects, and, consequently, the net climate impact, given the large contribution from contrails. Therefore, the uncertainty is more correlated with the extent to which the aircraft flies through highly uncertain persistent contrail-forming areas rather than the flight length (i.e., short-haul versus long-haul).

  Looking at Figure S15 in the supplementary materials, which was provided for the sensitivity analysis suggested by the reviewer in comment 1, we observe differing sensitivities for daytime and nighttime flights for the climate-optimized routing option (i.e., green lines, whether based on corrected or uncorrected relative humidity). During nighttime, as contrails have warming effects, the optimizer tends to avoid forming contrails for all ensemble weather scenarios, thereby avoiding uncertain contrail-forming areas, leading to reduced variability in the results. However, for daytime flights, in scenarios where cooling contrails can form (e.g., March and December), the uncertainty level increases as the aircraft tends to fly through contrail-forming areas to generate cooling contrails. Such a sensitivity is also evident in Figure 2 of the main paper, where the uncertainty ranges of the Pareto frontiers for daytime flights are wider in months with a high potential for generating cooling contrails (see Figures S5 and S6 for the likelihood of cooling contrail formation across different months).

  This can be seen in Figure 2, where, during the daytime, the level of uncertainty is more elevated, implying that daytime flights are more sensitive to meteorological uncertainty than nighttime flights for climate-optimized routing options.

- ***Comment 7***: The choice of weighting parameters for operating costs and climate impacts is somewhat arbitrary and might not reflect real-world priorities. A sensitivity analysis of these parameters would provide insights into how different priorities affect the optimisation results.

  Response: Thanks for this comment. The climate effects of non-CO_2 species can vary significantly across different scenarios, depending on factors such as meteorological conditions and aircraft type. Therefore, if included in the flight planning objective function to mitigate the corresponding impact, a large sensitivity to weighting parameters is expected. For instance, optimizing a flight departing on two different days with differing meteorological conditions, one with the possibility to form persistent contrails and another with no contrail formation could yield different solutions even with the same weight applied. This is because, for nearly identical operating costs, the magnitude of climate effects in the objective function can vary substantially. As a result, applying the same weights to these objectives in the objective function can lead to different relative importance and, consequently, different trade-offs. Therefore, a unique set of weights cannot be effectively determined to capture real-world priorities across all scenarios. A common approach is to solve the optimization for different weighting parameters and build a Pareto-frontier in order to select the best routing option meeting the flight planning criteria.

  In this study, for a more efficient weight selection, we first balance the magnitudes of operating cost and climate effects for each flight and then use a single controlling parameter (α) to prioritize them. The parameter α varies between 1 and 0, where $\alpha = 1$ and $\alpha = 0$ yield the cost-optimal and climate-optimal routing strategies, respectively, and intermediate values of α represent a trade-off between cost and climate impact.

The method for weight selection is now detailed in the Section Methods (Robust Aircraft Trajectory Optimization) when introducing the objective function.

To determine cost-efficient, climate-optimized trajectories, a weighted sum of operating cost (i.e., SOC) and average temperature response (i.e., ATR) is chosen as the objective function of the flight planning problem:

$$J(F) = \alpha \cdot \Big[0.75 \cdot \mathbb{E}\{\mathrm{FT}\} + 0.51 \cdot \mathbb{E}\{\mathrm{FB}\}\Big] + (1-\alpha) \cdot \mathrm{K} \cdot \mathbb{E}\{\mathrm{ATR}\} \tag{4}$$

where SOC is calculated from flight time (FT) and consumed fuel (FB). The controlling parameter $\alpha[-] \in [0,1]$ adjusts the trade-off between operational cost and climate impact, where $\alpha = 1$ and $\alpha = 0$ represent the cost-optimal and climate-optimal routing strategies, respectively. K [USD·K^{-1}] is a scaling parameter determined as: $\mathrm{K} = (\mathrm{SOC_{climate}} - \mathrm{SOC_{cost}}) \cdot (\mathrm{ATR_{cost}} - \mathrm{ATR_{climate}})^{-1}$, where for instance, $\mathrm{SOC_{climate}}$ is the SOC calculated when the optimization objective is only the climate impact (i.e., $\alpha = 0$), and $\mathrm{ATR_{cost}}$ is the ATR when the objective is only SOC (i.e., $\alpha = 1$).

In the revised supplementary materials, we have provided an example (see Figure (S16)-a) showing Pareto frontiers for six flight samples generated by considering different values of α. As can be seen in Figure (S16)-a, there can be considerable variability in the achieved mitigation potential for the same values of α, primarily due to the high scenario dependency of non-CO_2 climate effects, as discussed. This highlights the high sensitivity of the results to the weighting parameters when climate effects are included as an objective.

- ***Comment 8***: The solution-picking algorithm selects one routing option per flight based on aggregated climate effects and cost constraints. However, the methodology for determining the allowable cost increase and the proportion of rerouted flights is not fully transparent. A more detailed explanation of these criteria would enhance understanding and reproducibility.

  Response: We thank the reviewer for the suggestion and apologize for not providing sufficient clarity on the solution-picking approach. The sum of the operating costs of the cost-optimal routing option (i.e., routing option associated with $\alpha = 1.0$) for all flights is considered the baseline. The extra cost is calculated by adding a percentage increase relative to the baseline operating cost (e.g., 0.2% and 2.0% considered for results presented in the paper). Additionally, flights that the algorithm allows to select routes other than the cost-optimal option (i.e., when $\alpha \neq 1.0$) are considered rerouted. The number of these rerouted flights is penalized in the solution-picking algorithm. In the revised version of the manuscript, we have clarified these criteria (Section Methods, Solution Picking). In addition, we have provided an example (Figure S16) in the supplementary materials that illustrates the motivation for implementing the solution-picking algorithm and how it effectively identifies big-hit flights for rerouting and allocating extra costs. This example is referenced in the Methods section under 'Solution Picking.' The Jupyter Notebook for this example has been made available in the code availability section, allowing interested readers to better understand the solution-picking algorithm and reproduce the results and figures.

  Added Figure: Figure (S16)-b,c.

  Section Methods, Solution Picking

  ... (see Figure S16 for an illustrative example based on six flight samples) ...

  The increase in operating cost is assessed by considering the cost-optimal routing option (i.e., $\alpha = 1$) as the baseline, which is assumed to be the first element within the set of alternative trajectories optimized for each flight. The cost of the cost-optimal routing option is computed as:

$$\mathrm{SOC_{BAU}} = \sum_{k=1}^{N} x_k^1 \cdot \mathrm{SOC}_k^1 \tag{5}$$

where x_k^1 corresponds to the cost-optimal routing option for flight k. The allowable cost increase is then defined and constrained by:

$$\frac{1}{\mathrm{SOC_{BAU}}}\Big(\sum_{k=1}^{N}\sum_{i=1}^{o_k} x_k^i \cdot \mathrm{SOC}_k^i\Big) \leq P_\mathrm{c}, \tag{6}$$

where $P_\mathrm{c} \geq 1$ is a predefined parameter that limits the extra cost. In Eq. (6), $\sum_{k=1}^{N}\sum_{i=1}^{o_k} x_k^i \cdot \mathrm{SOC}_k^i$ represents the overall operational cost associated with the selected alternative trajectory for each flight. To ensure that only one routing option is chosen per flight, we introduce the following constraint: $\sum_{i=1}^{o_k} x_k^i = 1$, for $k = 1, \cdots, N$. To incorporate a penalty for the proportion of flights rerouted, we introduce the following constraint:

$$\frac{1}{N}\Big(\sum_{k=1}^{N} x_k^1\Big) \leq P_\mathrm{r} \tag{7}$$

where $P_\mathrm{r} \in [0, 1]$ represents the maximum allowable ratio of flights to be rerouted. In Eq. (7), $\sum_{k=1}^{N} x_k^1$ represents the number of flights flying their cost-optimal flight plan.

Code availability

The Jupyter Notebook for the example shown in Figure S16 (related to the solution-picking algorithm) is available via the link provided in the Data availability section.

- ***Comment 9***: While the paper accounts for uncertainties, it could benefit from a more explicit discussion of the limitations of current models and tools in predicting long-term climate impacts. This would provide a clearer context for the results.

Response: We agree that it is important to discuss the limitations of the models used, as well as the limitations of this study and potential future research directions. In the revised manuscript, we have added a dedicated discussion section addressing these aspects. Except for the first paragraph, which discusses the direct effects of aerosol emissions, their indirect impact on natural clouds, and the reason for their exclusion from the analysis, the rest has already been discussed in response to previous comments (e.g., climate change functions being valid only within Europe, and the need to extend the analysis to complete traffic scenarios to explore the operational manageability of climate-optimized routes).

Discussion

... . The analysis of non-CO_2 climate impacts and mitigation potential presented in this study did not account for the direct effects of aerosol emissions or their indirect impact on natural clouds (both low-level and cirrus clouds). Sulfate aerosols scatter incoming shortwave radiation, leading to a cooling effect, while soot aerosols absorb shortwave radiation, causing a warming effect. According to state-of-the-art research on aviation-induced climate impacts, the net direct effect of aerosol is cooling, although it is relatively small compared to that of NO_x emissions and contrails (see [6]). However, the aerosol-cloud effect remains highly uncertain, making it a topic of extensive ongoing research [7]. Currently, no models compatible with flight planning account for these aerosol-induced effects, which is the primary reason they were excluded from this study.

...

The considered traffic scenario was shown to capture larger traffic patterns when results are reported on a per-flight basis. However, for a more realistic estimation of mitigation potential and an assessment of operational feasibility, it is necessary to consider complete daily traffic scenarios and conduct a comprehensive analysis from the air traffic management perspective rather than focusing solely on individual flights. In particular, when aircraft trajectories are optimized independently, traffic patterns may shift significantly to avoid or, in some cases, intentionally fly through climate-sensitive areas, potentially affecting ATM performance in terms of sector demand, ATC workload, and complexity [12]. If needed, appropriate modifications should be applied to flight plans in order to maintain traffic stability while preserving climate optimality as closely as possible to the independently optimized trajectories. Such an approach would yield more realistic insights into the potential for climate impact mitigation, which remains the focus of ongoing research.

The potential of flight planning to mitigate climate effects explored in this study was focused on European flights due to the validity scope of aCCFs. Updated versions of aCCFs are under development, which will enable assessing the validity of this study's conclusions in other regions.

Reviewer 3

The authors conduct an end-to-end analysis of how much adjustments to flight trajectories (e.g., rerouting, deviations from flight plans) with the objective of reducing aviation climate impacts can do in terms of, e.g., reduced CO_2 and non-CO_2 (e.g., NO_x) impacts. The overall idea is well-motivated, and the paper is well-written. However, I have two significant concerns regarding the scope, and some of the initial input claims made by the author. I detail these comments below:

- ***Comment 1***: In the first introductory section, the authors present a very well-written, well-motivated, and thorough background of sustainable aviation initiatives. However, the scope and purpose of the article are a bit mis-aligned with the data presented. In particular, the authors portray the upcoming analysis as applicable to the entire international aviation system, but for their actual analysis/experimental set up, they focus only on European market segments. Even within Europe they focus only on a further subset of 150 flights. It is not clear at all what is the generalizability of the authors' claims, particularly because not only are there difference in the supply (e.g., flight schedules, fleet mixes, etc.) and demand (e.g., passenger travel behaviors, demand patterns), there are also different regulations/policies governing flights on a region-by-region level (sometimes even at an FIR-by-FIR level). I would suggest the authors either significantly reduce the scope, and clarify at the very beginning that they are only examining European flights, or expand their data analysis/experimental setup.

  Response: Thank you for raising this point. We apologize if the scope of this study was not sufficiently clarified. We acknowledge the reviewer's concern that our findings may not be generalizable to other regions. The analysis was restricted to European flights, primarily due to the scope of validity of algorithmic climate change functions (aCCFs), which are the only available modeling approach compatible with flight planning tools that provide climate sensitivity information for the most relevant non-CO_2 species (e.g., NO_x-induced effects, persistent contrails, and H_2O emissions).

  Based on the reviewer's suggestion, we have revised the title of the paper and further clarified the scope in both the abstract and introduction. Additionally, we have included a discussion section that addresses, among other points, the primary objectives of this study as an initial attempt at a large-scale analysis of climate-optimized flight planning, as well as the reviewer's concern regarding the need to extend the analysis to other regions, incorporate complete daily traffic scenarios, and analyze the results from a more operational perspective.

  Title
  ~~Pathways to Sustainable Aviation: Aligning Flight Plans with Climate Goals~~
  Toward Sustainable Aviation: Climate-Optimized Flight Planning in the European Airspace

  Abstract
  Overall, for a subset of European flights, a reduction in climate impacts of 12.5% and 21.3% is achievable with an increase in operational costs of 0.2% and 2.0%, respectively.

  Introduction
  ~~In this study, we close the existing gaps by comprehensively analyzing the potentiality of climate-optimized flight planning with a focus on optimizing trajectories over a one-year period.~~
  In this study, we take a step toward conducting a large-scale analysis of climate impact mitigation potential by focusing on optimizing a subset of European routes over a one-year period.

Discussion

Climate-optimized flight planning based on the constant traffic scenario involving 150 flights aimed to provide qualitative insights into specific aspects of this measure. In particular, we sought to address the following questions: Which non-CO_2 species can be most effectively mitigated through flight planning? Is it possible to reduce climate impacts with a limited number of trajectory re-plannings and a slight increase in cost? Is climate-optimized flight planning consistently effective across different days, months, and seasons? What changes in flight profiles can be expected? What are the differences between daytime and nighttime flights? And, is there a possibility of identifying big-hit scenarios based on weather forecasts prior to flight planning?

The considered traffic scenario was shown to capture larger traffic patterns when results are reported on a per-flight basis. However, for a more realistic estimation of mitigation potential and an assessment of operational feasibility, it is necessary to consider complete daily traffic scenarios and conduct a comprehensive analysis from the air traffic management perspective rather than focusing solely on individual flights. In particular, when aircraft trajectories are optimized independently, traffic patterns may shift significantly to avoid or, in some cases, intentionally fly through climate-sensitive areas, potentially affecting ATM performance in terms of sector demand, ATC workload, and complexity [12]. If needed, appropriate modifications should be applied to flight plans in order to maintain traffic stability while preserving climate optimality as closely as possible to the independently optimized trajectories. Such an approach would yield more realistic insights into the potential for climate impact mitigation, which remains the focus of ongoing research.

The potential of flight planning to mitigate climate effects explored in this study was focused on European flights due to the validity scope of aCCFs. Updated versions of aCCFs are under development, which will enable assessing the validity of this study's conclusions in other regions.

- ***Comment 2***: Figure 1 is a good overall perspective of the sustainable aviation ecosystem that the authors are operating within. However, it is not clear how the authors derive some of the claims made in the figure. In particular, the "influence on the radiation balance" is an extremely critical element when evaluating sustainable aviation impacts. It is not clear to me how the authors decided on the size of the warming/cooling impacts. It is also not clear how the "uncertainty levels" are determined. If Figure 1 is more notional/conjectured by the authors, it must be stated clearly. If Figure 1 is based on numerical data, it would be great to cite the source. As is, Figure 1 seems to be extremely authoritative in saying, e.g., contrail's cooling impact is significantly less than its warming impacts, and that the uncertainty levels between warming and cooling impacts can be compared (given the blurriness level). At best, this is a bit confusing, at worst, it is misleading.

  Response: The authors agree with the reviewer that the representation of the climate effects of individual species and their associated uncertainties was unclear, and we appreciate this valuable feedback. In the revised manuscript, we have modified this part of the figure. We now represent the radiative forcing of different species using bar plots, with uncertainties indicated by error bars. The radiative forcing values for each forcing agent are based on the state-of-the-art aviation-induced climate impact estimates provided by Lee et al. (2021) [6], cited in both the figure and caption.

  Changed Figure: Figure 1.

- ***Comment 3***: Some minor comments:

  – There are many typos throughout the paper that the authors should double-check (e.g., "two-thirds" is misspelled in the caption for Figure 1); In the subtitle for Figure 7(a), the word "humidity" is misspelled.

Response: Thank you for your careful review. We have thoroughly rechecked the paper and corrected all grammatical and typographical errors.

– This may be a stylistic difference (I will defer to the journal copy editors), but some of the figure captions (e.g., on Figure 6) are extremely long. This to me breaks up the flow of the paper, and is distracting – I would encourage the authors to integrate the explanations of the figures naturally into the appropriate places within the main text of the paper.

Response: Thank you for your suggestion. The initial aim was to make the figures self-explanatory through their captions. In response, in the revised manuscript, we have shortened the figure captions by removing redundant information already covered in the main text.

Redundant sentences removed from figure captions:

Figure 1:

~~By adjusting flight paths to avoid forming persistent warming contrails (e.g., areas of ice supersaturation), the corresponding climate impact can be mitigated.~~

Figure 2:

~~In daylight hours, when possible, aircraft tend to generate cooling contrails by flying through these areas of persistent contrail formation, thereby crossing uncertain regions [14]. **F-ATR20**: Average temperature response over the next 20 years with the future emission scenario, **SOC**: Simple operating cost.~~

Figure 4:

~~Examining the climate effects associated with climate-optimal routing options limited to increases of 0.2% and 2.0% in operating costs reveals that the mitigation potential is primarily derived from contrails. Referring to Figure S3, it can be concluded that on days with a higher probability of contrail formation, the potential for mitigation is greater, as observed in October and December. In contrast, during summer months, characterized by a lower likelihood of forming persistent contrails, the mitigation potential is reduced compared to other seasons~~

Figure 6:

~~Flying at lower altitudes is generally effective in mitigating the climate effects of non-CO_2 forcing agents, including contrails, NO_x emissions, and H_2O emissions. A decrease in speed leads to reduced fuel flow and NO_x emissions index, thus lowering NO_x emissions.~~

~~In scenarios permitting up to 30% of flights to reroute, changes in flight profiles are generally smaller than in scenarios with no rerouting restrictions, except on days characterized by significant climate impact mitigation opportunities. In such cases, the extra cost is primarily allocated to days and flights with the highest mitigation potential. As a result, with a smaller number of flights being rerouted, the optimizer tends to select the most climate-optimized routes from the set of alternatives for these flights (Methods, Aircraft Trajectory Optimization), leading to large reductions in speed on days with high mitigation potential to further decrease NO_x emissions alongside contrails climate impact. Figure S7 presents a comparison of flight profiles between the two climate-optimized routing options concerning a 2.0% additional cost.~~

Sentences moved to the main text:

Figure S7 presents a comparison of flight profiles between the two climate-optimized routing options concerning a 2.0% additional cost.

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The authors

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