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EDITORIAL

Reviews and Responses for
A Geospatial Approach to Modeling Airspace Risk Factors

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Reviewers: Esther Calvo Fernández, Fedja Netjasov, and Christian Verdonk Gallego

Editor: Enrico Spinielli

1. Original paper

DOI for the original paper: https://doi.org/10.59490/joas.2025.7402

2. Review - round 1

2.1 Reviewer 1

In this paper, the authors undertake an examination of midair collision risk using advanced geospatial modeling techniques and ADS-B data. Through innovative methodologies, the paper not only addresses existing gaps in airspace safety analysis but also proposes a framework for evaluating and mitigating collision risks in increasingly crowded skies.

Furthermore, the most remarkable contribution of this paper is its development of a dynamic risk assessment model that transcends traditional static analysis by incorporating real-time data and spatial analysis. This approach significantly enhances the accuracy and relevance of midair collision predictions, providing actionable insights for airspace management and safety optimization.

The contribution is valuable, but I have some remarks that I would like the authors to address:

a) In my opinion, the main and most remarkable contribution of this paper is its innovative use of Discrete Global Grid Systems for airspace analysis. However, I think this analysis is rather short and does not provide enough details on the potential for broader application and scalability of the proposed model. A deeper exploration of how this methodology can be adapted or scaled for use in different regions or under varying airspace conditions would greatly enhance the paper's utility and impact.

I would like to see a more comprehensive analysis of:

- The model's applicability in international airspace contexts, including regions with varying levels of ADS-B adoption.
- The potential for integrating other data sources, such as weather data, to further refine risk assessments.

I do not expect the authors to provide an exhaustive analysis (actually, this could be included in a future publication); however, I would appreciate having at least some preliminary analysis. For instance:

- A comparison of model predictions with historical collision data or near-miss incidents to validate its predictive accuracy.
- An examination of model performance in high-traffic scenarios, including simulations of peak travel seasons or major events.

b) In line 172, it is mentioned: “The case study was developed in order to satisfy the six geospatial model requirements listed in section 1”; however, those requirements are listed in section 2.

c) I would appreciate further clarification on a specific aspect of the risk metric (line 184-186) formula detailed in your study. The formula, as I understand it, aims to measure the proximity in time of two aircraft towards the same point in space (the absolute difference of critical times) and the imminence of this proximity (the minimum of the critical times). The formula is presented as: riskmetric = abs(ct(c1−a1)t1 − ct(c1−a2)t2) + min(ct(c1−a1)t1, ct(c1−a2)t2)

My confusion arises with the mention of "t1 and t2". In the context of assessing collision risk at a specific moment, I would assume both "critical times" should refer to the same temporal instance with respect to the same centroid (c1). Yet, the formula seems to imply different temporal instances for each aircraft’s critical time calculation. Furthermore, the subsequent explanation mentions "the critical times at time t1 and t2 between centroids c1 and c2 and aircraft a1 and a2," which introduces an additional centroid (c2) not previously accounted for in the formula. This inclusion leaves me puzzled, as the formula only references a single centroid (c1). Could you please provide further insight into these aspects? Specifically:

- The rationale behind using different temporal markers (t1 and t2) for calculating the critical times of aircraft a1 and a2 towards the same centroid.
- The reference to a second centroid (c2) in the explanation following the formula, and its role or relevance in the context of the model, given its absence in the formula itself.

d) I have a specific question regarding the "Single aircraft scenario" (line 211-216) you described. Could you please elaborate on the reasoning behind including a scenario with a single aircraft in a study primarily focused on assessing the risk of midair collisions between aircraft? While I understand that this scenario inherently presents no risk of collision between aircraft, I wonder if it serves a specific purpose in your model validation or if it perhaps considers potential collision risks with other non-aircraft entities, such as terrain?

2.2 Reviewer 2

Brief Summary:

This paper addresses the need for an innovative geospatial model tailored to complex airspace management, aiming to study any constituent entity of those airspace environments. It advocates for the application of Discrete Global Grid Systems (DGGS), based on the arrangement of the airspace into discrete cells with centroids, presenting arguments for their suitability across six newly proposed criteria. These criteria, introduced for the first time in this research, are a significant contribution to the field of large data analysis in the area.

Following a very detailed, comprehensive, and fit-for-purpose literature review, the paper shifts focus to practical applications by detailing a straightforward Mid Air Collision Risk model. The model presented aims to define a new risk model based on the relative dynamics of the aircraft concerning the centroids defined in the DGGS, rather than the relative dynamics between them, with the goal of facilitating easy implementation and understanding. The paper attempts to argue its practical relevance by presenting four use cases, each accompanied by visual representations that trace the evolution of these scenarios. The first two use cases are used for verification purposes, while the third and fourth are more actual “real-life” applications.

The results fail to convince of the usefulness of the cited risk metric. The key result, which has not been demonstrated or shown in the paper, is the evolution of the risk metric over time, for each grid cell, considering that as a feature associated with such centroids. However, it is clear to me that the use of such a DGGS is a major step forward as a key enabler for understanding the complexities and airspace risk encounters, mostly for UAS operations (Urban Air Mobility, Uncrewed Traffic Management). My recommendation is for the authors to undertake a major review, with the suggestion of orienting the use case towards metrics that can inform the risk assessment methodologies for UAS operations. Specifically, the Air Risk for SORA considers the density of manned aviation in the airspace of study. This kind of system may be a perfect technical enabler for this.

1. Originality and Contribution to the Field:
   The research presents a technical solution that appears to be a first-in-class for this type of study. The authors effectively demonstrate the theoretical relevance of these models. However, for a more robust foundation, I recommend reviewing and possibly including the following papers, which deal with regular grids in alignment with your proposal:
   - S. Ruiz, M. A. Piera, J. Nosedal, and A. Ranieri, ’Strategic de-confliction in the presence of a large number of 4D trajectories using a causal modeling approach’, 2014.
   - A. Jardines, M. Soler, and J. Garc, ’Data-Driven Occupancy Prediction in Adverse Weather Conditions using Thunderstorm and Traffic Observations’.
   - N. Schefers, M. A. Piera, J. J. Ramos, and J. Nosedal, ’Causal Analysis of Airline Trajectory Preferences to Improve Airspace Capacity’, Procedia Comput. Sci., vol. 104, December 2016, pp. 321–328.

   In relation to the need of generating the risk for all centroids, I would recommend the authors to adjust the need to compute this risk for all centroids or just a partial view of them. In airspaces for en-route operations, the density of the airspace is not larger, but for certain centroids that it is not the case. So, considering that the airspace can be fully characterised in terms of these centroids, a database working with them only would need to populate the specific features for some of them.
   However, the MAC model is not really fit-for-purpose, and it does not provide an added value to the risk modelling in the airspace. However, if it is properly scaled for a large period of time, it can be seen which centroids really have a higher risk, and therefore, the consideration for the study by safety management systems by Air Navigation Service Providers, or for the planning of UAS operations considering the likelihood of an airspace encounter. Consider that the risk is usually studied in terms of the separation between the encounter and the rate of closure. Your approach works can fit very well with this second element, but it fails to determine to transform the “temporal” risk measure to the actual separation distance. For example, in the case of the airport (LGA), aircraft in Final Approach should be separated at least 3NM, and if you were going to study the centroids along the descent path, it should be considered like that.
   I would recommend to include the PhD Thesis of Eduardo Garcia (Development of a 3D- Dimensional Mathematical Collision Risk Model Based on Recorded Aircraft Trajectories to Estimate the Safety Level in High Density En-Route Airspaces
   upm.es/21884/1/EDUARDO_JOSE_GARCIA_GONZALEZ.pdf)
2. Clarity of Research Question:
   The clarity of the research question could be improved by focusing more specifically on the six proposed criteria and how the use case (risk modelling) benefits from the use of the Discrete Global Grid Systems (DGGS).
3. Methodological Rigor:

While the use case is deemed fit-for-purpose, the proposed definition of the risk collision model fails to demonstrate its usefulness as a risk metric effectively. However, there is potential for innovation in how the risk at the centroids evolves, and further exploration in this area could strengthen the manuscript.

4. Quality of Presentation:
   Figure 5 is not relevant for the paper. Figure 6 and 7 require revision for better visibility and comprehension. Additionally, risk measurements for more centroids should be included, and risk colors should be accompanied by units of risk as defined by the authors (seconds). Tables with the historical evolution of the risk metrics for critical centroids should be included, maybe in an appendix.

Recommendation

A major revision is recommended, adjusting the Use Case to something more useful. A proposal might be to study the density of manned aircraft in Class G airspace and explore the evolution of density in each centroid more comprehensively. It is recommended to the authors to review the SORA methodology for Specific Operation Risk Assessment of UAS Operations. One key step is the determination of the risk encounter with manned aviation, and having a technical enabler like DGGS for characterising the airspace may be a substantial advancement in the field.

If maintaining the use case with Collision Risk, it is crucial to demonstrate the evolution of the indicator for specific cells, especially those associated with procedures at the airport of study (LGA).

2.3 Reviewer 3

GENARAL REMARKS:

Although paper is emphasizing in the Introduction section a "… need to develop new methods for modelling complex airspace environments…" and also in Research Objective section that paper will "… develop a methodology for creating a geospatial model of complex airspace environments" – this is not explicitly shown in the paper! Paper should be significantly improved in this part.

The application of a DGGS framework seems very simple – a geospatial airspace model is based on division of big volume into smaller cubes of certain dimensions! Authors didn't provide any explanation of influence of cell dimensions on risk values? On LGA example - cubes are 1km x 1km. It seems a pretty large for a safety assessment purpose? Are dimensions of cubes dependant of vehicle size? It should be. Shouldn't be the same for commercial aircraft and for a drone. Please elaborate more.

Related to midair collision risk model – although proposed model is rudimentary as authors say, it is not clear to me. I do not understand why in equation (1) authors were summing two values (abs and min part)? Value of risk ... domain should also be explained. It is unusual that lower risk is most severe!!! (as stated in Section 5). Please provide more explanation and description. Further on - it is not clear from Figures 2a and 2b how model is calculating risk based on relative position vectors.

Authors are claiming that "air vehicles are agnostic". Model considers aircraft as material points (aircraft trajectory is given by ADS-B data as a sequence of points), which in case of airplane could be wrong – a collision is not a situation when to material points came to certain proximity or collide. It could happen much before.

Results section - Two aircraft scenario - Example seems to me as not correct! One aircraft is flying on a certain height (which is not known) while other is landing ... there is not even theoretical possibility for collision ... Three aircraft scenario – "…relative position vectors of each pair of aircraft are converging at the fastest rate …" – this might be the case but it's not clear how the risk could be higher? Aircraft trajectories are diverging both in vertical and horizontal plane?

Conclusion - Author claim that model "…can perform time-varying analysis in a computationally efficient manner". This is not shown! We can only believe in that.

CONCLUDING REMARKS:

I believe that DGGS approach for airspace modeling has a potential but in this form this is not evident. I am encouraging authors to improve the paper. Methodology part should be significantly improved, emphasizing DGGS framework and ability of geospatial airspace model. Objective of the paper is not clear as well. Also, who can benefit from this kind of modeling? Who can use it and for what?

3. Response - round 1

3.1 Response to reviewer 1

1.1 Summary of reviewer #1 comments

In this paper, the authors undertake an examination of midair collision risk using advanced geospatial modeling techniques and ADS-B data. Through innovative methodologies, the paper not only addresses existing gaps in airspace safety analysis but also proposes a framework for evaluating and mitigating collision risks in increasingly crowded skies.

Furthermore, the most remarkable contribution of this paper is its development of a dynamic risk assessment model that transcends traditional static analysis by incorporating real-time data and spatial analysis. This approach significantly enhances the accuracy and relevance of midair collision predictions, providing actionable insights for airspace management and safety optimization.

The contribution is valuable, but I have some remarks that I would like the authors to address:

1.2 Scaling the method

In my opinion, the main and most remarkable contribution of this paper is its innovative use of Discrete Global Grid Systems for airspace analysis. However, I think this analysis is rather short and does not provide enough details on the potential for broader application and scalability of the proposed model. A deeper exploration of how this methodology can be adapted or scaled for use in different regions or under varying airspace conditions would greatly enhance the paper's utility and impact.

I would like to see a more comprehensive analysis of:

1. The model's applicability in international airspace contexts, including regions with varying levels of ADS-B adoption.
2. The potential for integrating other data sources, such as weather data, to further refine risk assessments.

I do not expect the authors to provide an exhaustive analysis (actually, this could be included in a future publication); however, I would appreciate having at least some preliminary analysis. For instance:

1. A comparison of model predictions with historical collision data or near-miss incidents to validate its predictive accuracy.
2. An examination of model performance in high-traffic scenarios, including simulations of peak travel seasons or major events.

Response

Methods applicability in international airspace contexts: The airspace model was designed with scalability in mind. It relies on knowing the 3D position of airspace entities (like weather storms or aircraft) and it assumes that the position obtained from the data is accurate. This means that in theory, the proposed model can be scaled to study any airspace region, including international airspace contexts, if data on the airspace entities of interest is available. In the paper, 2 different airspace regions are used to show this: a larger 100 km cubic area for presenting an overview of weather patterns and a smaller, higher resolution 5km cubic area used for all four scenarios presented in the results Section 5.

Potential for integrating other data sources: Extensive work was performed on this paper during the course of this review to address this comment. The new revision now includes a second data source (weather radar data) in addition to ADS-B air traffic data. Airspace risk results produced by the two data sources are compared in three steps of incremental complexity: 1) weather-only risk, 2) air traffic-only risk, and 3) combined risk. These added results demonstrate that the model can be adapted to include multiple types of data for different types of airspace entities individually and also in a manner that combines each data type in one same holistic airspace model.

Comparison of model predictions with historical collision data or near-miss incidents: A comparison of model predictions with historical collision data or near-miss incidents is a great idea to validate the work presented in this paper. It would be interesting and relevant validation of the proposed method, but it is out of scope for this paper and could possibly be addressed in future research.

Examination of model performance in high-traffic scenarios or major events: The two datasets that were selected for this paper for weather and air traffic data were chosen specifically for demonstrating that the model can be practical for multiple high-severity weather storms and for high-density air traffic scenarios. The air traffic data was selected during the United States Thanksgiving holiday weekend from November 23 to November 25, 2022, around the New York Metropolitan area, which features on average some of the highest traffic volumes yearly. The weather data was taken from January 2, 2022, at 21:00, which featured a historical winter snowstorm. Because the objective of this paper is to introduce the airspace model, simpler cases of one storm and two aircraft scenarios were introduced for validation purposes (easier to interpret and validate than for a higher number of entities). Then, two storms and three aircraft scenarios were used for demonstrating the model's scalability to n number of storms/aircraft (Change #7).

Changes in manuscript: There are no specific changes associated with comment 1.2 in the revised document.

1.3 Correction on section reference

In line 172, it is mentioned: "The case study was developed in order to satisfy the six geospatial model requirements listed in section 1"; however, those requirements are listed in section 2.

Response

All references to section numbers were updated to reflect the new revisions made to the paper.

Changes in manuscript: Changes #3, 4, 6, and 18 as identified in the revised document.

1.4 Clarification of the risk metric equations

I would appreciate further clarification on a specific aspect of the risk metric (line 184-186) formula detailed in your study.

The formula, as I understand it, aims to measure the proximity in time of two aircraft towards the same point in space (the absolute difference of critical times) and the imminence of this proximity (the minimum of the critical times).

The formula is presented as:

$$\text{riskmetric} = \text{abs}(ct(c1\check{\ }a1)t1\check{\ }ct(c1\check{\ }a2)t2) + \min(ct(c1\check{\ }a1)t1, ct(c1\check{\ }a2)t2)$$

My confusion arises with the mention of "t1 and t2". In the context of assessing collision risk at a specific moment, I would assume both "critical times" should refer to the same temporal instance with respect to the same centroid (c1).

Yet, the formula seems to imply different temporal instances for each aircraft's critical time calculation.

Furthermore, the subsequent explanation mentions "the critical times at time t1 and t2 between centroids c1 and c2 and aircraft a1 and a2," which introduces an additional centroid (c2) not previously accounted for in the formula. This inclusion leaves me puzzled, as the formula only references a single centroid (c1).

Could you please provide further insight into these aspects? Specifically:

1. The rationale behind using different temporal markers (t1 and t2) for calculating the critical times of aircraft a1 and a2 towards the same centroid.
2. The reference to a second centroid (c2) in the explanation following the formula, and its role or relevance in the context of the model, given its absence in the formula itself.

Response

The methodology section (Section 4) was completely re-done to address this comment. More specifically, Section 4.3 now includes a more detailed explanation of the equations and methodology used in the proposed risk model. In summary, the risk model calculates risk metrics for every centroid in the grid at every time step, where the risk metrics are in the form of the probability of a worst-case event occurring. The worst-case events for weather and air traffic are described in Section 4.3, and there are three different risk metrics that are used in the paper: a weather-only risk metric, an air traffic-only risk metric, and a combined weather and air traffic risk metric. In addition to the more detailed description of the risk model made during this revision of the paper in Section 4.3, pseudocodes were added in Appendix 12.2 and 12.3 detailing the logical breakdown of the risk model used in the Python code to obtain the results presented in the paper.

Changes in manuscript: Changes #9, 18, and 19 as identified in the revised document.

1.5 Relevance of the single aircraft scenario

I have a specific question regarding the "Single aircraft scenario" (line 211-216) you described. Could you please elaborate on the reasoning behind including a scenario with a single aircraft in a study primarily focused on assessing the risk of midair collisions between aircraft? While I understand that this scenario inherently presents no risk of collision between aircraft, I wonder if it serves a specific purpose in your model validation or if it perhaps considers potential collision risks with other non-aircraft entities, such as terrain?

Response

The intent of using a single aircraft scenario in the 1st submission of the paper was simply to show that a single aircraft scenario produced no risk of midair collision for all centroids and times. The reasoning behind using this approach was to present the results of the model in a sequential manner using increasingly complex scenarios (starting with a 1 aircraft scenario followed by a 2 aircraft scenario and then by a 3 aircraft scenario).

After consideration, the single aircraft scenario was removed from the paper, as was highlighted by review #1's comment 1.5, since it does not contribute to demonstrating or validating the proposed method. Rather, more focus was attributed to the 2 and 3 aircraft scenarios in the presentation and discussion of the results.

Changes in manuscript: Changes #11 as identified in the revised document.

3.2 Response to reviewer 2

2.1 Summary of reviewer #2 comments

This paper addresses the need for an innovative geospatial model tailored to complex airspace management, aiming to study any constituent entity of those airspace environments. It advocates for the application of Discrete Global Grid Systems (DGGS), based on the arrangement of the airspace into discrete cells with centroids, presenting arguments for their suitability across six newly proposed criteria. These criteria, introduced for the first time in this research, are a significant contribution to the field of large data analysis in the area.

Following a very detailed, comprehensive, and fit-for-purpose literature review, the paper shifts focus to practical applications by detailing a straightforward Mid-Air Collision Risk model. The model presented aims to define a new risk model based on the relative dynamics of the aircraft concerning the centroids defined in the DGGS, rather than the relative dynamics between them, with the goal of facilitating easy implementation and understanding. The paper attempts to argue its practical relevance by presenting four use cases, each accompanied by visual representations that trace the evolution of these scenarios. The first two use cases are used for verification purposes, while the third and fourth are more actual "real-life" applications.

The results fail to convince of the usefulness of the cited risk metric. The key result, which has not been demonstrated or shown in the paper, is the evolution of the risk metric over time, for each grid cell, considering that as a feature associated with such centroids. However, it is clear to me that the use of such a DGGS is a major step forward as a key enabler for understanding the complexities and airspace risk encounters, mostly for UAS operations (Urban Air Mobility, Uncrewed Traffic Management).

My recommendation is for the authors to undertake a major review, with the suggestion of orienting the use case towards metrics that can inform the risk assessment methodologies for UAS operations. Specifically, the Air Risk for SORA considers the density of manned aviation in the airspace of study. This kind of system may be a perfect technical enabler for this.

Response

A major revision of the paper was done based on the reviewer's recommendations. Specifically, much focus was placed on improving the results section to demonstrate the usefulness and practicality of the developed airspace model. This was mainly done by making use of 4 key centroids used as examples showing their evolution over time for each of the presented scenarios. Additional examples were provided in the new results presenting cases of high weather risk, low weather risk, high mid-air collision risk, and low mid-air collision risk. The paper also demonstrated how the model can be used to integrate multiple risk metrics for weather-related and mid-air collision-related risk into a combined risk metric that presents a more accurate and useful representation of real-life conditions around these 4 key centroids.

Changes in manuscript: Changes #9, #19, and #18 as identified in the revised document.

2.2 Originality and contribution to the field

The research presents a technical solution that appears to be a first-in-class for this type of study. The authors effectively demonstrate the theoretical relevance of these models. However, for a more robust foundation, I recommend reviewing and possibly including the following papers, which deal with regular grids in alignment with your proposal:

- S. Ruiz, M. A. Piera, J. Nosedal, and A. Ranieri, 'Strategic de-confliction in the presence of a large number of 4D trajectories using a causal modeling approach', 2014.
- Jardines, M. Soler, and J. Garc, 'Data-Driven Occupancy Prediction in Adverse Weather Conditions using Thunderstorm and Traffic Observations'.
- N. Schefers, M. A. Piera, J. J. Ramos, and J. Nosedal, 'Causal Analysis of Airline Trajectory Preferences to Improve Airspace Capacity', Procedia Comput. Sci., vol. 104, December 2016, pp. 321–328.

In relation to the need of generating the risk for all centroids, I would recommend the authors to adjust the need to compute this risk for all centroids or just a partial view of them. In airspaces for en-route operations, the density of the airspace is not larger, but for certain centroids that is not the case. So, considering that the airspace can be fully characterised in terms of these centroids, a database working with them only would need to populate the specific features for some of them.

However, the MAC model is not really fit-for-purpose, and it does not provide an added value to the risk modelling in the airspace. However, if it is properly scaled for a large period of time, it can be seen which centroids really have a higher risk, and therefore, the consideration for the study by safety management systems by Air Navigation Service Providers, or for the planning of UAS operations considering the likelihood of an airspace encounter. Consider that the risk is usually studied in terms of the separation between the encounter and the rate of closure. Your approach works can fit very well with this second element, but it fails to determine to transform the "temporal" risk measure to the actual separation distance. For example, in the case of the airport (LGA), aircraft in Final Approach should be separated at least 3NM, and if you were going to study the centroids along the descent path, it should be considered like that.

I would recommend including the PhD Thesis of Eduardo Garcia (Development of a 3D- Dimensional Mathematical Collision Risk Model Based on Recorded Aircraft Trajectories to Estimate the Safety Level in High Density En-Route Airspaces
upm.es/21884/1/EDUARDO_JOSE_GARCIA_GONZALEZ.pdf)

Response

Each of the references provided by reviewer #2 were studied and were integrated into the new version of the literature review in Sections 3.1 and 3.3.

Changes in manuscript: Changes #2 and 5 as identified in the revised document.

2.3 Clarity of research question

The clarity of the research question could be improved by focusing more specifically on the six proposed criteria and how the use case (risk modelling) benefits from the use of the Discrete Global Grid Systems (DGGS).

Response

The research objective was simplified and clarified in Section 2 (change #1). A discussion was added at the end of the methodology Section 4.3 listing how the risk model was designed to address each of the 6 requirements needed to satisfy the research objective (change #17). Lastly, the new results presented in Section 5 (Section 5.5) now include a discussion at the end of the section explaining how each of the 6 requirements of the research objective are satisfied based on the produced results in the paper.

Changes in manuscript: Changes #1, 17, and 18 as identified in the revised document.

2.4 Methodological rigor

While the use case is deemed fit-for-purpose, the proposed definition of the risk collision model fails to demonstrate its usefulness as a risk metric effectively. However, there is potential for innovation in how the risk at the centroids evolves, and further exploration in this area could strengthen the manuscript.

Response

The methodology section (Section 4) was completely re-done to address this comment. More specifically, Section 4.3 now includes a more detailed explanation of the equations and methodology used in the proposed risk model. In summary, the risk model calculates risk metrics for every centroid in the grid at every time step, where the risk metrics are in the form of the probability of a worst-case event occurring. The worst-case events for weather and air traffic are described in Section 4.3 and there are three different risk metrics that are used in the paper: a weather only risk metric, an air traffic only risk metric, and a combined weather and air traffic risk metric. In addition to the more detailed description of the risk model made during this revision of the paper in Section 4.3, pseudocodes were added in Appendix 12.2 and 12.3 detailing the logical breakdown of the risk model used in the Python code to obtain the results presented in the paper. The results presented in Section 5 were reworked to now demonstrate more clearly the usefulness of the model by showing the evolution of 4 selected centroids of interest over time for each of the presented scenarios.

Changes in manuscript: Changes #9, 18, and 19 as identified in the revised document.

2.5 Quality of presentation

Figure 5 is not relevant for the paper.

Figure 6 and 7 require revision for better visibility and comprehension. Additionally, risk measurements for more centroids should be included, and risk colors should be accompanied by units of risk as defined by the authors (seconds).

Tables with the historical evolution of the risk metrics for critical centroids should be included, maybe in an appendix.

Response

Figure 5 as well as the results and discussion for the 1 aircraft scenario were removed from the paper since they did not contribute to demonstrating or validating the proposed method. Rather, more focus was attributed to the 2 and 3 aircraft scenarios in the presentation and discussion of the results (Change 11).

Figure 6 is now replaced by Figure 14 (Change 13). The figure was revised to identify the aircraft and storm cell positions more clearly and the transparency of the risk centroids was increased to better visualize the results. Additionally, Figures 15 and 16 were added, which feature 2D visuals of the same results as the 3D results of Figure 14 at 500m and 2400m respectively (the altitudes of the 2 selected centroids of interest). The same approach was used for Figure 7 which was replaced by Figure 17 and is now accompanied by 2D risk maps in Figures 18 and 19 (Change 14).

To address the comment on producing tables with historical evolution of the risk metrics for critical centroids, the results in Section 5 of the paper were completely re-worked and now make use of 4 different selected centroids of interest to demonstrate the validity and practicality of the method. Instead of using tables, new figures were added which show the evolution of the risk metric values over time for these 4 key centroids (Figures 8, 13, and 21) in Changes #10, 11, 15. These 4 centroids of interest (termed Centroids #1, 2, 3, and 4 in the paper) were chosen since they highlight centroids which were identified to have high weather risk, low weather risk, high air traffic risk and low air traffic risk respectively. In addition, Section 5.3 discusses results where the proposed methodology is used to combine both weather and air traffic risk and the evolution of Centroids 1, 2, 3, and 4 over time for combined risk is also discussed in this section.

Changes in manuscript: Changes #10, 11, 13, 14, and 15 as identified in the revised document.

2.6 Recommendation

A major revision is recommended, adjusting the Use Case to something more useful. A proposal might be to study the density of manned aircraft in Class G airspace and explore the evolution of density in each centroid more comprehensively. It is recommended to the authors to review the SORA methodology for Specific Operation Risk Assessment of UAS Operations. One key step is the determination of the risk encounter with manned aviation, and having a technical enabler like DGGS for characterising the airspace may be a substantial advancement in the field.

If maintaining the use case with Collision Risk, it is crucial to demonstrate the evolution of the indicator for specific cells, especially those associated with procedures at the airport of study (LGA).

Response

The methodology and results sections (Sections 4 and 5) were both completely re-done to address this comment. The use case on mid-air collision risk was improved to address this comment and a use case looking at weather storm cells was added to this revision of the paper to demonstrate the practicality of DGGS frameworks to integrate multiple types of spatial datasets in one comprehensive and more realistic model of airspace risk.

More specifically, Section 4.3 now includes a more detailed explanation of the equations and methodology used in the proposed risk model. In summary, the risk model calculates risk metrics for every centroid in the grid at every time step, where the risk metrics are in the form of the probability of a worst-case event occurring. The two definitions adopted for worst-case events for weather and air traffic are described in Section 4.3 and there are three different risk metrics that are used in the paper to quantify the probability of these worst-case events happening: a weather only risk metric, an air traffic only risk metric, and a combined weather and air traffic risk metric. In addition to the more detailed description of the risk model made during this revision of the paper in Section 4.3, pseudocodes were added in Appendix 12.2 and 12.3 detailing the logical breakdown of the risk model used in the Python code to obtain the results presented in the paper.

The results presented in Section 5 were reworked to now demonstrate more clearly the usefulness of the model by showing the evolution of 4 selected centroids of interest over time for each of the presented scenarios. These 4 centroids of interest (termed Centroids #1, 2, 3, and 4 in the paper) were chosen since they highlight centroids which were identified to have high weather risk, low weather risk, high air traffic risk and low air traffic risk respectively. In addition, Section 5.3 discusses results where the proposed methodology is used to combine both weather and air traffic risk and the evolution of Centroids 1, 2, 3, and 4 over time for combined risk is also discussed in this section.

Changes in manuscript: Changes #10, 11, 13, 14, and 15 as identified in the revised document.

3.3 Response to reviewer 3

3.1 Mismatch between claims and what was done

Although the paper is emphasizing in the Introduction section a "… need to develop new methods for modelling complex airspace environments…" and also in the Research Objective section that the paper will "… develop a methodology for creating a geospatial model of complex airspace environments" – this is not explicitly shown in the paper! The paper should be significantly improved in this part.

Response

The research objective was simplified and clarified in Section 2 (change #1). A discussion was added at the end of the methodology Section 4.3 listing how the risk model was designed to address each of the 6 requirements needed to satisfy the research objective (change #17). Lastly, the new results presented in Section 5 (Section 5.5) now include a discussion at the end of the section explaining how each of the 6 requirements of the research objective are satisfied based on the produced results in the paper.

Changes in manuscript: Changes #1, #17, and 18 as identified in the revised document.

3.2 Add discussion on cell dimension

The application of a DGGS framework seems very simple – a geospatial airspace model is based on the division of a big volume into smaller cubes of certain dimensions! Authors didn't provide any explanation of the influence of cell dimensions on risk values? On LGA example - cubes are 1km x 1km. It seems pretty large for a safety assessment purpose? Are dimensions of cubes dependant of vehicle size? It should be. Shouldn't be the same for commercial aircraft and for a drone. Please elaborate more.

Response

The application of a DGGS framework was intentionally chosen to be simple in nature in order to be easily scalable to larger volumes of geospatial data and still be able to produce practical and interpretable insights in a computationally efficient manner. The description of the development of the DGGS geospatial airspace model was re-written in Section 4.2 to now include descriptions for the terms 'DGGS grid width' and 'DGGS cell size'. The purpose of this paper is to introduce the developed method rather than to test many cell size & grid width combinations. Consequently, 1 set of each was used for the weather only scenarios and air traffic only scenarios, although the authors plan to study the effect on the results of testing multiple combinations of DGGS grid width and DGGS cell size in future work. The set of DGGS grid width and DGGS cell size for the weather only results are 100 km and 2 km and the set of DGGS grid width and DGGS cell size for the air traffic only results are 5 km and 100 m. It is discussed in Section 4.2 that a smaller cell size and grid with is more effective for the air traffic scenarios when compared to the weather scenarios mainly because of the significant difference in the rates of change of position observed between aircraft movement and storm cell movement. Also, a common set of DGGS grid width and DGGS cell size values of 5 km and 100 m were used for the combined results of Section 5.3.

Changes in manuscript: Changes #8 as identified in the revised document.

3.3 Clarify the proposed risk model

Related to midair collision risk model – although proposed model is rudimentary as authors say, it is not clear to me. I do not understand why in equation (1) authors were summing two values (abs and min part)? Value of risk ... domain should also be explained. It is unusual that lower risk is most severe!!! (as stated in Section 5). Please provide more explanation and description. Further on - it is not clear from Figures 2a and 2b how model is calculating risk based on relative position vectors.

Response

The methodology section (Section 4) was completely re-done to address this comment. More specifically, Section 4.3 now includes a more detailed explanation of the equations and methodology used in the proposed risk model. In summary, the risk model calculates risk metrics for every centroid in the grid at every time step, where the risk metrics are in the form of the probability of a worst-case event occurring. The worst-case events for weather and air traffic are described in Section 4.3 and there are three different risk metrics that are used in the paper: a weather only risk metric, an air traffic only risk metric, and a combined weather and air traffic risk metric. In addition to the more detailed description of the risk model made during this revision of the paper in Section 4.3, pseudocodes were added in Appendix 12.2 and 12.3 detailing the logical breakdown of the risk model used in the Python code to obtain the results presented in the paper. The results presented in Section 5 were reworked to now demonstrate more clearly the usefulness of the model by showing the evolution of 4 selected centroids of interest over time for each of the presented scenarios. These 4 centroids of interest (termed Centroids #1, 2, 3, and 4 in the paper) were chosen since they highlight centroids which were identified to have high weather risk, low weather risk, high air traffic risk and low air traffic risk respectively. In addition, Section 5.3 discusses results where the proposed methodology is used to combine both weather and air traffic risk and the evolution of Centroids 1, 2, 3, and 4 over time for combined risk is also discussed in this section.

Changes in manuscript: Changes #9, #19, and #18 as identified in the revised document.

3.4 Clarification on the definition of a 'collision' used in the paper

Authors are claiming that "air vehicles are agnostic". Model considers aircraft as material points (aircraft trajectory is given by ADS-B data as a sequence of points), which in case of airplane could be wrong – a collision is not a situation when to material points came to certain proximity or collide. It could happen much before.

Response

A definition for a worst-case event was added in Section 4.3 which is the criteria used in the paper to identify a midair collision. The worst-case event for air traffic risk is where both aircraft in a pair of aircraft are exactly positioned at a centroid location for a specific time (see Section 4.3.2 for more details). The reasoning behind this is that the purpose of the proposed model is to be relatively simple, scalable, and data-driven; and using a point-based approach to model midair collisions using ADS-B data is one way to achieve this. Future work could also involve adding a safety margin around the material points-based approach currently in use to define midair collisions, which could also vary based on aircraft model, performance, relative collision speed, etc.

Changes in manuscript: Changes #9 as identified in the revised document.

3.5 Clarify results section

Results section - Two aircraft scenario - Example seems to me as not correct! One aircraft is flying on a certain height (which is not known) while other is landing ... there is not even theoretical possibility for collision ... Three aircraft scenario – "...relative position vectors of each pair of aircraft are converging at the fastest rate ..." – this might be the case but it's not clear how the risk could be higher? Aircraft trajectories are diverging both in vertical and horizontal plane?

Response

The results presented in Section 5 were reworked to now demonstrate more clearly the usefulness of the model by showing the evolution of 4 selected centroids of interest over time for each of the presented scenarios (see Changes #10, #11, #15). These 4 centroids of interest (termed Centroids #1, 2, 3, and 4 in the paper) were chosen since they highlight centroids which were identified to have high weather risk, low weather risk, high air traffic risk and low air traffic risk respectively. In addition, Section 5.3 discusses results where the proposed methodology is used to combine both weather and air traffic risk and the evolution of Centroids 1, 2, 3, and 4 over time for combined risk is also discussed in this section.

Additionally, all figures presented in the results section showing 2D and 3D risk maps were improved since the last paper revision to make the observations made more obvious. The figures were revised to identify the aircraft and storm cell positions more clearly and the transparency of the risk centroids was increased to better visualize the results. Additionally, Figures 15 and 16 were added, which feature 2D visuals of the same results as the 3D results of Figure 14 at 500m and 2400m respectively (the altitudes of the 2 selected centroids of interest). The same approach was used for Figure 7 which was replaced by Figure 17 and is now accompanied by 2D risk maps in Figures 18 and 19 (Change 14).

Changes in manuscript: Changes #14, 10, 11, and 15 as identified in the revised document.

3.6 Add results on computational efficiency

Conclusion - Author claim that model "…can perform time-varying analysis in a computationally efficient manner". This is not shown! We can only believe in that.

Response

A new Section 5.4 in the results was added discussing computational efficiency of the developed model. A table was also added in Appendix 12.4 comparing multiple model run times.

Changes in manuscript: Changes #16 and 20 as identified in the revised document.

3.7 Concluding remarks

I believe that DGGS approach for airspace modeling has a potential but in this form this is not evident. I am encouraging authors to improve the paper. Methodology part should be significantly improved, emphasizing DGGS framework and ability of geospatial airspace model. Objective of the paper is not clear as well. Also, who can benefit from this kind of modeling? Who can use it and for what?

Response

The methodology section (Section 4) was completely re-done to address this comment. More specifically, Section 4.3 now includes a more detailed explanation of the equations and methodology used in the proposed risk model. In summary, the risk model calculates risk metrics for every centroid in the grid at every time step, where the risk metrics are in the form of the probability of a worst-case event occurring. The worst-case events for weather and air traffic are described in Section 4.3 and there are three different risk metrics that are used in the paper: a weather only risk metric, an air traffic only risk metric, and a combined weather and air traffic risk metric. In addition to the more detailed description of the risk model made during this revision of the paper in Section 4.3, pseudocodes were added in Appendix 12.2 and 12.3 detailing the logical breakdown of the risk model used in the Python code to obtain the results presented in the paper. The results presented in Section 5 were reworked to now demonstrate more clearly the usefulness of the model by showing the evolution of 4 selected centroids of interest over time for each of the presented scenarios.

The research objective was simplified and clarified in Section 2 (change #1). A discussion was added at the end of the methodology Section 4.3 listing how the risk model was designed to address each of the 6 requirements needed to satisfy the research objective (change #17). Lastly, the new results presented in Section 5 (Section 5.5) now include a discussion at the end of the section explaining how each of the 6 requirements of the research objective are satisfied based on the produced results in the paper.

Changes in manuscript: Changes #1, 9, 17, 18, and 19 as identified in the revised document.

4. Review - round 2

4.1 Reviewer 1

The revised paper addresses the key points raised in my initial review, demonstrating significant improvements in scalability, methodological clarity, and focus:

a) Scalability: The authors have addressed scalability effectively by integrating meteorological data and using practical scenarios to demonstrate the model's adaptability. While the inclusion of historical validation was requested, their decision to leave this for future work is reasonable. Discussions on limitations in regions with low ADS-B adoption could be expanded.

b) Internal References: All references to sections and requirements have been corrected seamlessly. This issue is resolved.

c) Risk Metric Formula: The authors clarified the formula and provided pseudocode, which makes the methodology reproducible and clear. This was well-addressed.

d) Single Aircraft Scenario: The removal of the single aircraft scenario improves the focus and relevance of the paper.

4.2 Reviewer 2

GENERAL REMARKS:

I am deeply appreciative of the effort the authors invested in improving the paper. The improvement is evident and significant. The authors extended the methodology on weather risk modeling apart from aircraft collision modelling (Section 3). Also, the methodology is presented in more detail (Section 4), and the illustration of the model application is much improved with many 2D and 3D cases analysed (Section 5).

But, details in the methodology part (Section 4.3) revealed that the authors have calculated some risk metric (weather, aircraft, and combined) which are given/assumed to be TIMEs, but then have assigned some probability values to those metrics!? It is not clear how and why the authors did that!? In safety-related literature, safety is an antonym for risk, and risk is usually presented as a probability which is somehow calculated. Here, probability is assigned!? The whole concept is not logical to me! Please provide more explanations.

Computational efficiency (Section 5.4) is handled in more detail. But, still some results should be elaborated (see e.g. #15 – 67 hours spent in calculations!? Is this efficient? Relative to what?)

SPECIFIC REMARKS:

In the Author response to comment 3.1 and 3.7: The authors have stated the following:

- "The research objective was simplified and clarified in Section 2 (change #1)." - I would say it remains the same as in the original version.

- "A discussion was added at the end of the methodology Section 4.3 listing how the risk model was designed to address each of the 6 requirements needed to satisfy the research objective" – It is not. This is missing.

- "Section 5 (Section 5.5) now include a discussion at the end of the section explaining how each of the 6 requirements of the research objective are satisfied based on the produced results in the paper" - This section doesn't exist!

In the Author response to comment 3.2: Discussion has been provided. But, Figure 4 is not following this explanation ... centroids should be placed on 100 m not 1km? Is that it? So, I believe that figure should be modified.

In the Author response to comment 3.3: relative to Change #9 - Why 3 min and 30 min were chosen as min values? Please provide an explanation.

In the Author response to comment 3.7: Although some hints are given in the last paragraph of Section 6, it is still not clearly evident who can benefit from this methodology? Who can use it and for what? Please elaborate.

5. Response - round 2

5.1 Response to reviewer 1

1.1 General remarks

The revised paper addresses the key points raised in my initial review, demonstrating significant improvements in scalability, methodological clarity, and focus:

a) Scalability: The authors have addressed scalability effectively by integrating meteorological data and using practical scenarios to demonstrate the model's adaptability. While the inclusion of historical validation was requested, their decision to leave this for future work is reasonable. Discussions on limitations in regions with low ADS-B adoption could be expanded.

b) Internal References: All references to sections and requirements have been corrected seamlessly. This issue is resolved.

c) Risk Metric Formula: The authors clarified the formula and provided pseudocode, which makes the methodology reproducible and clear. This was well-addressed.

d) Single Aircraft Scenario: The removal of the single aircraft scenario improves the focus and relevance of the paper.

> **Response**
>
> A short description was added in Change #1, where The OpenSky Network dataset is introduced, which highlights the limitations in regions with low ADS-B adoption. Notably, known coverage gaps exist for low-altitude general aviation aircraft operating below 18,000 feet in the United States, where 978 UAT is commonly used, and for certain military and other sensitive government operations which are exempted from ADS-B Out broadcasting in specific conditions.
>
> Changes in manuscript: Change #1 as identified in the revised document.

5.2 Response to reviewer 2

2.1 General remarks

I am deeply appreciative of the effort the authors invested in improving the paper. The improvement is evident and significant. The authors extended the methodology on weather risk modeling apart from aircraft collision modelling (Section 3). Also, the methodology is presented in more detail (Section 4), and the illustration of the model application is much improved with many 2D and 3D cases analysed (Section 5).

Response

Changes in manuscript: There are no specific changes associated with comment 2.1 in the revised document.

2.2 Clarification on the risk metric

But, details in the methodology part (Section 4.3) revealed that the authors have calculated some risk metric (weather, aircraft, and combined) which are given/assumed to be TIMEs, but then have assigned some probability values to those metrics!? It is not clear how and why the authors did that!? In safety-related literature, safety is an antonym for risk, and risk is usually presented as a probability which is somehow calculated. Here, probability is assigned!? The whole concept is not logical to me! Please provide more explanations.

Response

In many domains, including aviation [1] and weather risk analysis [2], time-to-event metrics are commonly used to represent the temporal proximity of a hazardous event, where shorter times indicate higher urgency and potential severity.

The approach of assigning probability values to the calculated risk metric values, which are expressed in units of time, is based on well-established methodologies in safety and risk assessment literature, as discussed in the paragraph below. The proposed model does so using a deterministic threshold-based approach rather than a full probability distribution approach, the latter of which is what you are referring to in your comment, I believe.

The assignment of probability values to the weather and air traffic risk metrics aligns with established practices in risk assessment literature, such as the principles and foundational work outlined by Cook and Unwin [3] for the nuclear safety industry, as well as more recent studies that validate deterministic risk assessment methods done by Assis and Nogueira [4] in the field of environmental safety. The choice to use a deterministic threshold-based approach over probabilistic methods was made based on them offering improved scalability, reduced computational complexity, and ease of interpretation when compared to probabilistic methods [5], which are all requirements for the methodology as outlined in the objectives section (Section 2).

In this study, the worst-case scenario, represented by a risk metric of 0 minutes, is assigned a 100% probability, while the upper limits of 3 minutes for air traffic and 30 minutes for weather risk are assigned a 0% probability, reflecting the point beyond which risk is considered negligible. Similar approaches have been used in various engineering and environmental risk assessments (Oberndorfer et al. [6] for example), where deterministic models define critical thresholds offering a practical solution that can be applied across different datasets without extensive modifications. Vasconcelos et al. [7] explain that deterministic methods provide a more direct and actionable approach to risk management, making them particularly suitable for operational contexts where quick and scalable assessments are needed, whereas probabilistic methods typically require detailed assumptions about underlying distributions and significant computational resources.

Changes #3 and 5 were added to justify the selected risk metric values thresholds for weather and air traffic risk. Change #4 was added to make it clear that we are using a deterministic threshold-based approach rather than a full probability distribution approach. Change #4 also includes a description of why this choice is relevant to our research objectives.

Changes in manuscript: Changes #3, 4, and 5 as identified in the revised document.

2.3 Elaborate more on computational efficiency

Computational efficiency (Section 5.4) is handled in more detail. But, still some results should be elaborated (see e.g. #15 – 67 hours spent in calculations!? Is this efficient? Relative to what?)

Response

Model #15 from Appendix 12.4 uses a 10km grid width and 50m cell size. This corresponds to 8,000,000 centroids in the grid, and we are running the model and making multiple calculations in the code for obtaining the risk metric for each of these centroids every 1 second over the lapse of the dataset, which is 1 week long in this case (approximately 70 GB in size). It was included in the table to show how the methodology can scale from very small models (like #7, 8, 9) to a very large one (like #15). All times produced in the table were obtained using an ASUS ROG Zephyrus G15 laptop with an AMD Ryzen 9 5900HS CPU, an NVIDIA GeForce RTX 3070 GPU, and 16 GB of RAM.

The developed methodology was intentionally designed to be as computationally efficient as possible by doing two things: 1) we use the least amount of information possible (only 3D position over time) to study spatial entities, and 2) we use computationally efficient algorithms (Python modules and Spatialite database querying made for efficient spatial transformations). This approach enables the methodology to be used to analyze very large datasets and study complex airspace scenarios using a minimum amount of information to enable the use of more elaborate and time-consuming algorithms and calculations, which have proven promising in other models found in the literature.

Changes in manuscript: Change #7 as identified in the revised document.

2.4 Research objective

In the Author response to comment 3.1 and 3.7: The authors have stated the following:

- "The research objective was simplified and clarified in Section 2 (change #1)." - I would say it remains the same as in the original version.

Response

With respect to addressing reviewer comments 3.1 and 3.7 from review #1 on the topics of a mismatch between claims and what was done (comment 3.1) and a need to improve the conclusions of the paper (comment 3.7), only minor changes were made to the research objectives stated in Section 2 in Change #1 of review #1 (from the original submission of the paper to the revision #1 submission). Instead, to address reviewer comments 3.1 and 3.7 from review #1, a discussion was added in the conclusion (Section 6) which lists how the new results presented in Section 5 addresses each of the 6 requirements of the research objective (Change #18 from review #1).

Changes in manuscript: There are no specific changes associated with comment 2.4 in the revised document.

2.5 Discussion on the risk model

In the Author response to comment 3.1 and 3.7: The authors have stated the following:

- "A discussion was added at the end of the methodology Section 4.3 listing how the risk model was designed to address each of the 6 requirements needed to satisfy the research objective" – It is not. This is missing.

Response

This is an error on the part of the authors that was made in the response document. The discussion explaining how each of the 6 requirements of the research objective are satisfied based on the produced results is not found in Section 4.3 but rather in the conclusion (Section 6).

Changes in manuscript: There are no specific changes associated with comment 2.5 in the revised document.

2.6 Clarification on Section 5.5

In the Author response to comment 3.1 and 3.7: The authors have stated the following:

- "Section 5 (Section 5.5) now include a discussion at the end of the section explaining how each of the 6 requirements of the research objective are satisfied based on the produced results in the paper" - This section doesn't exist!

Response

This is an error on the part of the authors that was made in the response document. The discussion explaining how each of the 6 requirements of the research objective are satisfied based on the produced results is not found in Section 5.5 but rather in the conclusion (Section 6).

Changes in manuscript: There are no specific changes associated with comment 2.6 in the revised document.

2.7 New figure 4 that is more relevant

In the Author response to comment 3.2: Discussion has been provided. But, Figure 4 is not following this explanation ... centroids should be placed on 100 m not 1km? Is that it? So, I believe that figure should be modified.

Response

Figure 4 is used to illustrate visually the main concepts used in a DGGS framework (the cubic representation of the grid, the cell size, and centroids) rather than to depict the selected values of cell size and grid width used in the results. For this reason, a 1km cell size and 5km grid width are used in Figure 4 (rather than the selected 100m cell size and 5km grid width used in the results) since it is more easily visually interpretable when compared to the 100m cell size and 5km grid width used in the results.

The title of Figure 4 was updated in Change #2 to make this clarification more obvious.

Changes in manuscript: Change #2 as identified in the revised document.

2.8 Elaborate on the rationale behind the risk metric min/max thresholds

In the Author response to comment 3.3: relative to Change #9 - Why 3 min and 30 min were chosen as maximum thresholds? Please provide an explanation.

Response

The selection of 3 minutes for air traffic risk and 30 minutes for weather risk as maximum thresholds, with a worst-case scenario set at 0 minutes for the minimum threshold, is grounded in well-established methodologies from the literature. These thresholds were determined through a combination of historical data analysis to identify points where risk trends stabilized and expert knowledge to incorporate domain-specific considerations (validated by similar values used in existing literature). Historical data analysis has been widely used to pinpoint inflection points where risk values taper off, providing empirical support for the upper thresholds chosen, like the work done by Zhao et al. [8]. Additionally, expert knowledge incorporating domain-specific considerations in choosing these thresholds has been used in risk models in aviation, such as the research done by Kuchar and Yang [9], and utilized similar timeframes of 30 seconds to 5 minutes for collision risk assessments, while weather-related risk models [10] commonly adopt longer timeframes of around 30-60 minutes for storm tracking and decision-making.

One additional challenge encountered while developing our methodology is how the selection of these risk metric maximum thresholds influences the calculated combined risk metric values. This is made particularly challenging because aircraft typically travel at much higher speeds compared to weather storms, in some cases producing different ranges of values between the two. This was addressed by analyzing a large number of potential values and selecting thresholds within a closer range. This option produced a combined risk metric that remained representative and significant across both domains, mitigating discrepancies arising from differing timescales and ensuring meaningful integration of air traffic and weather risk assessments.

The developed model was intentionally designed so that it will work for whatever risk metric threshold the user chooses. Even though this paper is meant to only introduce the methodology and uses values of 3 minutes and 30 minutes, future research could use any number of alternative values or even develop more sophisticated ways to obtain relevant threshold values (statistical methods like quantile-based approaches or Monte Carlo simulations for example).

Changes #3 and 5 were added to justify the selected risk metric values thresholds for weather and air traffic risk. Change #4 was added to make it clear that we are using a deterministic threshold-based approach rather than a full probability distribution approach. Change #4 also includes a description of why this choice is relevant to our research objectives. Change #6 was added to explain the additional challenge encountered with the combined risk metric, which influenced the choice of threshold values of 3 minutes and 30 minutes.

Changes in manuscript: Changes #3, 4, 5, 6 as identified in the revised document.

2.9 Clarify who can benefit from the developed methodology

In the Author response to comment 3.7: Although some hints are given in the last paragraph of Section 6, it is still not clearly evident who can benefit from this methodology? Who can use it and for what? Please elaborate.

Response

Change #8 was added at the end of the conclusion (Section 6) describing in more detail who can benefit from the developed methodology and what main strengths distinguish it from other similar models.

Changes in manuscript: Change #8 as identified in the revised document.

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[10] M. P. Matthews and R. DeLaura, "Decision risk in the use of convective weather forecasts for trajectory-based operations," presented at the 14th AIAA Aviation Technology, Integration, and Operations Conference, 2014, p. 2717.

6. Review - round 3

6.1 Reviewer 1

The revised paper successfully addresses the key points raised in my previous review. The authors have significantly improved the paper, particularly in terms of scalability, methodological clarity, and focus.

I appreciate the effort put into improving the paper, and I believe it is now ready for publication.

6.2 Reviewer 2

The revised paper shows significant improvement over its initial version. The authors have provided comprehensive and satisfactory responses to my previous comments, fully addressing the concerns raised in the first round of review.

In my assessment, this paper represents a valuable contribution to the field of spatial modeling for risk assessment in Air Traffic Management (ATM). I encourage the authors to continue their research in this direction and, in future work, further integrate the spatial grid with temporal and operational dimensions.

For instance, both Use Cases presented are heavily influenced by wind conditions and runway configurations at LGA. It is likely that incorporating these factors will lead to substantial variations in the computed metrics for each spatial cell. As noted, this remains an important avenue for further exploration.

6.3 Reviewer 3

The authors improved the paper significantly. They seriously considered all suggestions and comments and explained them in more detail. The paper is mature enough and is ready for publication. I have neither further comments nor suggestions.