nature portfolio

Peer Review File

Amplified Threat of Tropical Cyclones to U.S. Offshore Wind Energy in a Changing Climate

Corresponding Author: Dr Karthik Balaguru

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

Version 0:

Decision Letter:

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

Dear Dr Balaguru,

Your manuscript titled "Amplified Threat of Tropical Cyclones to U.S. Offshore Wind Energy in a Changing Climate" 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.

Specifically, we ask you to: (i) compare the historical simulation of CMIP6 against the observation in terms of TC occurrence frequency, TC track and TC intensity in the Atlantic basin; (ii) confine the conclusion on the future projection to an uncertainty assessment and add the uncertainty analysis to all analyses conducted in this work; (iii) improve your results section by incorporating a clearer metric discussion, and a careful data consideration and compellingly demonstrate the robustness of the arguments and interpretations in your discussion section.

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:

Link Redacted

** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

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,

Olusegun Dada, PhD
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Alireza Bahadori, PhD
Associate Editor
Communications Earth & Environment

EDITORIAL POLICIES AND FORMAT

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The study "Amplified Threat of Tropical Cyclones to U.S. Offshore Wind Energy in a Changing Climate" employs climate simulations combined with a synthetic TC model to assess the risk to offshore wind farms and turbines posed by Atlantic tropical cyclones under changing climate conditions.
The manuscript is clear and well-written, making it accessible to a broad readership. This is indeed a novel study that is not only important for the scientific community but also for policymakers and investors.
However, after careful consideration, I have some minor comments:

1. Line numbers are missing, which makes it difficult to provide specific comments.
2. Introduction: at line 12. “With the projected development ……..damages are expected to increase even further.” Please add the reference for that?
3. Why the authors focu only on the fragility function of 5 MW turbines? Please comment on it in the introduction. The authors mentioned that future turbine installations in this region will range from 11 MW to 15 MW. I recommend including a fragility analysis for 10 MW or 15 MW turbines, as this would provide valuable information for investors and policymakers.

Results:
1. Please check the labeling of figures 1 and 2? It appears that there are no 'g, ... k' labels on these figures as indicated.
2. On page 5, it is mentioned that 'On average, 27.5% of TCs in RAFT make U.S. landfall over the historical period, consistent with the observed value of about 25.8%'. Please clarify where this analysis is presented? If it is in the supplementary information (SI), please indicate that.

Discussions:
1. Please explicitly state whether the study focuses on floating offshore wind turbines or fixed-bottom wind turbines.

Clarifying this aspect will provide readers with a clearer understanding of the context of the research
2. Please comment on the fragility analysis concerning floating wind turbines. I strongly recommend adding a fragility analysis specifically for floating wind turbines, especially if it differs from the analysis conducted for fixed-bottom turbines.

Methods:
1. It would be beneficial for readers if you could add the input variables used for the RAFT model.

Overall
Overall, the manuscript is well-written. Incorporating the proposed revisions would further improve its clarity and impact. The findings offer valuable insights that are highly relevant and beneficial for wind farm decision-makers, investors, and industry stakeholders.

Reviewer #2 (Remarks to the Author):

This works includes two parts. First, the TC-track and TC-intensity are projected for the future using Risk Analysis Framework for Tropical Cyclones (RAFT) given the projected large-scale winds from CMIP6 dataset. Second, the derived TC-related information is input to turbine fragility functions to assess the risk of to offshore wind turbines posed by Atlantic TCs in future climate.

This manuscript was written well with a good logical flow. However I cannot recommend it to be accepted by this journal. My main concern is large uncertainties existing in the analysis. While the uncertainty is a common issue in climate change projection, the TC-projection seems more serious in this regard due to its high sensitivity to model resolution and model uncertainty.

This work lacks of an effective justification that CMIP6 can well resolve the TC track and TC-intensity in Atlantic basin. Without this justification, all conclusions and findings would be pale and weak. The authors seemed aware of this issue and cited a reference. However this reference was only about RAFT, not related CMIP data at all. The authors should at least compare historic simulation of CMIP6 against the observation in terms of TC occurrence frequency, TC-track and TC-intensity in Atlantic basin. In addition, for scientific rigorousness, any conclusion on the future projection should be confined with an uncertainty assessment. All analyses conducted in this work should add the uncertainty analysis.

Reviewer #3 (Remarks to the Author):

In this interesting paper, the authors to assess how evolving Atlantic tropical cyclone (TC) behavior may impact offshore wind (OSW) resources in a changing climate. Specifically, they use TCs generated by the RAFT model and subsequent fragility analysis to investigate how shifts in TC intensity and landfall frequencies may influence OSW turbines' vulnerability to both yielding and buckling. They find substantial increases in OSW exposure to TCs and significantly amplified risks of both turbine yielding and buckling for both 20- and 50-year storms. Their findings suggest a critical enhancement of the risk TCs pose to OSW infrastructure in a future climate.

Major Comments

1. In the current manuscript, I find the results section somewhat difficult to follow due to some inconsistencies in the text. For instance, in the second subsection it is not always clear whether the authors are discussing the frequency of landfalling TCs or the overall frequency of TCs basin-wide. Similarly, the authors present results for several different regions along U.S. coastlines but do not initially indicate that they will be assessing results at this level (i.e. Gulf vs. Atlantic coasts for yielding/buckling risks, changes to TC wind speed/intensity, and changing landfalling TC frequency, or New York vs. North Carolina vs. Texas for yielding-/buckling-inducing winds). I suggest the authors revise their Results section to provide better clarity on their findings, particularly to ensure that it is clear which metric they are discussing.

2. There are results presented in this manuscript that are not represented visually in a figure or in a table. Specifically, I see no figure/table describing the changing frequency of landfalling TCs that the authors cite as a contributing factor to increased OSW exposure to TCs. I would encourage the authors to carefully consider all the data they present in their results and ensure that it is supported by a figure or table.

3. The Discussion in the current manuscript is exceptionally short relative to what one usually sees in scientific research articles, and while I appreciate the authors' efforts to be concise, I believe they can include additional relevant discussion on the validity of their results, implications of their findings, and caveats to their approach. Regarding these revisions, I will also point out that much of the text in their Results section is interpretation of their findings, rather than statement of results, and would be better suited to the Discussion section. I encourage the authors to carefully consider both sections in regard to this and my previous comments to ensure that their findings, and their interpretation of them, are presented to the reader in the most straightforward and logical way possible.

Minor Comments

1. Figures 1 and 2 – the authors reference panels g, h, j, and k in their figure captions, but these figures only include panels a-f. I encourage the authors to double check that all figure captions and in-text references to figure panels are consistent with the figures themselves.

2. Results—when the authors specify that they associate yielding with Category 2&3 TCs and buckling with Category 4&5 storms in the beginning of the “Tropical Cyclone Impacts on Turbine Risk” subsection, I suggest they either provide a brief explanation of why they make this determination or direct the reader to the Methods, as it is currently not immediately clear that they aren’t simply making this assumption rather than basing their decision on the fragility analysis.

3. I suggest the authors cite additional relevant literature, both in the Introduction but particularly in the Discussion, especially when making broad statements (for example, that previous work suggests a decline in overall TC frequency in a changing climate, or that changes to TC behavior in a changing climate is an active research area).

4. Related to Major Comment 3, I suggest the authors provide additional discussion on how their use of the 5 MW offshore reference turbine as the basis for the fragility analysis may impact the accuracy of their results, given that most OSW turbines in the study region are 11-15 MW in size. I understand that this choice was made based on data availability, but this seems to be an important caveat and the extent to which it may impact the results presented here should be discussed in more detail.

5. I’m noticing some inconsistency regarding the in-text terminology referring to the regions defined in Table 1—for instance, the authors often refer to the Atlantic Coast region as the East Coast. I suggest they carefully revise their text to ensure their region names remain consistent so as not to confuse readers. Again, it would also be helpful to have these regions briefly defined at the beginning of the Results section.

6. As the authors provide individual statistics for the Atlantic and Gulf Coasts in addition to the overall calculated percentages, I suggest they add text to the Methods specifying the latitude and longitude bounds they used to separate these regions for their calculations.

7. In the first paragraph of the Discussion, the authors state that they find overall increases in TC frequency in the study region, but I do not see this finding discussed in the Results section. I suspect they mean there is an increase in the frequency of landfalling TCs, but this needs to be clearer. If that is not the case and they do find an increase in overall future TC frequency in their model, this should be discussed in more detail, as most literature predicts the opposite (see the IPCC AR6, https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-11/, and related references therein).

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 Balaguru,

Your revised manuscript titled "Amplified Threat of Tropical Cyclones to U.S. Offshore Wind Energy in a Changing Climate" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to 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,

Alireza Bahadori, PhD
Associate Editor
Communications Earth & Environment

Olusegun Dada, PhD
Editorial Board Member
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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have improved the manuscript, addressing all comments thoroughly. Accepted.

Reviewer #2 (Remarks to the Author):

This is a revised version, which I reviewed before. I found that the authors have well addressed my concerns. I do not have any more questions.

Reviewer #3 (Remarks to the Author):

I am exceptionally satisfied with the authors' responses to reviewer comments and subsequent manuscript revisions. I found the revised manuscript significantly improved and recommend it for publication.

We thank the reviewers for their thoughtful and constructive comments and suggestions, which have helped improve our manuscript significantly. Please find below our point-by-point response to the comments (reviewer comments in black, author responses in blue).

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

The study "Amplified Threat of Tropical Cyclones to U.S. Offshore Wind Energy in a Changing Climate" employs climate simulations combined with a synthetic TC model to assess the risk to offshore wind farms and turbines posed by Atlantic tropical cyclones under changing climate conditions.
The manuscript is clear and well-written, making it accessible to a broad readership. This is indeed a novel study that is not only important for the scientific community but also for policymakers and investors.
Thank you for your positive feedback on our manuscript. We're glad you found the study clear and impactful for both the scientific community and policymakers. We appreciate your support.

However, after careful consideration, I have some **minor comments**:

1. Line numbers are missing, which makes it difficult to provide specific comments.
   This issue has been resolved, and line numbers have since been added to the manuscript.

2. Introduction: at line 12. "With the projected development ....damages are expected to increase even further." Please add the reference for that?
   Thank you for bringing this to our attention. In response, we have performed additional literature review and added eight citations for this statement (lines 36-37) to support the claim that coastal risk to people and property will increase in the future.

3. Why the authors focus only on the fragility function of 5 MW turbines? Please comment on it in the introduction. The authors mentioned that future turbine installations in this region will range from 11 MW to 15 MW. I recommend including a fragility analysis for 10 MW or 15 MW turbines, as this would provide valuable information for investors and policymakers.
   Thank you for your insightful comment. The focus on the fragility function of 5 MW turbines in our study is driven by the availability of robust, accessible fragility curves that account for both wind and wave loadings, the primary forces that TCs inflict upon offshore wind turbines. Specifically, the fragility curve employed is based on the National Renewable Energy Laboratory (NREL) 5 MW offshore reference turbine, whose properties and corresponding fragility curves are well-documented and publicly available.

   Notably, two of the three currently operational offshore projects in the U.S. utilizes 6 MW turbines, which further justifies our choice as it is closely aligned with our 5 MW baseline [1]. We acknowledge the importance of evaluating larger turbines—such as 10 MW or 15 MW—for future installations, however in this study emphasize that our objective was to present timely and relevant findings that can aid the planning phases of current offshore wind projects. Additionally, although our results specifically pertain to 5 MW turbines, the spatial intensity and damage maps may provide valuable insights that can be extrapolated to larger turbines, albeit with a potentially higher risk profile.

We concur that future research should include a fragility analysis for larger turbines to enrich the data available to investors and policymakers.
Consequently, we have included a brief discussion on this topic in lines 75-81 of the Introduction as well as in lines 264-270 of the Discussion.

Results:

1. Please check the labeling of figures 1 and 2? It appears that there are no 'g, ... k' labels on these figures as indicated.
   This typo in the caption has been corrected for both Figures 1 and 2.

2. On page 5, it is mentioned that 'On average, 27.5% of TCs in RAFT make U.S. landfall over the historical period, consistent with the observed value of about 25.8%'. Please clarify where this analysis is presented? If it is in the supplementary information (SI), please indicate that.
   To address the analysis of the landfall frequency of TCs, we have made the following additions and clarifications:

   1. **Methods:**
      - We have included a detailed methodology under the "Tropical Cyclone Frequency Analysis" subsection in lines 342-366. This explains the criteria for identifying landfall events, specifically counting instances where the center of a TC crosses within 30 km of the U.S. coastline. We have additionally added 95% confidence intervals for the simulated mean landfall proportion derived from ensemble data to account for inter-model variability in landfall patterns.

   2. **Results:**
      - To supplement our findings regarding coastal TC frequency, we have added Table 2 to outline the frequency behavior for three coastal subregions and totals within the study domain for Category 1-5 TCs.

   3. **Supplement:**
      - We have included the comparison of RAFT-simulated landfall frequencies with historical observations to the "Supplementary Note: Tropical Cyclone Model Validation" in lines 27-34. This section now includes the mean landfall percentages for total TCs (tropical storms and Category 1-5 TCs) as well as specifically Category 1-5 TCs, validating the consistency between simulations and observations.

- Furthermore, we have added basin-wide TC spatial frequency validation into this section to provide additional context for validating RAFT's performance in capturing the broader spatial patterns of TCs (lines 35-41).

Discussions:

1. Please explicitly state whether the study focuses on floating offshore wind turbines or fixed-bottom wind turbines. Clarifying this aspect will provide readers with a clearer understanding of the context of the research.
   This study is based upon fixed-bottom turbines investigated by Zuo et al. (2018, 2020) [2,3]. This detail has been added to the Introduction in line 71.

2. Please comment on the fragility analysis concerning floating wind turbines. I strongly recommend adding a fragility analysis specifically for floating wind turbines, especially if it differs from the analysis conducted for fixed-bottom turbines.
   Thank you for your thoughtful comment. We acknowledge that FOTWs are poised to be an important tool in meeting U.S. renewable energy goals, however we exclude them from this study to maintain a clear and focused scope. Given that our study assesses risk along the East and Gulf Coasts, which feature shallow waters conducive to fixed-bottom turbines, we have focused our analysis on these structures. Although there is significant interest in floating wind solutions for deeper waters, this technology is primarily applicable to areas like the West Coast and Gulf of Maine [4], which do not experience the severe TC impacts emphasized in our study. The results would likely differ in some aspects for FOWTs, though relevant insights regarding the spatial distribution of TC risk on offshore wind infrastructure can still be gleaned from our analysis on fixed-bottom turbines. We have added this justification to the Introduction in lines 71-75.

Methods:

1. It would be beneficial for readers if you could add the input variables used for the RAFT model.
   We have added the RAFT model's input variables into the Methods section on "Tropical Cyclone Simulations" in lines 302-305.

Overall, the manuscript is well-written. Incorporating the proposed revisions would further improve its clarity and impact. The findings offer valuable insights that are highly relevant and beneficial for wind farm decision-makers, investors, and industry stakeholders.

Reviewer #2 (Remarks to the Author):

This works includes two parts. First, the TC-track and TC-intensity are projected for the future using Risk Analysis Framework for Tropical Cyclones (RAFT) given the projected large-scale winds from CMIP6 dataset. Second, the derived TC-related information is input to turbine fragility functions to assess the risk of to offshore wind turbines posed by Atlantic TCs in future climate.

This manuscript was written well with a good logical flow. However I cannot recommend it to be accepted by this journal. My main concern is large uncertainties existing in the analysis. While the uncertainty is a common issue in climate change projection, the TC- projection seems more serious in this regard due to its high sensitivity to model resolution and model uncertainty. This work lacks of an effective justification that CMIP6 can well resolve the TC track and TC-intensity in Atlantic basin. Without this justification, all conclusions and findings would be pale and weak. The authors seemed aware of this issue and cited a reference. However this reference was only about RAFT, not related CMIP data at all. The authors should at least compare historic simulation of CMIP6 against the observation in terms of TC occurrence frequency, TC-track and TC-intensity in Atlantic basin. In addition, for scientific rigorousness, any conclusion on the future projection should be confined with an uncertainty assessment. All analyses conducted in this work should add the uncertainty analysis.

Thank you for your thoughtful and constructive feedback. We appreciate your important concerns and have taken your comments into serious consideration, which have allowed us to substantially improve our study. Below, we address your concerns regarding uncertainty quantification and model validation.

Uncertainty quantification:

We understand the importance of addressing the uncertainties inherent in climate change projections, especially concerning tropical cyclone (TC) projections. In response, we have made significant revisions to our manuscript to quantify and present the uncertainties more transparently.

1. **Confidence Intervals:**
   We have constructed and affixed confidence intervals to all results presented in our study, including historical and future averages as well as reported changes. These confidence intervals are based on the ensemble mean, which helps mitigate uncertainties stemming from individual models. Tables 1 and 2 now report historical and future findings for TC intensity, damage risk, return periods, and TC frequency, along with 95% confidence intervals and significance testing.
2. **Multi-model Ensemble Approach:**
   We acknowledge that future global climate model projections are subject to significant uncertainty. This is the primary reason for basing our results on a multi-model ensemble average, which helps balance and reduce uncertainties from individual models. Utilizing a multi-model ensemble has several advantages: it reduces the bias inherent in individual models, enhances the robustness of projections, provides a better representation of uncertainties, and improves confidence intervals. By incorporating results from multiple distinct models, we account for the variability and potential errors specific to each model, thus providing a more balanced and reliable projection.

   For example, the reported proportion of TC landfalls in both historical and future climates is based on the full multi-model ensemble, accounting for variability in landfall patterns between distinct global climate models. Confidence intervals for regional changes are computed based upon spatial variability exhibited by the ensemble mean using nine CMIP6 models. This approach helps address uncertainties and provides a more robust estimation of future projections.

Model Validation:
We have significantly enhanced the validation section of our manuscript to ensure the robustness and confidence of our study, detailed in Supplementary Information Section 1: Tropical Cyclone Model Validation (lines 13-68). This expanded section now includes comprehensive evaluations of RAFT's ability to simulate tropical cyclones in the Atlantic basin. Specifically, we have added visual distributions for key performance metrics, such as 6-hourly translation speed, lifetime maximum intensity, and the seasonality of TCs, compared to observed metrics from IBTrACS. For each of these metrics, we calculate and report the simulated and observed mean values and Mean Absolute Errors (MAEs) to provide clear and quantitative validation against observed data. For TC frequency, the spatial correlation coefficient along with its significance are also provided.

TC Simulation Methodology:
We would like to clarify a potential misunderstanding regarding our methodology. The purpose of the RAFT model is, in part, to address the limitations of CMIP6 global climate models (GCMs) in directly resolving TCs. Specifically, the resolution required for simulating TCs would incur high computational costs that would be prohibitive in generating the 900,000 TCs this study is based upon. The synthetic TC database constructed with RAFT therefore offers a reasonable and efficient pathway for the robust assessment of North Atlantic TC wind risks. Instead of using CMIP6 models to simulate TCs directly, RAFT generates synthetic TC tracks and intensities that are consistent with the large-scale climatic conditions provided by the CMIP6 models. The RAFT database includes 50,000 synthetic TC tracks and along-track intensities forced by each of the nine CMIP6 models utilized in this study for each period. As discussed in our response concerning model validation, these RAFT-generated TC tracks are in reasonable agreement with the observed spatial distribution of TC tracks, peak intensities, and basin-scale TC statistics.

An additional important point regarding RAFT's ability to capture TC behavior in the Atlantic basin concerns bias-correction via quantile mapping. Historical and future TC intensities simulated by RAFT are bias-corrected using quantile delta mapping to align RAFT simulated TCs more closely with observed behavior. This method calibrates the distribution of modeled TC intensities by mapping the quantiles of the simulations to those of the observed data, significantly improving the reliability and accuracy of RAFT in representing historical TC characteristics. The quantile mapping approach is a widely used technique to bias-correct modeled TC data using observations [e.g., 14, 15]. Further discussion on this methodology has been included in lines 305-311 of the manuscript.

By adding these changes, we believe we have strengthened the robustness of our analysis. We have thoroughly addressed the uncertainties associated with global climate simulations and provided a comprehensive validation against historical observations both near the coast as well as at the basin-scale, thereby enhancing the scientific rigor of our conclusions and substantially improving our manuscript. We hope that this additional analysis and resulting modifications to our study meet your concerns.

Reviewer #3 (Remarks to the Author):

In this interesting paper, the authors to assess how evolving Atlantic tropical cyclone (TC) behavior may impact offshore wind (OSW) resources in a changing climate. Specifically, they use TCs generated by the RAFT model and subsequent fragility analysis to investigate how shifts in TC intensity and landfall frequencies may influence OSW turbines' vulnerability to both yielding and buckling. They find substantial increases in OSW exposure to TCs and significantly amplified risks of both turbine yielding and buckling for both 20- and 50-year storms. Their findings suggest a critical enhancement of the risk TCs pose to OSW infrastructure in a future climate.
Thank you for your positive and constructive feedback on our manuscript. We're glad you found the study interesting and the results to be significant. Your suggestions have helped us substantially improve both the clarity and quality of our study.

Major Comments

1. In the current manuscript, I find the results section somewhat difficult to follow due to some inconsistencies in the text. For instance, in the second subsection it is not always clear whether the authors are discussing the frequency of landfalling TCs or the overall frequency of TCs basin-wide. Similarly, the authors present results for several different regions along U.S. coastlines but do not initially indicate that they will be assessing results at this level (i.e. Gulf vs. Atlantic coasts for yielding/buckling risks, changes to TC wind speed/intensity, and changing landfalling TC frequency, or New York vs. North Carolina vs. Texas for yielding-/buckling-inducing winds). I suggest the authors revise their Results section to provide better clarity on their findings, particularly to ensure that it is clear which metric they are discussing.
   Thank you for your insightful feedback regarding the clarity of the Results section. We appreciate the opportunity to improve the readability and coherence of our manuscript. Below, we address your concerns regarding the clarity of our discussions on TC frequency and regional assessments.

   1. **Domain Clarification:**
      - Unless otherwise explicitly stated, all results in the manuscript focus on the entire domain of interest, comprised of the coastal region within 200 km of the shoreline along the U.S. Atlantic and Gulf coastlines. We have updated the Introduction to explicitly state different domains assessed in lines 82-88 along with further justifications and details in lines 342-345 and 352-354 of the Methods section.
      - The only specific discussion within the Results about landfalling TCs is now confined to a single paragraph (lines 166-181) in the section "Tropical Cyclone Impacts on Turbine Risk", ensuring clarity and preventing ambiguity on the metric being discussed.

- The discussion regarding basin-wide TC frequency is solely confined to the validation section (Supplementary Information Section 1: Tropical Cyclone Model Validation, lines 13-68). While our primary analysis focuses on the nearshore region, we have added Figure S1 to illustrate basin-wide spatial TC frequency using observations vs RAFT simulations (panels a and b), along with other relevant TC performance metrics at the basin-scale.

2. **Regional Focus:**
    - At the end of the Introduction (lines 82-90), we have added a brief overview to indicate that we will be assessing results at multiple regional levels (i.e., Gulf vs. Atlantic Coast, and specific states like New York, North Carolina, and Texas). This provides the reader with a roadmap for the upcoming subsections.
    - We have updated Table 1 and added Table 2 to present results explicitly at a regional level for the Northeast, Southeast, and Gulf Coasts. This detailed regional breakdown will enable readers to more clearly understand the variability in exposure and risk between these regions.

By implementing these changes, we believe we have improved the clarity and coherence of the Results section, ensuring that it is clear which metric is being discussed and which region is being analyzed. We hope that these modifications satisfactorily address your concerns and enhance the overall quality of our manuscript.

2. There are results presented in this manuscript that are not represented visually in a figure or in a table. Specifically, I see no figure/table describing the changing frequency of landfalling TCs that the authors cite as a contributing factor to increased OSW exposure to TCs. I would encourage the authors to carefully consider all the data they present in their results and ensure that it is supported by a figure or table.
Thank you for your valuable feedback regarding the representation of our results. We appreciate the importance of ensuring that all presented data is supported visually for clarity and comprehensiveness.

To address your suggestion, we have added Table 2 to the manuscript. This table outlines the historical and future TC frequency values for events of different intensities (Category 1-5) for each region. Specifically, Table 2 provides detailed regional breakdowns for the Northeast, Southeast, and Gulf Coasts, which highlights the changing frequency of OSW exposure to TCs – a critical factor contributing to changes in landfall.

To further supplement this information, we have added Figure S1 in Supplementary Information Section 1: Tropical Cyclone Model Validation (lines 13-68). Figure S1 illustrates the historical simulations versus the observations for model validation purposes, providing a visualization of TC frequency in the Atlantic basin. A figure based on a similar methodology in estimating future changes in TC frequency using RAFT can be found in Figure S1d of Balaguru et al. (2023) [12], which visualizes the projected change (future-historical) in TC frequency at the basin-scale. We note this within the

Results to support our discussion on the projected increase in TC landfalls (lines 177-181).

We believe that the additions of Table 2, Supplementary Figure 1, reference to a relevant figure depicting changes in TCF using CMIP6-forced RAFT simulations, and the detailed textual discussion of landfalling TC frequency all serve to provide a comprehensive and supported representation of our findings.

3. The Discussion in the current manuscript is exceptionally short relative to what one usually sees in scientific research articles, and while I appreciate the authors' efforts to be concise, I believe they can include additional relevant discussion on the validity of their results, implications of their findings, and caveats to their approach. Regarding these revisions, I will also point out that much of the text in their Results section is interpretation of their findings, rather than statement of results, and would be better suited to the Discussion section. I encourage the authors to carefully consider both sections in regard to this and my previous comments to ensure that their findings, and their interpretation of them, are presented to the reader in the most straightforward and logical way possible.
We appreciate your suggestions for including additional relevant discussion points and reorganizing the content to enhance the organization of our manuscript. We have substantially improved our Results and Discussion sections accordingly. Specifically:

1. **Validity of Results:**
   - We now discuss the validity of our modeling approach, including a reference to the increased consensus observed among CMIP6 models on future ocean warming patterns. When considered along with RAFT's ability to effectively simulate TCs within the Atlantic basin, these methodologies support the reliability of our findings on the projected increases in TC intensity and frequency. (lines 230-242)
   - We address uncertainties in our risk analysis methodology related to the lack of empirical performance metrics for large-scale OSW turbines exposed to extreme TC conditions. We elaborate on these points in lines 262-275 of the Discussion section, where we discuss implications for extrapolating to higher wind speeds and larger wind turbines, along with the sensitivity analysis resulting in similar findings. This detailed discussion helps affirm the robustness of our results despite the uncertainties.
   - Additionally, we have substantially expanded the model validation section of the Supplementary Information (Section 1: Tropical Cyclone Model Validation, lines 13-68). This expanded section now includes comprehensive evaluations of RAFT's ability to simulate tropical cyclones in the Atlantic basin. Specifically, we have added visual distributions for key performance metrics, such as 6-hourly translation speed, lifetime maximum intensity, and the seasonality of TCs, compared to observed metrics from IBTrACS. For each of these metrics, we calculate and report the simulated and observed mean values and Mean Absolute Errors (MAEs) to provide

clear and quantitative validation against observed data. For TC frequency, the spatial correlation coefficient along with its significance are also provided.

2. **Implications of Findings:**
   - The expanded Discussion explores the broader implications of our results for the planning and development of Wind Energy Areas (WEAs) and the OSW energy sector. It highlights the necessity of strategically siting turbines in lower-risk areas and enhancing design standards to ensure the sustainability and resilience of renewable energy infrastructure in the face of escalating TC risks (lines 248-253).
3. **Caveats and Limitations:**
   - We now provide a comprehensive examination of the limitations and uncertainties associated with our study in lines 260-284. This includes inherent uncertainties in both our TC simulation methodology as well as our risk analysis methodology. We additionally emphasize the influence of site-specific factors and climatological impacts on turbine damage variability and alignment with past research on TC intensification under global warming (lines 262-281).

In response to your feedback, we have also reorganized the Results section to focus purely on the presentation of our data and findings. Interpretative text has been relocated to the Discussion section to ensure a clear and concise statement of results. This reorganization enhances the clarity and logical flow of the manuscript, allowing readers to differentiate between the presentation of data and the interpretation of findings.

Minor Comments

1. Figures 1 and 2 – the authors reference panels g, h, j, and k in their figure captions, but these figures only include panels a-f. I encourage the authors to double check that all figure captions and in-text references to figure panels are consistent with the figures themselves.
   This typo in the caption has been corrected for both Figures 1 and 2.

   Results—when the authors specify that they associate yielding with Category 2&3 TCs and buckling with Category 4&5 storms in the beginning of the "Tropical Cyclone Impacts on Turbine Risk" subsection, I suggest they either provide a brief explanation of why they make this determination or direct the reader to the Methods, as it is currently not immediately clear that they aren't simply making this assumption rather than basing their decision on the fragility analysis.
   In response to your suggestion, we have made revisions to ensure that the basis for associating turbine tower yielding with Category 2 and 3 TCs, and buckling with Category 4 and 5 TCs, is explicitly stated. Specifically:
   - We have included a brief explanation in the "Tropical cyclone impacts on turbine risk" subsection, and direct readers to Supplementary Figure S7 which contains the fragility curves upon which these associations are based.

- Additionally, we refer readers to the "Fragility Analysis" subsection of the Methods section (377-411) for a detailed description of the fragility analysis.

2. I suggest the authors cite additional relevant literature, both in the Introduction but particularly in the Discussion, especially when making broad statements (for example, that previous work suggests a decline in overall TC frequency in a changing climate, or that changes to TC behavior in a changing climate is an active research area).
   Thank you for this valuable point. We have accordingly reviewed and incorporated far more additional relevant literature to substantiate our statements. Specifically, this includes but is not limited to the following:

1. **Introduction:**
   We have added citations to provide a more comprehensive background on:
   - The increasing potential for damage along the U.S. coast due to tropical cyclones under climate change (lines 36-38).
   - The projected decline in overall TC frequency and the complex changes in TC behavior under a changing climate (lines 46-55).
2. **Discussion:**
   - We have enriched our discussion with additional citations to reinforce the points about the active research area regarding climate change and its influence on TC behavior (line 237), specifically in our discussion around TCF (lines 214-224).
   - We have added additional citations regarding potential changes in U.S. landfall under global warming (lines 228-229).

   We believe that these revisions strengthen the manuscript by grounding our statements in a broader body of scientific literature.

3. Related to Major Comment 3, I suggest the authors provide additional discussion on how their use of the 5 MW offshore reference turbine as the basis for the fragility analysis may impact the accuracy of their results, given that most OSW turbines in the study region are 11-15 MW in size. I understand that this choice was made based on data availability, but this seems to be an important caveat and the extent to which it may impact the results presented here should be discussed in more detail.
   Thank you for your insightful comment. While basing our analysis on the fragility function of 5 MW turbines in our study is driven by the availability of robust, publicly available fragility curves that account for both wind and wave loadings, our objective was to present timely and relevant findings that can aid the planning phases of current offshore wind projects. Notably, two of the three currently operational offshore wind projects in the U.S. utilizes 6 MW turbines, which provides some justification in our choice as it is closely aligned with our 5 MW baseline [1]. Although our results specifically pertain to 5 MW turbines, the TC intensity and damage maps provide valuable insights that can be extrapolated to larger turbines, albeit with a potentially different risk profile.

We acknowledge the importance of evaluating larger turbines—such as 10 MW or 15 MW—for future installations, and we concur that future research should include a fragility analysis for larger turbines to enrich the data available to investors and policymakers. To further emphasize this important point, we have included a brief discussion on this topic in lines 77-81 of the Introduction as well as in lines 264-270 of the Discussion.

4. I'm noticing some inconsistency regarding the in-text terminology referring to the regions defined in Table 1—for instance, the authors often refer to the Atlantic Coast region as the East Coast. I suggest they carefully revise their text to ensure their region names remain consistent so as not to confuse readers. Again, it would also be helpful to have these regions briefly defined at the beginning of the Results section.
   The manuscript has been updated accordingly to assure consistent terminology when referring to study regions. Additionally, at the end of the Introduction (lines 82-88), we have added a brief overview to indicate that we will be assessing results at multiple regional levels (i.e., Gulf vs. Atlantic Coast, and specific states like New York, North Carolina, and Texas). We have also updated the Methods section "Tropical Cyclone Frequency Analysis" to define regional bounds comprising study areas assessed here in lines 342-345.

5. As the authors provide individual statistics for the Atlantic and Gulf Coasts in addition to the overall calculated percentages, I suggest they add text to the Methods specifying the latitude and longitude bounds they used to separate these regions for their calculations.
   We have revised the Methods section to include the specific latitude and longitude bounds used to delineate the Northeast, Southeast, and Gulf subregions for our calculations. This update can be found in lines 342-345.

6. In the first paragraph of the Discussion, the authors state that they find overall increases in TC frequency in the study region, but I do not see this finding discussed in the Results section. I suspect they mean there is an increase in the frequency of landfalling TCs, but this needs to be clearer. If that is not the case and they do find an increase in overall future TC frequency in their model, this should be discussed in more detail, as most literature predicts the opposite (see the IPCC AR6, https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-11/, and related references therein).
   Thank you for highlighting this important point. We apologize for any confusion regarding our findings on TC frequency.

   In response to your comment, we have clarified our discussion to accurately reflect our findings. Additionally, we have ensured that our observations are discussed in detail in the Results section, with references to Table 2, which outlines the changes in TC frequency by category for each region. To further illustrate these findings, we have added a reference to a figure based on a similar methodology in estimating future changes in TC frequency using RAFT forced by CMIP6 which visualizes the projected change (future-historical) in TC frequency at the basin-scale (Figure S1d of Balaguru et al. (2023) [12]). We note this in lines 177-181 to support our findings of increased TC frequency and landfall in coastal regions, despite some literature predicting overall decreases in total TC frequency.

Furthermore, we have expanded the Results section to explicitly discuss these findings (lines 166-181), highlighting that increases in overall TC frequency are observed for all coastal regions assessed in this study, with the most significant increases occurring for stronger storms (Table 2). This detailed discussion is now complemented by Table 2 along with a reference to an illustration for TCF within the Atlantic basin, providing a comprehensive view of the changes.

Regarding agreement with the literature, uncertainty in projecting tropical cyclone frequency (TCF) in the Atlantic basin is significant, with internal climate variations and systematic differences among models contributing to differing conclusions. The IPCC's 6^{th} assessment report suggests a global decline in TCF with medium confidence, with some studies finding decreasing trends specifically in the Atlantic basin [e.g., 5, 13]. Conversely, multiple studies [e.g., 6, 7, 9] foresee an increase in annual TC counts in the North Atlantic region. Mixed opinions are reported by the multi-study review Knutson et al. [8], who indicate limited confidence in global TCF decreases. Walsh et al. [11] highlight significant multidecadal variability driven by various internal and external mechanisms, illustrating the ongoing debate over the relative contributions of internal variability versus radiative forcing to observed increases in TC activity since the 1970s.

In summary, it is evident that significant uncertainty remains in climate projections of TC frequency due to internal climate variations, methodological differences, and the influence of anthropogenic forcing. These discrepancies highlight the ongoing debate and complexity in detecting and attributing trends in TC activity. Further research with advanced modeling techniques and a deeper understanding of regional climatic dynamics is essential to reconcile these differing projections and enhance the robustness of future TC frequency predictions.

We have accordingly expanded our discussion in lines 214-224 to address the uncertainties in TCF projections, particularly in the Atlantic basin. This additional context highlights ongoing debates and the complexity of projecting tropical cyclone activity.

References:

[1]: McCoy, Angel, Walter Musial, Rob Hammond, Daniel Mulas Hernando, Patrick Duffy, Philipp Beiter, Paula Pérez, Ruth Baranowski, Gage Reber, and Paul Spitsen. 2024. Offshore Wind Market Report: 2024 Edition. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-90525. https://www.nrel.gov/docs/fy24osti/90525.pdf

[2]: Zuo, H., Bi, K., & Hao, H. (2018). Dynamic analyses of operating offshore wind turbines including soil-structure interaction. *Engineering Structures*, *157*, 42-62.

[3]: Zuo, H., Bi, K., Hao, H., Xin, Y., Li, J., & Li, C. (2020). Fragility analyses of offshore wind turbines subjected to aerodynamic and sea wave loadings. Renewable Energy, 160, 1269-1282.

[4]: https://www.whitehouse.gov/briefing-room/statements-releases/2022/09/15/fact-sheet-biden-harris-administration-announces-new-actions-to-expand-u-s-offshore-wind-energy/

[5]: Xi, D., Lin, N., Jing, R., Harr, P., & Oppenheimer, M. (2024). Uncertainties Inherent from Large-Scale Climate Projections in the Statistical Downscaling Projection of North Atlantic Tropical Cyclone Activity. *Journal of Climate*.

[6]: Hall, T. M., Kossin, J. P., Thompson, T., & McMahon, J. (2021). US tropical cyclone activity in the 2030s based on projected changes in tropical sea surface temperature. *Journal of Climate*, *34*(4), 1321-1335.

[7]: Jewson, S. (2023). Tropical Cyclones and Climate Change: Global Landfall Frequency Projections Derived from Knutson et al. *Bulletin of the American Meteorological Society*, *104*(5), E1085-E1104.

[8]: Knutson, T., Camargo, S. J., Chan, J. C., Emanuel, K., Ho, C. H., Kossin, J., ... & Wu, L. (2020). Tropical cyclones and climate change assessment: Part II: Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society*, *101*(3), E303-E322.

[9]: Bhatia, K., Vecchi, G., Murakami, H., Underwood, S., & Kossin, J. (2018). Projected response of tropical cyclone intensity and intensification in a global climate model. *Journal of Climate*, *31*(20), 8281-8303.

[10]: Villarini, G., Vecchi, G. A., Knutson, T. R., Zhao, M., & Smith, J. A. (2011). North Atlantic tropical storm frequency response to anthropogenic forcing: Projections and sources of uncertainty. *Journal of climate*, *24*(13), 3224-3238.

[11]: Walsh, K. J., McBride, J. L., Klotzbach, P. J., Balachandran, S., Camargo, S. J., Holland, G., ... & Sugi, M. (2016). Tropical cyclones and climate change. *Wiley Interdisciplinary Reviews: Climate Change*, *7*(1), 65-89.

[12]: Balaguru, K., Xu, W., Chang, C. C., Leung, L. R., Judi, D. R., Hagos, S. M., ... & Ting, M. (2023). Increased US coastal hurricane risk under climate change. *Science advances*, *9*(14), eadf0259.

[13]: Chand, S. S., Walsh, K. J., Camargo, S. J., Kossin, J. P., Tory, K. J., Wehner, M. F., ... & Murakami, H. (2022). Declining tropical cyclone frequency under global warming. *Nature Climate Change*, *12*(7), 655-661.

[14]: Begmohammadi, A., Blackshaw, C. Y., Lin, N., Gori, A., Wallace, E., Emanuel, K., & Donnelly, J. P. (2024). Integrating Climatological-Hydrodynamic Modeling and Paleohurricane Records to Assess Storm Surge Risk. *Journal of Geophysical Research: Oceans*, *129*(1), e2023JC020354.

[15]: Gori, A., Lin, N., Xi, D., & Emanuel, K. (2022). Tropical cyclone climatology change greatly exacerbates US extreme rainfall–surge hazard. *Nature Climate Change*, *12*(2), 171-178.

We thank the editor and the reviewers for their positive feedback and acceptance of our manuscript. We have addressed and outlined the suggested editorial requests in the attached "Editorial Requests Table." We believe that our manuscript now complies with the journal's format requirements, thereby enhancing the accessibility of our work.

EDITORS' COMMENTS:

Your revised manuscript titled "Amplified Threat of Tropical Cyclones to U.S. Offshore Wind Energy in a Changing Climate" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have improved the manuscript, addressing all comments thoroughly. Accepted.

Reviewer #2 (Remarks to the Author):

This is a revised version, which I reviewed before. I found that the authors have well addressed my concerns. I do not have any more questions.

Reviewer #3 (Remarks to the Author):

I am exceptionally satisfied with the authors' responses to reviewer comments and subsequent manuscript revisions. I found the revised manuscript significantly improved and recommend it for publication.