Author Response to Reviewer Comments

WES-2026-32: Grand Challenges in Designing Resilient Wind Energy Systems in Areas Prone to Tropical Cyclones

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We sincerely thank both reviewers for their thorough and constructive evaluation of our manuscript. Their comments have significantly improved the quality and completeness of this work. Below, we provide a point-by-point response to each comment. Reviewer comments are shown in blue, our responses in green.

Response to Reviewer 1

Reviewer 1 recommends acceptance upon minor revisions. We address each comment below.

Minor Revisions

Comment 1 (Abstract, L8): Reviewer Comment: *The North Sea has its own hazards; I don't know if it would be characterized as "less hazardous."*

Author Response: We agree that the North Sea poses its own set of environmental hazards (e.g., severe extratropical storms, high waves). Our intent was to contrast regions with and without tropical cyclone exposure specifically. We have revised the phrasing to "non-cyclone regions" to avoid implying the North Sea is generally less hazardous.

Comment 2 (Table 1): Reviewer Comment: *What does a hyphen signify in the "shortest distance to TC" column? Direct passage of eyewall? Unknown? What about hyphens in the other columns? What are the numbers in parentheses within the blade damage and tower collapse columns? What does "foundation" mean in the tower collapse column? Are these all onshore? The caption could be used to answer these, or the column labels could be improved.*

Author Response: We thank the reviewer for highlighting the lack of clarity in Table 1. We have expanded the table caption to explain all symbols and conventions used. More specifically, the revised Table 1 caption now includes the following clarifications: (i) a hyphen (–) indicates that the information was not reported or is unavailable in the cited reference; (ii) numbers in parentheses indicate the number of turbines affected (e.g., blade damage or tower collapse); (iii) "Foundation" in the tower collapse column indicates that foundation failure was reported rather than tower collapse; (iv) added a column or footnote indicating whether the site is onshore or offshore. [Table 1]

Comment 3 (L150): Reviewer Comment: *Consider mentioning that lidars on offshore platforms need to be corrected for wave motions and that is not necessarily a trivial task for producing* *higher-order statistical moments for wind.*

Author Response: Thank you for this suggestion. We have added the following note ... "One important consideration for offshore-mounted radar or lidar systems is the correction required for wave-induced platform motion. This is a non-trivial task, particularly for lidar systems deployed on offshore platforms, where accurate estimation of higher-order turbulence statistics such as turbulence intensity, spectral characteristics, and spatial coherence is required (Gottschall et al., 2014; Désert et al., 2021)." We have also added two new references Gottschall et al. (2014) and Désert et al. (2021).

Comment 4 (Figure 5): Reviewer Comment: *What is a "storm" here? Based on the yellow line being TC Cat 1+, I imagine that "storms" aren't TCs but other events?*

Author Response: We agree this needed clarification. "All Storms" in Figure 5 refers to all named tropical weather systems in the HURDAT2 database, including tropical depressions, tropical storms, and hurricanes. The yellow line filters to only those reaching Category 1 or higher on the Saffir-Simpson scale. We have revised Figure 5 caption to define "All Storms" as all named tropical weather systems (tropical depressions, tropical storms, and hurricanes) recorded in the HURDAT2 database.

Comment 5 (L229): Reviewer Comment: *An argument to consider here is that these mesoscale (and greater) models typically have numerical diffusion to dampen noise at small scales. Thus, the Nyquist frequency of the model will be* $2\Delta x$ *but often much of that signal is damped and the* effective resolution *of the model may be closer to* 5–$6\Delta x$ *(Knievel et al., 2007). So for resolving a signal of 2 km you may actually need* $\Delta x = 333$–400 *m.*

Author Response: This is an excellent point. The distinction between nominal and effective resolution is critical for interpreting mesoscale model outputs, particularly for wind energy applications. We have incorporated the following discussion with the suggested reference ... "Moreover, the effective resolution of numerical models is significantly coarser than the nominal grid spacing due to numerical diffusion that dampens energy at the smallest resolved scales. While the Nyquist limit is $2\Delta x$, the effective resolution is typically 5–$7\Delta x$ (Skamarock, 2004), implying that resolving flow features of approximately 2 km may require a grid spacing of $\Delta x \approx 280$–400 m." Upon further review, the Knievel et al. (2007) reference was not used as suggested by the reviewer, as the 6th-order numerical diffusion scheme described therein is no longer the default in WRF. Instead the Skamarock (2004) paper is referenced for the effective resolution.

Comment 6 (L285+): Reviewer Comment: *Some of these studies are LES with grid spacing of ∼100 m which, borrowing from the suggestion from the IWRAP dataset, could also be too coarse for wind energy purposes especially considering the effective resolution of the models.*

Author Response: Thank you for this suggestion. We have added a caveat noting that LES studies at ∼100 m grid spacing may also be too coarse for capturing all turbulence scales relevant to wind turbine design. The note is in Section 2.4: "However, it should be recognized that LES studies with grid spacings of approximately 100 m may still be too coarse to fully resolve the turbulence scales relevant to wind turbine structural loading (Sanchez-Gomez et al., in prep.), particularly when considering the effective resolution of the numerical methods employed." Added reference to Sanchez-Gomez et al. (in prep.) on hurricane Laura-induced loads and sensitivity to turbulent inflow conditions.

Comment 7 (L323): **Reviewer Comment:** *Consider clarifying that precipitation may be less impactful* to wind turbines. *It can be very impactful to other applications.*

Author Response: We agree and have clarified the scope of this statement. It now reads: "Precipitation, while less impactful to wind turbine structural loading than wind and waves, should also be reviewed..."

Technical Suggestions

Comment T1 (L214): **Reviewer Comment:** *"AI/ML" has not been defined and in other parts of the paper is referred to only as "ML" or "ML/AI."*

Author Response: We have defined "artificial intelligence and machine learning (AI/ML)" on first use and standardized the terminology throughout the manuscript.

Comment T2 (L253): **Reviewer Comment:** *SWAN not defined.*

Author Response: We have added the full name at first use ... "Simulating WAves Nearshore (SWAN)" at L253.

Comment T3 (L299): **Reviewer Comment:** *I don't think this is the right citation for the WRF model. The website says to use: Skamarock et al. (2019).*

Author Response: We thank the reviewer for catching this. We have updated the citation to the official recommended reference, Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, Z. Liu, J. Berner, W. Wang, J. G. Powers, M. G. Duda, D. M. Barker, and X.-Y. Huang, 2019: A Description of the Advanced Research WRF Version 4. NCAR Tech. Note NCAR/TN-556+STR, 145 pp. doi:10.5065/1dfh-6p97.

Comment T4 (L391): **Reviewer Comment:** *Models are out of chronological order.*

Author Response: Corrected.

Comment T5 (L454): **Reviewer Comment:** *Space before period.*

Author Response: Fixed.

Comment T6 (L495): **Reviewer Comment:** *Format of citation changed and isn't consistent with other parenthetical citations in the sentence. Maybe remove "e.g.," here and on line 498?*

Author Response: We have standardized the citation format in this passage by removing "e.g.," at L495 and L498 and ensured consistent parenthetical citation format throughout the sentence.

Comment T7 (Section 3.2.2): **Reviewer Comment:** *This section in particular seems to place citations in the middle of the sentence and is pretty hard to read.*

Author Response: We have restructured several sentences in Section 3.2.2 to improve readability by moving citation lists to the end of sentences or consolidating them.

Comment T8 (L556): **Reviewer Comment:** *Hyphen needs trailing space.*

Author Response: Fixed.

Comment T9 (L581): Reviewer Comment: *Missing "respectively" or are they both functions for probability density and cumulative probability?*

Author Response: We have clarified the notation. The revised text reads: "...where f_X and F_X are functions providing the probability density and cumulative distribution of random variable X, respectively."

Comment T10 (Section 5): Reviewer Comment: *Why are the sub-sections presented as dashed items here and not sub-sections (e.g., 5.1, 5.2, etc)?*

Author Response: We agree that formal sub-section numbering improves navigability and consistency with the rest of the paper. We have converted the dashed items in Section 5 to numbered sub-sections.

Comment T11 (L647): Reviewer Comment: *Missing space after sentence.*

Author Response: Fixed.

Comment T12 (L662): Reviewer Comment: *Models out of chronological order.*

Author Response: Corrected.

Response to Reviewer 2

Reviewer 2 recommends major revisions. We appreciate the detailed and constructive feedback, which has helped us substantially strengthen the manuscript. We address each comment below.

Specific Comments

Comment 1 — Scope: offshore substations and cables: **Reviewer Comment:** *The paper is oriented toward project infrastructure ("wind energy systems"), but is currently limited to turbines and their foundations. All infrastructure governed by standards, especially offshore substations and cables (array, export cable landfalling), should be identified and considered for a publication in "grand challenges" to be comprehensive. For example, sediment transport will vary based on TC features, path, and soil properties, resulting in potentially uncovered cables not buried below the stable seabed. Additionally, work has been done in the oil and gas domain to quantify maximum wave crest heights generated by TCs (substation deck heights), but there remain gaps in the characterization and usage of these values in both O&G and offshore wind. These aspects should also be addressed in this paper; please update Table 2 accordingly.*

Author Response: We agree that a comprehensive treatment of "wind energy systems" should extend beyond turbines and foundations. We have expanded the manuscript to address offshore substations and cable infrastructure (array cables, export cables, and landfalling cable sections). Specifically, we have added discussion on: (i) sediment transport and scour effects on cable burial stability under TC conditions; (ii) maximum wave crest height characterization for substation deck clearance, drawing on O&G experience and remaining gaps; and (iii) the relevant standards and guidelines applicable to these components. Table 2 has been updated accordingly. The added new paragraphs are in Sections 2.5, 2.6.2, 3.1, and 5 discussing substations and cable infrastructure under TC loading. Finally, the updated Table 2 now includes relevant standards for offshore substations (e.g., API RP 2A-WSD, ISO 19902) and cable protection (e.g., CIGRE TB 610, DNV-RP-J301).

Comment 2 — LiDAR measurements and turbulence model references: **Reviewer Comment:** *Section 2.1 discusses turbulence measurement by LiDAR of TC winds. Das 2022 presented LiDAR measurements of TCs (Wind profile and structure during severe storms in the Gulf of Mexico, OMAE2022-86835) and Holmes 2024 (https://doi.org/10.12989/was.2024.39.4.305) proposes a turbulence model for TCs. It is suggested these works be engaged with in a review of TCs and turbulence.*

Author Response: We thank the reviewer for pointing us to these relevant works. Holmes (2024) proposes a turbulence model specifically designed for TC conditions and has been incorporated into the discussion of turbulence characterization. We have also reviewed the Das (2022) work on lidar-based observations of TC wind profiles in the Gulf of Mexico.

Comment 3 — LES symmetry and extra-tropical transition: **Reviewer Comment:** *Current LES models show more or less symmetrical tropical cyclone features about the eye. TCs traveling through higher latitudes do not exhibit such symmetry, however; how is this accounted for in the proposed models? What biases are currently exhibited in both modeled winds and ocean features when such extra-tropical transitions are not represented?*

Author Response: Thank you for pointing out this important point. We have revised this paragraph to focus specifically on the limitations of *idealized* TC simulations rather than LES in general.

In meso-microscale coupled simulations, asymmetries in the LES are largely transferred from the mesoscale simulations, so limitations in the LES stem from limitations in the mesoscale representation of the storm. Idealized simulations, however, are typically initialized with axisymmetric profiles or rely on internal forcing methods that inherently impose symmetry. We have rewritten the paragraph to make this distinction clear and to emphasize the importance of mesoscale–microscale coupling for producing realistic wind and wave fields. The revised paragraph can be found in Section 2.3. and it discusses: (i) the symmetric initialization of idealized frameworks and its suppression of mesoscale variability (Rotunno et al., 2009); (ii) how mesoscale simulations of historical storms naturally capture asymmetries; (iii) the relevance for storms undergoing extra-tropical transition; (iv) biases in modeled winds and ocean features when ET processes are not represented; and (v) the need for mesoscale–microscale coupling. [Section 2.3]

Comment 4 — Coupling synthetic tracks to metocean models: **Reviewer Comment:** *Section 2.2.1 on synthetic storm track modeling addresses winds. Considering dataset concurrency and coherence, please extend this discussion to the state of the art and future needs for fully coupling metocean models (from which ocean design values are obtained) to synthetic storm track datasets.*

Author Response: We agree that the connection between synthetic storm tracks and coupled metocean modeling is critical for deriving consistent ocean design values. We have extended the discussion in Section 2.2.1 to address the current state-of-the-art in coupling these systems and future research needs. More specifically we discuss (i) the need for concurrent and coherent wind, wave, surge, and current fields derived from synthetic track catalogs; (ii) current approaches for coupling parametric wind models to spectral wave and ocean circulation models; (iii) challenges in maintaining physical consistency across the coupled system; and (iv) future needs for fully integrated synthetic metocean datasets.

Comment 5 — Observational gaps and rarest events: **Reviewer Comment:** *Continuing with synthetic tracks, models are naturally reliant on observations for calibration and validation, and will be subject to gaps in temporal and spatial features in this record, in addition to events occurring after observations were put in place (i.e., post 1979). Please comment on the influence of this gap on the range of modeled storm features, especially concerning the rarest events that may fall outside of the observation window.*

Author Response: The relatively short reliable observational record (approximately 45 years of satellite-era data, post-1979) constrains the statistical basis for calibrating synthetic track models, particularly for the most extreme events. We have added a paragraph in Section 2.2.1 discussing: (i) the limited temporal extent of the reliable observational record and its influence on the statistical representation of the rarest TC events; (ii) known biases in pre-satellite-era records (undercounting, intensity underestimation); (iii) the consequence that return periods of 500+ years extrapolate well beyond the observational window; and (iv) strategies to address this, including paleotempestology, climate model ensembles, and sensitivity analyses.

Comment 6 — Parametric models and multidecadal coupled metocean hindcasts: **Reviewer Comment:** *Starting at line 341, parametric models are discussed. Please connect this and its representation/non-representation in current input to design methods such as multidecadal coupled metocean hindcasts. The work of Cox, Cardone, et al in reconstructed winds and coupled ocean models has contributed to fundamental advances in project engineering and should also be referenced.*

Author Response: We agree that the connection between parametric wind models and their use in coupled metocean hindcasts for design is an important aspect that was underrepresented. We have added a discussion in Section 2.5 connecting parametric wind field models to their role as forcing inputs for coupled metocean hindcasts used in engineering design. We have also referenced Powell, Murillo, Dodge et al. (2010), "Reconstruction of hurricane Katrina's wind fields for storm surge and wave hindcasting," *Ocean Engineering*.

Comment 7 — "Training" terminology (L366): **Reviewer Comment:** *The sentence starting on 366 should be reformulated. "Training" is not the correct word for inclusion of nonlinear features represented in 3rd-generation spectral wave models.*

Author Response: We agree. The term "Training" was an ambiguous term to use in the context of the sentence. We have reformulated the sentence.

Comment 8 — Breaking saturation and largest waves (L367): **Reviewer Comment:** *Consider referring to the originating work by Holthuijsen ("Wind and waves in extreme hurricanes", 2012) on breaking saturation. More work than Qiao 2020 has been conducted on the largest waves generated by TCs; it is fairly established that they are wind-driven. Please include more than one reference for this concept.*

Author Response: We agree and have added the foundational reference by Holthuijsen et al. (2012) along with additional references supporting the established understanding that the largest TC-generated waves are wind-driven.

Comment 9 — Cable terminology and hydrodynamic advances (L380): **Reviewer Comment:** *Line 380: substitute "array" or "export" cable for "submarine"; these have different electrical properties. The line continues with, "as hydrodynamic modeling advances…". Please indicate what this means and what those advances are/would be from existing methods. Breaking and surge are captured to varying degrees in current-day methods, and most are coupled, although coupling characteristics vary in quality.*

Author Response: We have corrected the cable terminology and clarified the discussion on hydrodynamic modeling advances. More specifically, we have replaced "submarine cables" with "array and export cables" and (ii) revised the subsequent text to specify what hydrodynamic modeling advances are needed beyond current capabilities, acknowledging that breaking and surge are already captured to varying degrees in existing coupled models, while identifying remaining gaps in coupling quality and resolution.

Comment 10 — TC-generated breaking wave modeling and Section 5: **Reviewer Comment:** *As you note in line 420, wave breaking/slamming is not fully characterized in offshore wind design. Please elaborate on the state of knowledge and gaps in TC-generated breaking wave modeling and include this significant feature in section 5.*

Author Response: We have expanded the discussion of breaking wave characterization in TC conditions and included it as a future research recommendation in Section 5. The expanded discussion includes (i) the state of knowledge regarding TC-generated breaking waves, including current modeling approaches and their limitations for offshore wind design; and (ii) breaking wave modeling as a future research priority in Section 5.

Comment 11 — Compounding effects in design (Section 3.1): Reviewer Comment: *Are there any compounding effects to consider in the design process concerning both higher modeled waves and higher safety factors, including the uncertainty around derived parameters? Please comment.*

Author Response: Yes, compounding effects are a significant concern. When TC-driven wave heights are larger and more uncertain than their extra-tropical counterparts, the combination with higher safety factors (which are also needed to account for the greater variability in TC conditions) can lead to compounding conservatism in the design process. We have added this discussion.

Comment 12 — Total load environment and storm path proximity (Section 3.1): Reviewer Comment: *How should a designer assess the total load environment with respect to location and proximity to historical storm paths?*

Author Response: We have added guidance on how designers should approach the assessment of total load environment relative to site location and historical storm track proximity, including: the use of synthetic storm track catalogs filtered by proximity, directional hazard analysis, and the importance of considering the full range of storm approach angles and intensities rather than relying solely on historical storm tracks.

Comment 13 — Sensitivity of risk quantification to TC paths (Section 4): Reviewer Comment: *How sensitive is risk quantification to TC paths?*

Author Response: Risk quantification is highly sensitive to TC path characteristics, as small changes in track position can result in large differences in local wind speed, wave height, and surge levels. We have added this discussion.

Comment 14 — Minimum number of events for reliable risk estimates (Section 4): Reviewer Comment: *What is the minimum number of events required for a "reliable" risk estimate?*

Author Response: This is an important practical question. We have added a discussion in Section 4 on the minimum catalog size required for stable risk estimates. Catalog size depends on the target return period, site location, and desired confidence level. Referenced existing guidance suggesting that catalogs of ∼10,000–100,000 years of synthetic activity are typically needed for robust estimation of 500- to 10,000-year return period events.

Comment 15 — Remove speculative content (L553–560): Reviewer Comment: *Lines 553–560 are speculative and a "grand challenges" paper is not the right forum for these ideas. These lines should be removed.*

Author Response: We agree that the passage on roaming turbines and some of the more speculative concepts was not appropriate for a Grand Challenges paper. We have removed the identified lines.

Comment 16 — Current measurements in design activities (L621): Reviewer Comment: *Line 621 mentions better temporal and spatial coverage of current measurements. However, the paper does not address the representation or mis-representation of currents in design activities. Please elaborate on this. Spatial and temporal availability of wave measurements (and associated* *spectral parameters) should also be considered, alongside the effect of missing measurements on assimilated data products.*

Author Response: We have expanded the discussion to address these gaps. In particular we have added a discussion in Section 5 on: (i) the representation and mis-representation of ocean currents in current design practice, including the reliance on sparse in-situ measurements and reanalysis products that may not capture TC-driven current extremes; (ii) the limited spatial and temporal availability of wave measurements and spectral parameters in TC-prone regions; and (iii) the impact of measurement gaps on the quality of assimilated and hindcast data products used for design.

Comment 17 — Definition of "surviving" a TC: **Reviewer Comment:** *Operation and maintenance of energy systems hinges on the definition of what "surviving" a TC means. How should academia, developers, and i.e., the insurance industry go about establishing a definition of what this means?*

Author Response: Thank you for making this point. This is a critical point that bridges engineering design, operational practice, and financial risk transfer. We have added a new paragraph in Section 5 to discuss the need for a consensus definition of "surviving" a TC, addressing: (i) structural survival vs. operational readiness post-storm; (ii) allowable damage states and recovery timelines; (iii) the role of inspection and certification protocols; and (iv) the importance of aligning definitions across academia, developers, regulators, and the insurance industry to enable consistent risk communication.

Comment 18 — GCM resolution and future work for TC risk: **Reviewer Comment:** *Section 2.2.4 discusses the influence of climate change. Continuous improvement of the GCMs is ongoing, however, their coarse resolution still poses a challenge to drawing meaningful conclusions for wind projects/individual installations. Are there any recommendations for future work for this domain to better inform TC risk?*

Author Response: We have added recommendations for future work in this area including: (i) dynamical and statistical downscaling approaches; (ii) the use of large-ensemble high-resolution GCM experiments targeting TC-active basins; (iii) the integration of GCM projections with synthetic track models to produce climate-conditional hazard estimates; and (iv) the need for uncertainty quantification frameworks that propagate GCM uncertainties through to site-level design parameters.

Technical Comments

Comment T1 (L367): **Reviewer Comment:** *"terms that transfers" — grammatical error.*

Author Response: Fixed.

Comment T2 (L713): **Reviewer Comment:** *"assumptions" — grammatical error.*

Author Response: Fixed.

References

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