

# *Second Review: Fully Coupled High-Resolution Atmosphere-Ocean-Wave Simulations of Hurricane Henri (2021): Implications for Offshore Load Assessments*

## General Comments

The revised version of the article needs drastic improvement in figure quality, and continues to overstate the performance of the AOW case, or, at the very least, does not recognize the deficiencies in model performance. The article fails to put the findings in context to relevant literature. Much of what is claimed has been shown before in other articles outside of wind energy and the tie to wind energy within this study is entirely conjecture.

I believe in the importance of coupling the atmosphere, ocean, and waves as there have been numerous studies on the topic to date that have clearly shown reasons to include the fully-coupled effects in simulations. This paper does not build off of the previous papers on the topic and instead simply tries to loosely apply the same findings specifically to offshore wind energy. This paper doesn't show the impacts to wind energy production, wakes, or structural loads on wind turbines, it just simulates a single hurricane (poorly) and highlights the portions of the simulations that are improved by including atmosphere-ocean-wave coupling (which has been well documented in the literature).

I recommend the paper be rejected by Wind Energy Science. There is no novelty to this study and there are no relevant findings or analysis specific to wind energy.

I would encourage the authors to pursue the future work mentioned within the study which does contain novel ideas. The model framework shows promise (as have the other atmosphere-ocean-wave coupled frameworks) and if the impacts on wind energy are desired, consider targeting specific wind energy applications in future publications.

As mentioned previously, the figures are not publication quality and as a reviewer are extremely discouraging to see. The figures tell the story. When they run off the page, have illegible text and symbols, etc., the paper suffers greatly.

We sincerely thank the reviewer for the careful, critical, and constructive evaluation of our manuscript. We have taken these comments seriously and have performed revision of the manuscript to address concerns. Our detailed responses are provided below.

### 1. Figure quality and recognition of model deficiencies

*“this article needs drastic improvement in figure quality and continues to overstate the performance of the AOW case, or, at the very least, does not recognize the deficiencies in model performance”*

- **Figure Quality:** We have made an effort based on both reviewers' comments and suggestions to improve the figure quality including the figure resolution, font size, panel organization. We are happy to continue to address any concerns from the reviewers and publication office to ensure our figures are publication ready.

- **Clarification of Study Objectives and Model Deficiencies:** We acknowledged that the simulations of Hurricane Henri (2021) are not optimal, particularly with respect to track bias and intensity overestimation. We note that spectral nudging constraints can substantially reduce these errors; however, such techniques were intentionally omitted in this study to isolate the physical effects of atmosphere-ocean-wave coupling on storm structure. By allowing the model to evolve freely, we can better diagnose how coupled physics alter the storm's structure. These limitations and the rationale behind this choice are now clearly articulated in Section 4.1.

The objective of this study is to examine how the inclusion of coupled ocean and wave processes alters storm evolution and wind structure (e.g., hub-height wind speeds and vertical wind profiles) relative to partially coupled (e.g., atmosphere-wave or atmosphere-ocean coupling) or uncoupled configurations (atmosphere only). In particular, this work provides relevant meteorological and oceanographic information to inform future high-fidelity load modeling, offshore wind design studies, and risk assessment. The work also makes a necessary step toward transitioning offshore wind energy assessments from idealized or uncoupled parameterizations to a fully consistent, physics-based representation of environmental forcing under extreme weather conditions. In addition, to respond to your next comment about our scientific novelty, we have listed four key points that separate our study from previous studies even using similar modeling tools. We have revised the manuscript to avoid overstating model performance and to clearly articulate both its strengths and limitations.

## 2. Literature context and scientific novelty

*“Much of what is claimed has been shown before in other articles outside of wind energy”  
“This paper does not build off of the previous papers on the topic and instead simply tries to loosely apply the same findings specifically to offshore wind energy”*

We have expanded the literature review in Introduction to better situate our work within the evolution of coupled modeling (e.g., Warner et al., 2010). While we acknowledge that mechanisms like SST cooling are well-documented, our work builds a “bridge” between TC coupled modeling research and offshore wind applications through several novel technical extensions:

- **Technical extensions beyond standard coupled systems:** While previous studies often utilize nested-grid frameworks (e.g., COAWST), our framework utilizes unstructured ocean meshes (FVCOM) with sub-3 km refinement. This addresses the limitations of nested-grid artifacts and allows for a more seamless representation of coastal and shelf processes critical to offshore wind sites.
- **Non-breaking wave physics:** We include explicit representation of non-breaking wave-induced vertical mixing, a process often omitted in standard frameworks, but shown to be a critical factor in regulating air-sea fluxes.
- **Wind-pressure-roughness decoupling:** We demonstrate that near-surface wind intensity is not only determined by the pressure gradient force, but also wave-dependent surface

roughness which is treated dynamically and consistently in a fully coupled atmosphere-ocean-wave system. To our knowledge, no previous studies have clearly documented how the exclusion of wave dynamics affects the wind-pressure relationship, particularly the tendency for simplified roughness parameterization to overstate frictional effects at high intensities. This highlights that wave-involved roughness and associated air-sea processes can also modify storm dynamics and wind structure. The angular momentum budget analysis presented in Section 5 provides a mechanistic explanation for this result.

- **Process-level evaluation using rich observations:** The availability of airborne Doppler radar, dropsondes, and wave buoy observations during Hurricane Henri enables evaluation of coupled feedback at spatial and temporal scales relevant to the marine boundary layer, and at both near-surface and higher altitudes, making the model evaluation more completed and enabling and diagnosed mechanism analysis that is not available in previous studies.

### 3. Relevance to offshore wind energy and “conjecture”

*“The tie to wind energy within this study is entirely conjecture”*

We agree that the manuscript does not demonstrate impacts on turbine-specific metrics like wake recovery or structural loads. However, our focus is on the fundamental meteorological and oceanographical drivers that dictate these metrics. Inaccurate environmental boundary conditions inevitably lead to incorrect load and production models. By demonstrating that uncoupled models may misrepresent hub-height wind speeds and vertical wind profiles, we help clarify the environmental conditions that should be accurately represented for subsequent engineering and standards-based assessments (e.g., within IEC frameworks).

In fact, we have done analysis for coupling effect on design standard metrics (e.g., turbulence, veer and shear) in our original manuscript, given the length and the focus on the study, we decided to leave those analyses to a separate manuscript. We have revised the text to clarify that the relevance is process-based, establishing the physically consistent environmental forcing required for any reliable downstream engineering analysis. We have revised the manuscript to frame offshore wind energy as the motivating context and critical boundary condition for future application-specific studies, rather than a demonstrated outcome of this specific paper.

### 4. Lack of wind energy production or load analysis

*“This paper doesn’t show the impacts to wind energy production, wakes, or structural loads on wind turbines”*

Again, this manuscript focuses on the meteorological and oceanographic forcing rather than the turbine response.

Accurate characterization of the meteorological and oceanographical environment is a prerequisite for any reliable load or wake modeling. We view this work as a foundational step, providing a validated coupled modeling framework upon which wind energy-specific studies can build. To prevent any misunderstanding of this scope. We have revised the title and Introduction to more accurately reflect this focus on “Environments” rather than “Wind Energy Impacts.” We also explicitly state in Section 6 that turbine-level analyses using C-WFS are the subject of our planned future work.

## Specific comments

- 1) For example, the paper states that the vertical profile of wind speed for the AOW case “aligns more closely with observations... [which] is critical for offshore wind energy...” but the figure shows that only bias is improved. None of the simulations capture any of the structure as shown in the observations that are relevant to wind energy (e.g., apparent jet-like feature, low-level shear, shear across the typical rotor swept area, etc.) and this is not discussed at all by the authors.

The vertical profiles shown represent the lower ~2 km of the atmosphere, where TC-induced winds exert first-order control on the environmental forcing experienced by offshore infrastructure. Within this context, the improvement noted for AOW case reflects a reduction in bias in hub-height wind speeds and shear which are necessary baseline conditions for any subsequent application-specific analysis. We have revised this statement in the manuscript to clarify that the relevance to offshore wind energy lies in establishing physically consistent environmental boundary conditions that support any subsequent detailed wind energy modeling and design studies.

- 2) It is clear that AOW increases SST cooling, but it is not clear if this is being done accurately. From table 3, the first column shows that A was already below the OSTIA temperature and AOW continued to cool it further from observations. The second and third columns again show cooling but at this point the starting point was warmer than OSTIA so it comes off as an improvement. Do you only show “improvement” if you start with a warm-biased SST?

We thank the reviewer for this comment. We would like to clarify that SST in experiment A is prescribed from GFS analysis and therefore highly sensitive to track biases relative to the best track. As a result, when the simulated storm track deviates from the observed track, particularly after 00 UTC 22 August (Fig. R1a), storm-induced cold-wake cooling is absent in A, even during periods when such cooling is evident in observations (e.g., 12 UTC 22 August; Fig. R2b). This explains why SSTs in A may remain cooler or warmer than OSTIA independent of storm forcing.

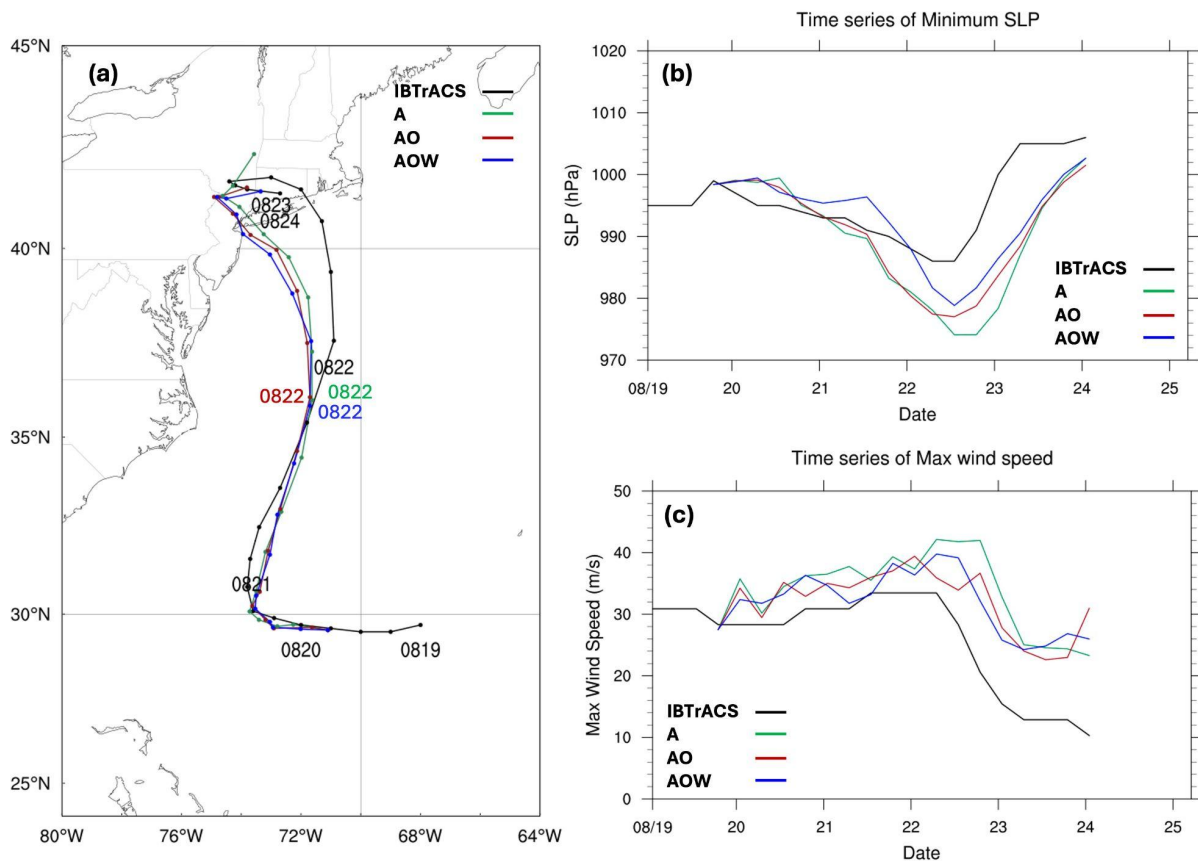
Because all three simulated storm tracks deviate from the observed track, especially after 00 UTC 22 August, we evaluate SSTs in a storm-centered coordinate (300 km × 300 km) to ensure a consistent comparison of storm-induced cooling regardless of track differences (Fig. R2b). Within this framework, SST variability in OSTIA is dominated by the storm-induced cold wake, making it suitable for assessing the relative cooling response among experiments rather than absolute SST bias.

Storm-induced SST cooling is closely linked to storm intensity and translation speed and should therefore be interpreted alongside the simulated MSLP (Fig. R1b) and storm motion (Fig. R1a). At 12 UTC 20 August, although the simulated storms are located near the observed position, their slower translational speeds lead to eastward position biases. Consequently, experiment A does not exhibit cold-wake cooling near the storm center, while cooler SSTs appear farther west where the observed storm was located. In contrast, the coupled AO and AOW simulations show pronounced SST cooling in the eastern and southern quadrants relative to the storm center. This enhanced cooling is consistent with slower storm motion between 06 and 12 UTC, which promotes stronger vertical mixing and upwelling, leading to lower storm-centered mean SSTs (Table 3).

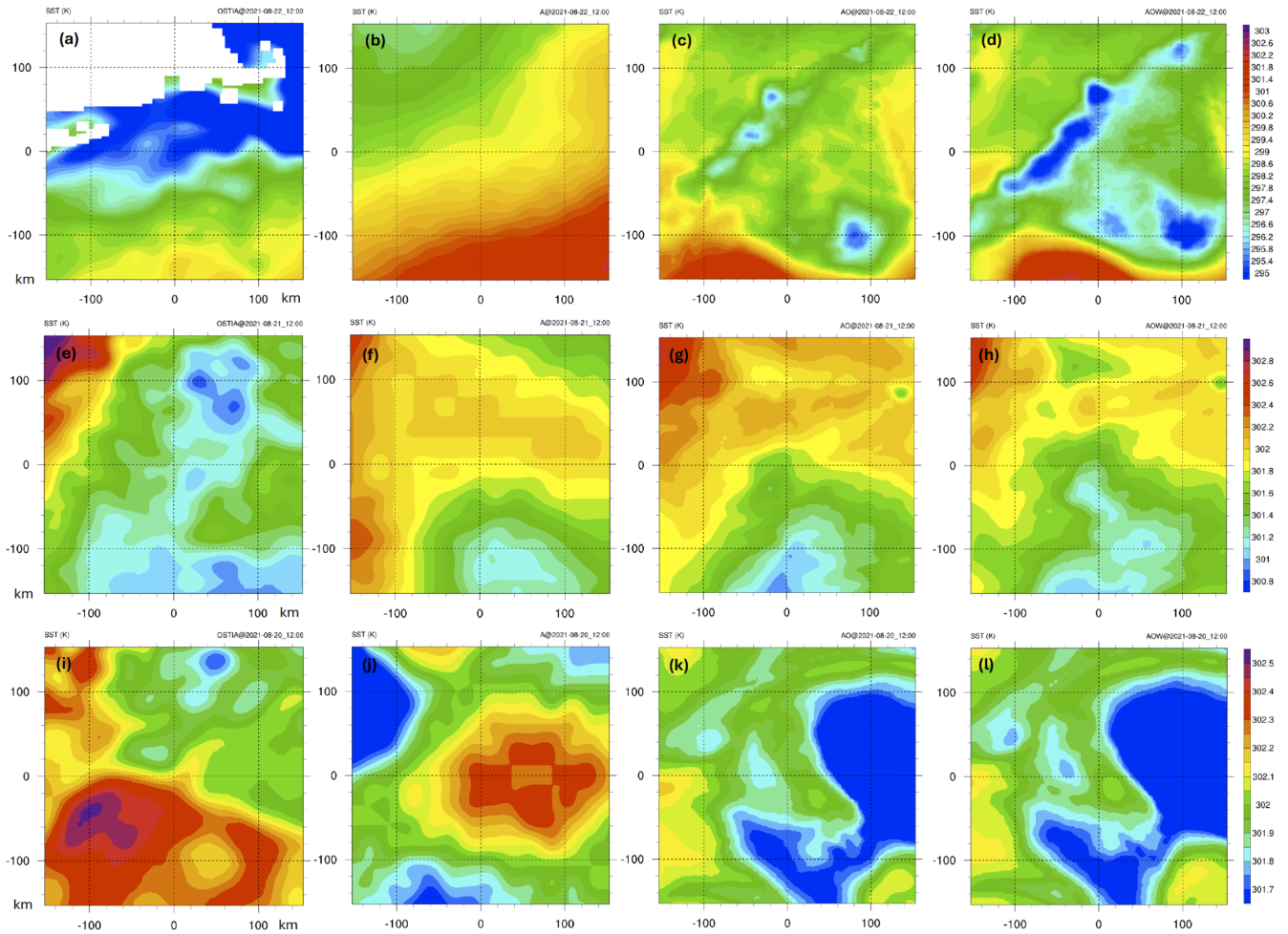
As the storms intensify, coupled processes in AO and AOW become more active, producing clear storm-induced cooling signals (third and fourth columns of Fig. R2). By 12 UTC 22 August, when the storms reach peak intensity, the difference between AO and AOW becomes more pronounced, reflecting the

additional wave-induced mixing in AOW. **Importantly, this enhanced cooling occurs regardless of whether the initial SST is warmer or cooler than OSTIA, demonstrating that the improvement is not conditional on an initial warm bias but instead reflects the physical impact of enhanced atmosphere–ocean–wave coupling.**

In addition, we conducted multiple sensitivity experiments using different initialization times and SST datasets and consistently observed similar relative cooling behavior among the experiments. This further confirms that the results are robust and not contingent on initial SST bias, but rather arise from the inclusion of dynamic air–sea–wave coupling, consistent with previous studies (e.g., Zhao et al., 2017, 2022).



**Figure R1. Comparison of simulated (a) track, (b) minimum sea-level pressure (SLP), and (c) maximum 10-m wind speed of Hurricane Henri with IBTrACS Best Track data from 18 UTC 19 to 00 UTC 24 August 2021. Black lines show IBTrACS data; green, red, and blue lines represent experiments ‘A,’ ‘AO,’ and ‘AOW,’ respectively.**



**Figure R2.** Distribution of SST in a 300 km  $\times$  300 km storm-centered coordinate at 12 UTC on August 20<sup>th</sup> (bottom row), 12 UTC on August 21<sup>st</sup> (middle row), and 12 UTC on August 22<sup>nd</sup> (top row). The first column shows SST derived from OSTIA, the second column presents SST values from 'A', the third column displays SST from 'AO', and the fourth column shows SST from 'AOW' simulation.

- 3) The Sanchez Gomez et al. 2023 paper is commonly cited as an offshore paper. It is not. Additionally, in the paragraph starting on L331, the authors claim wind-wave interactions have been “overlooked” and call this an “oversight” of the papers they cite. Assuming they meant to reference the offshore Sanchez Gomez et al. 2023 paper, this is clearly stated as a limitation of the study and note the potential importance of including these effects in future work. To call this an “oversight” is dishonest and misleading. The references selected in this paragraph are cherry-picked to overemphasize the findings in this paper. Where are the studies that have already looked at atmosphere-ocean-wave coupling for hurricanes? A quick google search shows that several exist and have already highlighted the importance of such coupling. Kim, Hyun-Sook, et al. "Skill assessment of NCEP three-way coupled HWRP-HYCOM-WW3 modeling system: hurricane lura case study." *Weather and Forecasting* 37.8 (2022): 1309-1331. Li, Zhenning, et al. "How Does Air-Sea Wave Interaction Affect Tropical Cyclone Intensity? An Atmosphere-Wave-Ocean Coupled Model Study Based on Super Typhoon Mangkhut (2018)." *Earth and Space Science* 9.3 (2022): e2021EA002136. Chen, Shuyi S., et al. "Directional wind-wave coupling in fully coupled atmosphere-wave-ocean models: Results from CBLAST-Hurricane." *Journal of the Atmospheric Sciences* 70.10 (2013): 3198-3215.

We acknowledge that, as the reviewer notes, many studies have examined air-sea interactions and their influence on TC characteristics. However, many of these prior investigations focus on mesoscale storm dynamics and intensity rather than boundary layer processes relevant to offshore wind energy applications (e.g., Chen et al., 2013; Kim et al., 2022; Li et al., 2022). Our objective is to demonstrate that the newly proposed coupled modeling framework is capable of representing these interactions and to demonstrate that such processes are important for assessing offshore infrastructure risk under extreme conditions.

We have revised the manuscript to remove language suggesting negligence or omission. We describe these citations as relying on simplified or one-way atmospheric or oceanic representations, consistent with their stated objectives in Section 4.4. The revised text more accurately reflects the intent and limitations of the existing literature and positions the present work as an extension motivated by these acknowledged or implicit methodological boundaries.

- 4) L343-345 - the claim is that because the AOW model reasonably captures wind/wave misalignment the simulation now represents more realistic turbine loads?

We have revised the manuscript text to clarify that resolving wind–wave misalignment improves the physical realism of the simulated environmental conditions (i.e., wave generation and propagation), which are relevant to offshore infrastructure under extreme events such as tropical cyclones. We agree that capturing wind–wave misalignment alone does not directly demonstrate improved representation of offshore turbine loads. This change maintains the intended scientific message while ensuring the wording accurately reflects the scope of the study.

### Minor corrections:

Fig. 3 - off the page, impossible to read labels, legend, etc.

Figure 3 has been updated with larger labels and a clearer legend. In addition, panel (d) has been rearranged and placed below panels (a)–(c) to improve readability.

Fig 7 - The caption says this is a vertical distribution but it is not. The word “panel” should be changed to “row” and the lines/dots are very difficult to see. Ticks are illegible and there is a bunch of very small font around the figure.

We have updated the caption accordingly. The figure has also been revised to improve readability: line markers and dots are now more distinct, and we removed the small, cluttered font elements around the plot.

Fig 8 - Panel A is already shown in a previous figure. Labels impossible to read.

Panel A has been deleted and the locations of stations 41001 and 41002 are added to Figure 3(a).

L378-379 - Charnock does not ignore wave effects. It is a function of wind speed but estimates the roughness due to waves. If you want to say it ignores wave direction; sure.

We thank the reviewer for the comment and agree. The text has been revised to clarify that Charnock’s formulation implicitly represents wave-induced roughness through wind speed, but does not explicitly account for wave-state information such as wave direction or wave age in the uncoupled simulations.

### Technical Suggestions:

L166 - “cecentering” spelling?

Done.

L171 - “fro”

Done.

L242 - "To To" 252 - "this this"...

Done.

L378 - "Charnock formulation's formular"

Done.

## References

- Chen, S. S., Zhao, W., Donelan, M. A., and Tolman, H. L.: Directional wind–wave coupling in fully coupled atmosphere–wave–ocean models: Results from CBLAST-Hurricane, *Journal of the Atmospheric Sciences*, 70(10), 3198–3215, <https://doi.org/10.1175/JAS-D-12-0157.1>, 2013.
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## Review of “Fully Coupled High-Resolution Atmosphere-Ocean-Wave Simulations of Hurricane Henri (2021): Implications for Offshore Load Assessments”

The article presents a newly developed coupled atmosphere-wave-ocean model that has been tested in a single Hurricane case at the US East Coast. The authors motivate their topic and choice of journal with the load and structural vulnerabilities exhibited by turbines during tropical cyclones, mainly due to wind-wave misalignment. This article is mainly an introduction to the new coupled modeling system, along with a case-study validation for extreme conditions. As such, it could have fitted in other Copernicus journals such as Geoscientific Model Development. However, it also falls within the broad topic of "wind and the atmosphere" and "fluid mechanics", and thus a publication in WES can be justified.

Overall, the manuscript is well written and logically structured. A variety of observational data types are utilized to evaluate the performance of the simulations. In total, three different scenarios are tested: atmosphere-only, atmosphere-ocean-coupled, and atmosphere-wave-ocean-coupled (AWO). The validations indicate that AWO performs best, although it still exhibits some deviations from the observations, particularly when compared to the best-track data.

I recommend publication of this article after minor revisions.

We are sincerely grateful to the reviewer for their time, thoughtful comments, and constructive questions, all of which have enhanced the clarity and robustness of our manuscript. Below, we provide a detailed, line-by-line response to each of the reviewer’s comments.

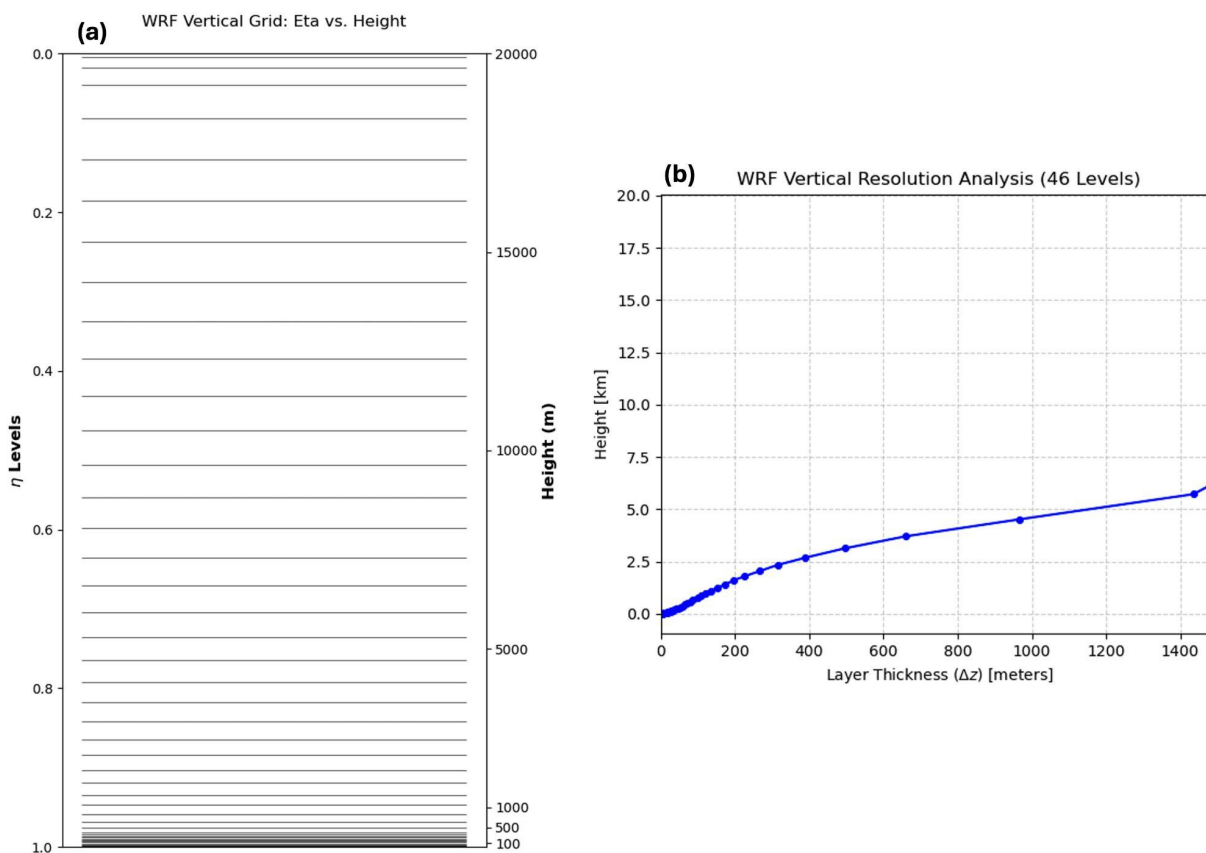
### Minor revisions

- line 138: 46 vertical levels seem to be rather coarse, considering that 12 of them are below 100 m and the hurricane stretches all the way to the tropopause. Can you show a plot of the levels, and have you checked the sensitivity of your results to the number of model levels?

We appreciate the reviewer’s comment regarding vertical resolution. The vertical grid used in this study is designed with enhanced resolution in the lower troposphere, with closely spaced levels near the surface to better resolve planetary boundary layer (PBL) processes and surface fluxes that influence hurricane structure and wind-wave coupling. Figure R1 illustrates the vertical level distribution, highlighting the intentionally dense spacing within the PBL and a gradual increase in layer thickness with height.

The primary focus of this study is on near-surface and PBL processes relevant to offshore wind hazard assessment. While hurricanes extend to the tropopause, the chosen vertical grid provides sufficient resolution to represent the large-scale upper-level storm structure while prioritizing resolution in the lower troposphere, which is most critical for the objectives of this study. Notably, comparisons with available observations presented in the manuscript indicate that the 46-level configuration captures the main TC characteristics relevant to this study.

In addition, during manuscript preparation, we conducted sensitivity experiments varying the number of eta levels from 46 to 58. While modest differences in peak storm intensity were observed, these differences did not substantially affect storm track, near-surface wind fields, or the coupled wind-wave response examined here. The main conclusions of the study remained unchanged, indicating limited sensitivity to vertical resolution within this range. Any systematic biases associated with the chosen vertical resolution would be expected to affect all coupled experiments in a similar manner; therefore, the relative differences among simulations and the primary conclusions of this study are unlikely to depend on the number of vertical levels used.



**Figure R1. (a) Distribution of the 46 WRF eta levels and their corresponding heights (m). (b) Vertical profile of layer thickness (m) as a function of height.**

- line 155: Which period do you discard as spin-up time? You mention that SWAN is started from a quiescent state, thus it would need some time to spin up. Also, WRF is known to not perform well in the first couple of hours. How do you initialize FVCOM? Ocean models usually require a long spin-up time. Did you check that?

All experiments were initialized at 18:00 UTC on 19 August 2021 and simulated for 102 hours. For wave evaluation, we discarded the first 6 hours as a wave spin-up period, consistent with standard SWAN practice when starting from a quiescent state.

To address the concern regarding WRF, our analysis focuses on times at least 18 hours after initialization (i.e., SST), when the model has largely adjusted to the initial conditions and the storm structure is well established.

Regarding FVCOM, the initial fields of temperature, salinity, sea surface height, and velocity fields were derived from HYCOM reanalysis, ensuring that vertical stratification was accurately represented. The model was initialized 30 hours prior to the first evaluation time (00:00 UTC 21 August; Figs. 4-5). This lead time allows the oceanic boundary layer and coastal dynamics to reach a dynamical adjusted state and fully respond to high-frequency wind-wave coupling before hurricane-strength winds impact the domain. The oceanic adjustment relevant to hurricane forcing occurs on relatively short time scales: the upper-ocean response to intense wind stress is dominated by rapid boundary-layer processes including Ekman

adjustment (~1 day), mixed-layer deepening (hours to < 1 day), and near-inertial motions. In shallow and coastal regions, the shelf response to wind stress typically evolves over ~10-20 hours. Accordingly, the 30-hour pre-forcing initialization period is sufficient to allow surface stress, velocity fields, and turbulence closure to dynamically adjust and equilibrate while maintaining fidelity to the observed pre-storm ocean state. Comparison with OSTIA satellite SST demonstrates that FVCOM reasonably captures the pre-storm thermal state and the subsequent dynamical cooling patterns, supporting the statements described above.

- Code and data availability: While it is difficult to share the simulation results due to storage, the setup files of the different models, WRF, SWAN, FVCOM, and their coupling can be shared more easily. The same goes for the analysis scripts to reproduce the table and plots. I suggest putting those on Zenodo to make the study better reproducible. Please also add the repository for the coupler. Is the coupled modeling system that you developed publicly available?

We are in the process of publishing all experiments, configurations, and code on our project page at <https://wdh.energy.gov/project/trexo>. A DOI will be available once this process is finalized, and we expect it to be issued well before the manuscript is published online.

## Technical corrections

- There are some typos, e.g. l 171 "fro" -> "for", line 408 double ".", line 469 "therodymaic" -> "thermodynamic". Careful revision of the entire manuscript regarding this is needed.

All noted typographical errors have been corrected, and the entire manuscript has been thoroughly reviewed to improve clarity and consistency.

- There are some double words, e.g. line 242 "To To .." and line 252 "This This ...". Here also a check of the entire manuscript is also needed

All noted typographical errors have been corrected, and the entire manuscript has been thoroughly reviewed to improve clarity and consistency.

- S1 is never explicitly mentioned. Please add a reference add an appropriate place or remove it from the Supplementary material.

An explicit reference to Figure S1 has now been added to the manuscript.

- Figure 3 is too wide for the page; I cannot see the legend of Figure (d) properly. I suggest adding the dropsonde positions to (a) and then making it bigger. This also makes it easier to compare the dropsonde locations to the deviating tracks of the simulations compared to the best-track data

Figure 3 has been updated with larger labels and a clearer legend. In addition, panel (d) has been rearranged and placed below panels (a)–(c) to improve readability.

- Line 297 mentions S3 explicitly

We have ensured that this reference is properly cited as **Figure S3** in the revised manuscript.

- Figure 7 covers a big domain, bigger than the area that is analysed in the remaining article. With this zoom level, it is difficult to see the details around the track. I suggest zooming to 20°N and 60°W-90°W at least to make it easier to compare. Still larger-scale features are visible

We have updated Figure 7 to focus on the region between 20°-50°N and 55°W-90°W. This zoomed-in view improves visibility of the storm track and associated features, while still maintaining sufficient domain size to show large-scale patterns.

- Figure 8: Sub-figure title of figure (b) - (g) is too small

The panels in Figure 8 (b)-(g) have been enlarged for improved readability. In addition, to avoid repetition, panel (a) has been removed, and the locations of stations 41001 and 41002 are now indicated in Figure 3(a).