

## Reviewer 1

Dear authors,

Your paper tries to assess the sensitivity of the Fitch scheme in wake simulations by implementing it on a newly developed PBL scheme. I am certain that this manuscript is interesting and has some value but I am not sure whether in its actual state displays correctly this value, since I think the reader cannot gain much from all the numbers you reach with your simulations. So in the following, you find a list of major and minor/specific comments.

Dear Reviewer, we sincerely thank you for taking the time to read through the manuscript and offering feedback. We have substantially updated our manuscript following your suggestions, and we believe that the article is now much stronger and more interesting to read. Please find an itemized response below where our response is marked in red text.

Major comments:

1. My main comment is that the reader does not gain much when reading your work (this sounds harsh but I will try to explain). You compare results from Fitch using two PBL schemes. You do not conclude which PBL scheme is better. You do not conclude which PBL scheme is better with Fitch either. You basically simulate wakes and report the results and basically claim that since the results can be quite different then you suggest to use many different PBL schemes when simulating mesoscale wakes to get an idea of the uncertainty. This is of course valid but then what? One could then say you need to try all wind farm parametrization to get an idea of the uncertainty (and all PBL schemes available). I would think this would be a waste of resources. What I think it would have been nice to see here is some arguments/analysis in which given the differences between the wake simulations one could already say something about the ability of the Fitch scheme to model wakes. Or, better, that the authors have developed a methodology which could use the results of the simulations to gain knowledge about the accuracy of the Fitch scheme. All the quantitative results with regards to the differences under the idealized and the mid-Atlantic case are not really used to anything (I mean the actual numbers) and will not really help anybody to discern anything about the Fitch scheme and/or PBL schemes used. Maybe, one could also simply say: what should be the maximum differences in wind speeds and turbulence deficits when simulating wakes with different PBL schemes when using the same farm parametrization?

While your feedback is blunt, we have taken it to heart. As this is your main comment, we have emphasized our response here and broken it up into five parts.

1. The motivation for this manuscript could have been clearer and stronger.

Both reviewers noted that this manuscript was not engaging, so we have updated the introduction to more clearly highlight the important and time-sensitive problem that our research addresses (L25-49). Our primary motivation for conducting this analysis is as follows: offshore wind resource assessments are necessary for the rapidly developing offshore wind industry, but these resource assessments suffer from a lack of quality observations in most of the U.S. offshore wind resource areas. Thus, the offshore research agenda within the U.S. has explicitly solicited researchers to improve uncertainty quantification for offshore wind resource assessments. This call has come from academia (e.g., Archer et al. (2014), "Meteorology for Coastal/Offshore Wind Energy in the United States Recommendations and Research Needs for the Next 10 Years", which states that Research Need #2 is Uncertainty Quantification, especially in the form of ensemble simulations, which is what our research enables) as well as U.S. federal scientific agencies (e.g., Shaw et al. (2019) "Workshop of research needs for offshore wind resource characterization", in which the need for uncertainty quantification is stressed multiple times). Our research directly addresses the need to improve uncertainty quantification of offshore wind resource.

2. Our article improves the capability for uncertainty quantification, **which is distinct from model validation**, but also crucial to ensure reliable numerical models.

As addressed above, there is an established need to quantify uncertainty in numerical models of wind resource, especially for regions that lack high quality observations. The National Research Council of the National Academies published a book that describes the importance of (and distinctions between) uncertainty quantification and validation, "Assessing the Reliability of Complex Models: Mathematical and Statistical Foundations of Verification, Validation, and Uncertainty Quantification". While validation answers the question of "How accurately does the model represent reality for the quantities of interest?", uncertainty quantification addresses "How do the various sources of error and uncertainty feed into the uncertainty in the model-based predictions of the quantities of interest?". These questions are interrelated but distinct and co-equal parts of the verification, validation, and uncertainty quantification (VUQ) process. The book states that "the first UQ task is to quantify uncertainties in model inputs", and we do precisely this by developing and implementing new WRF code that allows users to vary the PBL scheme in a wind farm simulation. In our paper, we demonstrate that indeed there is a great deal of wind resource uncertainty that is associated with the choice in PBL scheme. Perhaps our

most simple and most important finding is that “the 3DPBL generates 4.7%-7.8% less power than MYNN” in the period and test case considered in our analysis. This finding, while technically specific to our analysis, could have serious implications for the financial viability of the offshore wind industry when similar analyses are conducted by interested stakeholders, and we demonstrate this finding without employing observations. (We point out that observations of wakes in US waters are not available given the lack of offshore deployment in US waters.)

We concede, as the book notes, that “VVUQ tasks are interrelated”. However, our work (1) enhances the ability of researchers to conduct VVUQ studies for wind farm simulations in the future and (2) demonstrates **for the first time** that, indeed, future VVUQ studies should vary the PBL scheme. Both reviewers note that our paper already feels too long, and as such, it would not be possible to additionally conduct a thorough validation study that meets the best practices delineated in the book, such as

- “Principle: Validation assessments must take into account the uncertainties and errors in physical observations (measured data).”
- “Best practice: If possible, use a broad range of physical observation sources so that the accuracy of a model can be checked under different conditions and at multiple levels of integration.”
- “Principle: Validation and prediction often involve specifying or calibrating model parameters.”
- “Principle: The uncertainty in the prediction of a physical [quantity of interest] must be aggregated from uncertainties and errors introduced by many sources, including discrepancies in the mathematical model, numerical and code errors in the computational model, and uncertainties in model inputs and parameters.”

We believe that a future article that carries out such a validation study and meets these principles would indeed be valuable, especially when conducted in conjunction with observations from upcoming field campaigns that include focused efforts to characterize mesoscale wake effects (e.g., AWAKEN/ARISE) and atmospheric phenomena in the U.S. offshore waters (e.g., WFIP3).

3. Now that our idealized simulations do not share large-scale forcing, it is increasingly important that we simulate a real case study with both MYNN and the 3DPBL that share large-scale forcing.

As discussed in greater detail below, following your feedback we have re-run all the idealized simulations so that their NWF hub-height wind speeds match. This effort necessitated tuning the large-scale forcing for each simulation. As such, the idealized simulations and real simulations highlight two distinct effects now. The idealized

simulations explore the question of “How does the unique momentum recovery parameterization of each PBL scheme affect wakes”, and (as we discuss in greater detail in the manuscript) the real simulations ask “How do differing predictions of hub-height wind speed affect wakes?”. Thus, the real simulations that we have run take on even greater importance now.

#### 4. The scope of our article is consistent with the scope of other published WFP sensitivity studies, some of which have been published in *Wind Energy Science*.

- Bodini et al. (2021) published a WRF wind resource assessment study in *WES* (no WFP, but ultimately addressing the same fundamental question of uncertainty associated with a PBL) in the offshore US that did not compare to observations. This paper employed a 16-member WRF ensemble that was generated using in-built WRF capabilities.
- Pryor et al. (2021) published a WRF WFP sensitivity in onshore US in *JAMC* that also did not compare to observations.

Thus, our methodology is consistent with other academic publications that address the same fundamental question we investigate.

#### 5. Final, itemized response to additional concerns raised in this comment

Thus, with this in mind:

- "One could then say you need to try all wind farm parametrization to get an idea of the uncertainty (and all PBL schemes available). I would think this would be a waste of resources": This approach is exactly how Archer et al. (2014) suggest conducting uncertainty quantification, and correspondingly, how uncertainty quantification has been proposed along these lines in turbine-free wind resource assessments (e.g. Bodini et al. (2021)) and turbine-including assessments (e.g. Pryor et al. (2021)). Our work is the first to expand the uncertainty quantification capabilities to account for variance in PBL scheme in turbine-including simulations, a factor that has often been shown to be the largest source of uncertainty in turbine-free simulations (e.g. Optis et al. (2020)).
- "All the quantitative results with regards to the differences under the idealized and the mid-Atlantic case are not really used to anything (I mean the actual numbers) and will not really help anybody to discern anything about the Fitch scheme and/or PBL schemes used." Taking this feedback, we have substantially reduced the number of overly detailed quantitative comparisons throughout the manuscript. However, we have retained the most important quantitative differences, such as

statements similar to "the 3DPBL generates 4.7 %–7.8 % less power than MYNN in August 2020".

2. Your introduction is way too long. Particularly Section 1.2 is not really needed and it falls very much into kind of the same comment I just made about many numbers (from a number of previous wake works) without much meaning. The last paragraph of that subsection can be kept and will be sufficient. Also all the Fitch studies before Archer et al. (2020) are wrong (due to the bug in the model) and so they should not be mentioned. Lastly, what the introduction really lacks is why trying now Fitch with the 3DTKE PBL scheme? Would it be better? More realistic? Totally wrong? I guess the reader would tend to think that a 3D PBL scheme is better than a "2D" one such as MYNN

Regarding the length: We have cut Section 1.2 and have adapted its most important contents into the rest of the introduction.

Regarding the TKE advection bug: We have updated the manuscript to include the statement " We note that some Fitch WFP simulations, those with TKE advection turned on prior to Archer et al. (2020) were subject to a bug in the WRF code, and as such, the results from these studies should be interpreted with caution" (L81-83).

Regarding the discussing the 3DPBL in the intro: In an effort to keep the introduction short and engaging, we discuss the motivation for the 3DPBL in the Methods (L105-108). Crucially, we also emphasize that the NCAR 3DPBL parameterization is different than the 3DTKE parameterization. We have updated the manuscript to clarify this "To avoid confusion regarding nomenclature of new turbulence models, we note that the NCAR 3DPBL is different from the 3DTKE PBL scheme (Zhang et al., 2018)" (L101-103).

3. Second paragraph in Sect. 2.1: these lines should be complemented with the formulations so that the reader can get an idea of the advantages/extensions of the 3D TKE PBL.

Thank you for this suggestion. We wanted to do include the 3DPBL formulations in the initial draft of the manuscript, but we ultimately omitted copying the formulations from Juliano et al. (2022) to this paper, as the matrix equations in the original paper take up an entire page (Ref. Fig. 1). We include the reference to the paper with these formulations. Instead, we qualitatively and quantitatively discuss the major differences between the two PBL schemes in the manuscript (L109-133).

$\frac{q}{2l_1} \frac{\partial U}{\partial x}$	$-\frac{\partial V}{\partial y}$	$-\frac{\partial W}{\partial z}$	$2\frac{\partial U}{\partial y} - \frac{\partial V}{\partial x}$	$2\frac{\partial U}{\partial z} - \frac{\partial W}{\partial x}$	$-\frac{\partial V}{\partial z} - \frac{\partial W}{\partial y}$	0	0	0	0	$\langle u^2 \rangle$	$\frac{q^3}{6l_1} + 3C_1 q^2 \frac{\partial U}{\partial x}$
$-\frac{\partial U}{\partial x}$	$\frac{q}{2l_1} + 2\frac{\partial V}{\partial y}$	$-\frac{\partial W}{\partial z}$	$2\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}$	$-\frac{\partial U}{\partial z} - \frac{\partial W}{\partial x}$	$2\frac{\partial V}{\partial z} - \frac{\partial W}{\partial y}$	0	0	0	0	$\langle v^2 \rangle$	$\frac{q^3}{6l_1} + 3C_1 q^2 \frac{\partial V}{\partial y}$
$-\frac{\partial U}{\partial x}$	$-\frac{\partial V}{\partial y}$	$\frac{q}{2l_1} + 2\frac{\partial W}{\partial z}$	$-\frac{\partial U}{\partial y} - \frac{\partial V}{\partial x}$	$2\frac{\partial W}{\partial x} - \frac{\partial U}{\partial z}$	$2\frac{\partial W}{\partial z} - \frac{\partial V}{\partial x}$	0	0	$-2\beta_8$	0	$\langle w^2 \rangle$	$\frac{q^3}{6l_1} + 3C_1 q^2 \frac{\partial W}{\partial z}$
$\frac{\partial U}{\partial x}$	$\frac{\partial U}{\partial y}$	0	$\frac{q}{3l_1} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y}$	$\frac{\partial V}{\partial z}$	$\frac{\partial U}{\partial z}$	0	0	0	0	$\langle uv \rangle$	$C_1 q^2 \left( \frac{\partial V}{\partial x} + \frac{\partial U}{\partial y} \right)$
$\frac{\partial W}{\partial x}$	0	$\frac{\partial U}{\partial z}$	$\frac{\partial W}{\partial y}$	$\frac{q}{3l_1} + \frac{\partial U}{\partial x} + \frac{\partial W}{\partial z}$	$\frac{\partial U}{\partial y}$	$-\beta_8$	0	0	0	$\langle uw \rangle$	$C_1 q^2 \left( \frac{\partial W}{\partial x} + \frac{\partial U}{\partial z} \right)$
0	$\frac{\partial W}{\partial y}$	$\frac{\partial V}{\partial z}$	$\frac{\partial W}{\partial x}$	$\frac{\partial V}{\partial x}$	$\frac{q}{3l_1} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z}$	0	$-\beta_8$	0	0	$\langle vw \rangle$	$C_1 q^2 \left( \frac{\partial W}{\partial y} + \frac{\partial V}{\partial z} \right)$
$\frac{\partial \theta}{\partial x}$	0	0	$\frac{\partial \theta}{\partial y}$	$\frac{\partial \theta}{\partial z}$	0	$\frac{q}{3l_1} + \frac{\partial U}{\partial x}$	$\frac{\partial U}{\partial y}$	$\frac{\partial U}{\partial z}$	0	$\langle u\theta \rangle$	0
0	$\frac{\partial \theta}{\partial y}$	0	$\frac{\partial \theta}{\partial x}$	0	$\frac{\partial \theta}{\partial z}$	$\frac{\partial V}{\partial x}$	$\frac{q}{3l_1} + \frac{\partial V}{\partial y}$	$\frac{\partial V}{\partial z}$	0	$\langle v\theta \rangle$	0
0	0	$\frac{\partial \theta}{\partial z}$	0	$\frac{\partial \theta}{\partial x}$	$\frac{\partial \theta}{\partial y}$	$\frac{\partial W}{\partial x}$	$\frac{\partial W}{\partial y}$	$\frac{q}{3l_1} + \frac{\partial W}{\partial z}$	$-\beta_8$	$\langle w\theta \rangle$	0
0	0	0	0	0	0	$\frac{\partial \theta}{\partial x}$	$\frac{\partial \theta}{\partial y}$	$\frac{\partial \theta}{\partial z}$	$-\frac{q}{\Lambda_1}$	$\langle \theta^2 \rangle$	0

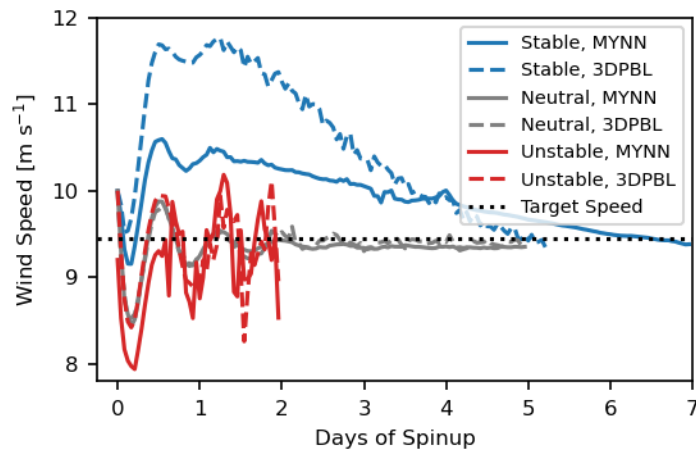
(19)

Response Figure 1. The page-long 3DPBL equations, as documented in Juliano et al (2022).

- Text between lines 198 and 208: due to the use of a new PBL scheme, it would be interesting to see the development with time of the turbine-free simulations and find out why 3 days are indeed needed to develop the ABL and reach quasi-steady state (it just reads as a quite extremely long spin up period). By the way, you do not

mention (I think) the type of boundary conditions during spin up and wake simulations.

Thank you for the suggestion. We have added a section discussing the spin-up of the simulations at the start of Section 3.1 (L235-242).



Response Figure 2. Figure 2 in the updated manuscript. Hub-height wind speed at the center of each domain during spin-up in the idealized turbine-free simulations. The last 24 hours of each simulation is taken as the performance period for the NWF simulations.

The boundary conditions for the idealized simulations during spin-up can be found in the updated Table 1. We now explicitly state that the wake simulations use the same boundary conditions as the turbine free simulations (L184).

5. Idealized simulations: to compare fairly the Fitch scheme with the two PBL schemes, you should aim to get the same wind speed and direction at hub height. Therefore you should not use the same geostrophic wind for all simulations. The problem is clear for the unstable simulation where it does not make sense at all to compare the wake results given the large differences in wind speed.

Thank you for suggesting that we adjust our idealized simulations to match hub-height wind speeds. We reran all the idealized simulations with this constraint in mind. Your suggestion made it much easier to compare wake effects across all stabilities and PBL schemes. We believe that the idealized results are much clearer now.

As a result of the new simulations, the entirety of Section 3 has been updated. The key findings of the new idealized results can be quickly ascertained from the updated Conclusions (discussed immediately below).

6. Conclusions: the manuscript is already quite long and so such a long conclusion (which is not really concluding statements) is not needed. Can the reader get some nearly like bullet-points from your work? Also, and in relation to my comment 1, there are way too many sentences with a number of values that do not mean much if you do not have a reference or measurements. This is very clear between lines 657 and 674

We have truncated the conclusion, putting the key takeaways in a bullet list (L515-535). We have significantly reduced the amount of numerical values included in the Conclusion to focus instead on the main science messages, and we retained only the most important numbers.

Specific comments:

7. Line 4: "were only compatible with one PBL scheme" this is a general comment but I guess you mean the specific case of the WRF model, which is not mentioned at that point.

We now clarify that MYNN has been the only PBL scheme to work with Fitch "as of the Weather Research and Forecasting model v4.3.3" (L4)

8. Line 8: "internal" the reader does not know what you mean by internal so maybe drop the word and be specific in the abstract

We have replaced the phrase "internal wake" with "wind speed losses within the plant" in Line 8, and we have also amended the rest of the abstract accordingly.

9. Line 10: add "atmospheric" before "stability"

The updated abstract no longer uses the phrase "stability".

10. Line 27 "their impacts in numerical" I guess you mean "their impacts on atmospheric variables when implemented in numerical weather..." or so

The text in Line 27 has been entirely removed in the process of more strongly motivating this paper.

11. Line 31: you provide some low and high losses... what are the cases for this? I mean these are because of the size of wind farms?

Lee and Fields (2021) summarize that average total wake losses have been reported to be as low as 6.1% and as high at 40%. The 6.1% number comes from Mortensen et al. (2012) and the 40% number comes from Tindal (2009). It is difficult for us to say specifically why these differ, as both of these sources are conference presentations, and we do not have



access to them. We speculate that this spread occurs because of a number of reasons. As you suggest, one possible reason is the differing size of wind farms.

12. Line 57: maybe delete "generation"

We have deleted the surrounding section of text in order to make the introduction more concise, but thank you for catching that error.

13. Line 64: you have some ? signs when making a particular reference... this is not the first time

All the missing references have now been corrected, thank you.

14. Line 155: remove "to" before "behave"

We have removed "to".

15. Line 164: again a ? in a reference

All the missing references have now been corrected, thank you.

16. Line 165: not sure whether you define "Sq"

In an effort to keep the manuscript engaging and cut down on overly detailed comparisons, we have removed the Results section regarding TKE budget. As such, we have struck the Methods content where "Sq" was mistakenly not defined.

17. Line 180: why not using the value suggested in Archer et al. (2020)?

We remain with 100% TKE because Larsén and Fiscereit (2021) saw better performance with 100% TKE instead of 25% TKE, as we now note in L233.

18. Line 198: why not using the roughness of the sea? These parameterizations are mostly used offshore and it will be more straightforward to compare to the mid-Atlantic case

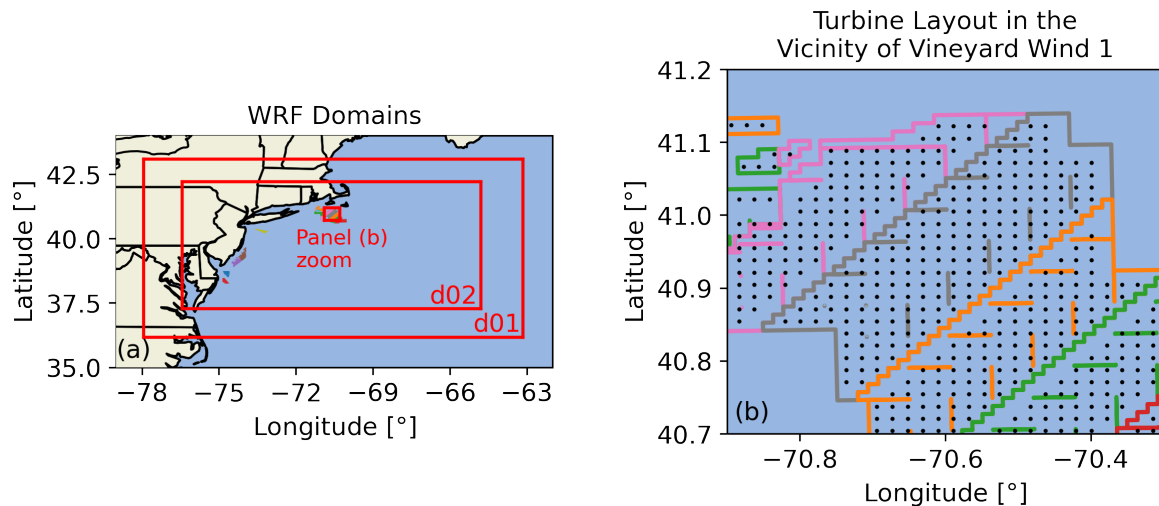
The new idealized simulations now use the roughness of the sea (0.0001 m) instead of the previous land roughness.

19. Line 199: the sentence kind of suggests that the hub height wind speed is very close to the geostrophic wind speed but that is not necessarily the case. So why 10 m/s?

Thank you for correcting our statement. Some of our updated idealized simulations are now run with 9 m/s geostrophic winds, so we have removed the corresponding text. We initially decided to force with 10 m/s geostrophic winds to be consistent with the idealized Fitch et al. (2012) study.

20. Figure 1. This figure can be changed to show the model domains and maybe an inset with a zoom of the vineyard wind 1 with the turbine arrangement would be nice

We have updated Figure 1 to show the model domains as well as a zoom in of Vineyard Wind 1. We have attached the updated figure below for convenience.



Response Figure 3. Figure 1 in the updated manuscript.

21. Line 238 and similar: all these references to manuscripts in preparation are not useful. Particularly the one at this line is not needed (also that in line 252)

We have now removed all references to manuscripts that are in preparation.

22. Sentences in lines 264-265 and 286 are redundant given each of the sentences before them

The redundant sentence in L264-265 has been removed. The statement in L286 has been updated to improve clarity.

23. Figure 2: do you say somewhere whether these profiles are instantaneous output at some time? Are they spatial averages over the whole domain? Are they time-averaged? Also the profiles should be somehow smoother; however they show some weird peaks, e.g., the highest wind speed of the stable MYNN or those below the lowest farm boundary in the stable TKE

Thank you for noting our omission. We have updated the Methods section to note that the performance period of the simulations required running "for 24 hours" (L184). We have also updated the caption for Figure 2 to clarify that these profiles are horizontally averaged over the extent of the domain as well as averaged for a day.

The wind speed profiles of the updated simulations appear to be smoother, but please let us know if this is still an issue. The “weird” TKE peaks at the surface of the 3DPBL simulations arises from the vertical staggering (or destagging) of how TKE is represented within the 3DPBL versus the surface layer scheme. This issue is being addressed in upcoming versions of the 3DPBL, but (based on the similarity of TKE between MYNN and the 3DPBL) this mismatch does not appear to strongly affect TKE profiles. We now note “The sharp peaks in TKE at the lowest level of the 3DPBL simulations are tied to the staggered representation of TKE in the new PBL scheme, and future versions of the 3DPBL will correct this issue.” (Figure 3 caption)

24. Also about the result in Fig 2 for the unstable TKE: why is MYNN 3 times lower than 3DTKE? You mention this is related to the empirical constants but the stable and neutral ones seem fine

The structural changes from MYJ (which is where the 3DPBL constants come from in this work) to MYNN focused on convective conditions (L126-127). Thus, we expected and indeed did see the strongest differences between the two PBL schemes in unstable conditions.

25. Line 300 maybe you can add after “values” whether these are from instantaneous values at a given time

We now clarify that these values come from “daylong time-averaged hub-height wind speeds” (L268).

26. Figure 3 and related results: why not aligning the wind with x so that when you make the cross (side) analyses the plots are easy to digest

We align our side views of the wake with the x-axis following Fitch et al. (2012). For example, see Figure 2 in that paper.

27. Line 327 “wakes erode” not sure how general is the erode term in wakes, could you replace it by recovery? I think you have different instances with this

The concept of wakes eroding appears throughout literature. For example “Wakes erode very quickly during unstable conditions” in Bodini et al. (2017) and “The results showed that under unstable conditions, the wake eroded rapidly” in Sun et al. (2020). We like this mental image as a complement to “wind speeds recovering”, as we believe it paints a more vivid picture and helps keep the language more engaging.

28. Line 384 the ref. to your not published work can be changed. Some others have seen this as well

The reference has been published during the process of the review for this manuscript, and we have updated the reference accordingly.

29. Line 432 delete one “of the”

We have corrected this typo, thank you.

30. Line 480 Not really true as TKE was quite different for the unstable case

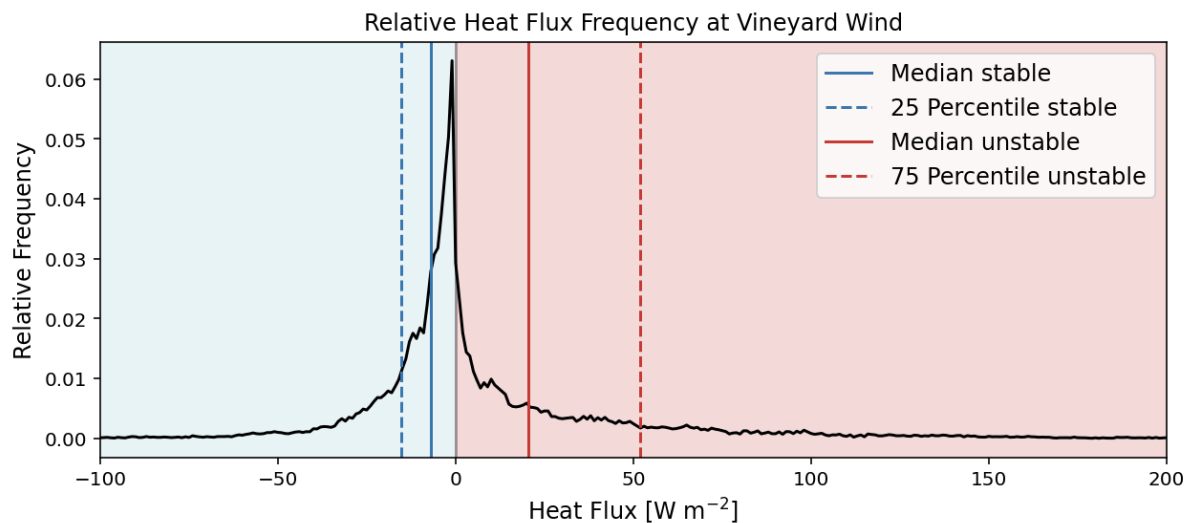
We have removed the sentence entirely.

31. Line 491: I think you need to add “on land” after “near-neutral stratification”

We have clarified that we are referring to “onshore” atmosphere (L405), thank you.

32. Line 491-494: a figure with the frequency distributions of these surface heat fluxes would be nice

We decided to omit the heat flux figure from the manuscript as we believe this information borders on the line of being overly detailed, but we include the figure in our response here for your reference.



Response Figure 4. Heat flux distribution at the Vineyard Wind centroid.

33. Figure 9 how are the winds above the boundary layer? Are they close? Maybe an inset showing the full profile would be nice

Due to the large size (>10 TB) of the monthlong 5-minute resolution dataset, we were only able to retain data in the lowest 500 m, and thus we are unable to show winds above the boundary layer. This approach is consistent with NREL’s other wind databases.

34. Line 516 replace “off” by “on”

We have replaced “off” with “on”. (L428)

35. Line 600 “amplification” I am not sure what you actually mean

Thank you for catching our ambiguous wording. We have changed “This amplification is particularly true” to “This power production difference is particularly true” (L490).

36. There are way too many avoidable references and also many references to your work (where any of the coauthors are involved)

We have cut down on many of the references by removing Section 1.2. Please let us know if there are any specific references that are unwarranted in the updated manuscript.