

A Twenty-Year Analysis of Winds in California for Offshore Wind Energy Production Using WRF v4.1.2

Review 1

Dear Reviewer, thank you for taking the time to review our manuscript and thank you for the insightful feedback. We have provided an itemized response below, where our comments are marked in red.

General comments:

This paper deals with the differences in the modelled datasets between two different model setups. I would expect two different setups to produce different results, however, it is currently unclear which one of these setups is better, as the comparison with observations is not yet available. Regrettably, the performance of the PBL scheme near the surface (e.g. when compared to buoys) is not indicative of the performance at the hub heights. Moreover, even if we look at the verification results for buoys (Table A1) it is hard to argue that one setup is better than the other. The paper argues that the differences in wind-speed results from different PBL schemes can be explained by differences in frequency between different atmospheric stability classes. Do we know which of the PBL schemes provides a better (closer to observations) description of stability? Not at this point, regrettably. In summary, I am afraid that the lack of comparison with hub height observations diminishes the applicability of the conclusions carried out in this paper.

In this manuscript, we primarily conduct a model inter-comparison study. We believe these types of studies to be essential, especially for trying to understand uncertainty of modeled wind resource (Research Need #2, from Archer et. al 2014). Additionally, model inter-comparison studies are explicitly called for in the “model experiment description papers” category in GMD (fifth bullet at https://www.geoscientific-model-development.net/about/aims_and_scope.html).

However, we additionally agree that it valuable and timely to compare to the simulations to hub-height wind speed measurements from lidar, which have only recently become available. In this spirit, we conducted a limited validation study for the month of October 2020 that maintains the model-focused nature of this analysis while also increasing the applicability of the conclusions of this paper. This analysis is detailed in the new Appendix B (L 427-447), and we summarize the analysis here.

We use measurements from two lidars---one deployed off the coast of Humboldt and the other near Morro Bay. As neither CA20 nor the WIND Toolkit contain wind information for October 2020, we run two new month-long simulations. The first simulation uses the same set up as CA20, and the second simulation uses the same set up except YSU is used instead of MYNN, to correspond to the WIND Toolkit setup.

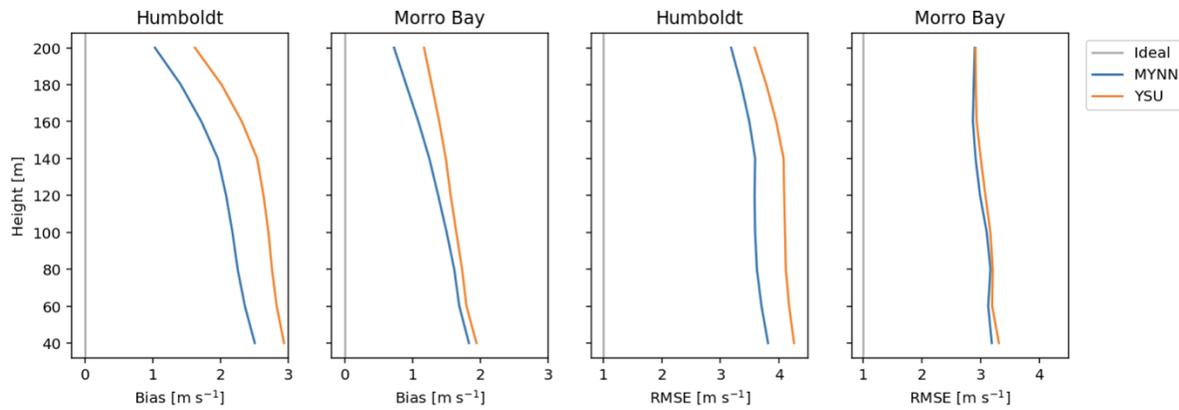


Figure R1: Profiles of wind speed bias and RMSE at Humboldt and Morro Bay for the October 2020 MYNN and YSU simulations.

We find that, for this month, MYNN outperforms YSU (Fig. R1). In Humboldt, MYNN wind speed profiles show a bias between 1.0 and 2.5 m s^{-1} . The YSU wind speed profiles have a bias that is approximately 0.5 m s^{-1} larger at all heights. MYNN also shows a smaller RMSE than YSU here. Additionally, MYNN outperforms YSU at Morro Bay in terms of bias and RMSE, although by smaller quantities. The difference in performance at the two locations may be tied to modeled stability: the models at Humboldt show predominantly weakly stable and moderately stable values of the bulk Richardson number, whereas they show a greater spread of stabilities at Morro Bay (Fig. R2).

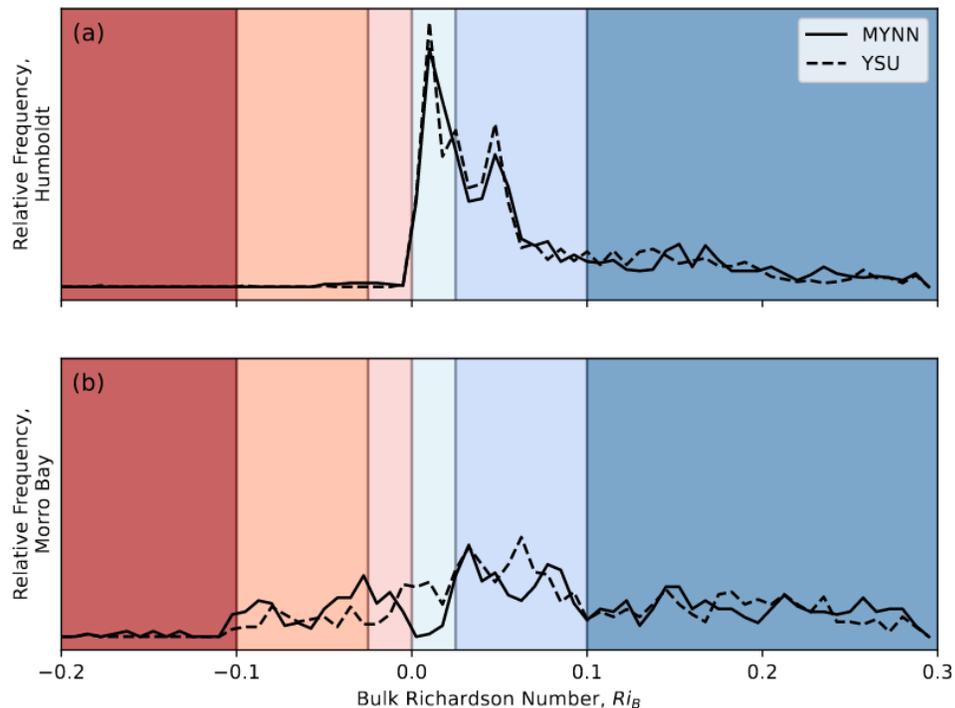


Figure R2: Bulk Richardson numbers at the location of the Humboldt and Morro Bay lidars for the MYNN and YSU simulations in October 2020.

Thus, this initial comparison suggests that MYNN is more accurate than YSU at these two locations, and therefore, it could be postulated that CA20 is more accurate than the WIND Toolkit. Future studies will expand this analysis beyond a month to study modeled winds under a longer observational window.

Specific comments (major)

- Changes in the MYNN PBL scheme: “The WIND Toolkit was developed using a 7-year (2007–2013) simulation with WRF 3.4.1. CA20 builds upon this by using WRF 4.1.2 across a 20-year period (2000–2019).” (Line 76-77). CA20 uses the MYNN parametrization scheme, the WIND Toolkit uses the YSU scheme (Lines 85-89). The problem is that in WRF version 3.7 the MYNN scheme underwent significant changes, and indeed the authors acknowledge this (Line 192). The thing that I do not understand is why if the WRF version is one of the factors that is analyzed during the sensitivity study, why aren’t the changes in the MYNN parametrization scheme also included in the sensitivity analysis (as a separate parameter)? There are no methodological difficulties, one would just need to run both WRF versions with the MYNN scheme, instead of the YSU scheme, as it was already done. The reason why I would like to see such analysis is that changes in the MYNN scheme can lead to significantly worse verification results at hub heights when compared to observations (see Figure 8, section 5.3 in Hahmann et al. 2020).
- Our sensitivity study (summarized in Figure 6 of the manuscript) aims to study the factors that have changed between the WIND Toolkit and CA20. As noted, CA20 uses MYNN and WRF 4.2.1 whereas the WIND Toolkit uses YSU and WRF 3.4.1. While MYNN saw major changes in 3.7.1, the winds in the WIND Toolkit come from YSU and not MYNN, so we do not believe this update to the MYNN PBL scheme is directly relevant for this sensitivity study.

Nonetheless, other studies (such as Hahmann et al. 2020) have shown that the change to MYNN in WRF 3.7.1 can significantly impact hub-height wind. To contribute to this scientific discourse, we additionally simulated a month of winds in October 2020 using WRF 3.4.1 and MYNN. This additional month of simulation enables comparison to the aforementioned lidar measurements.

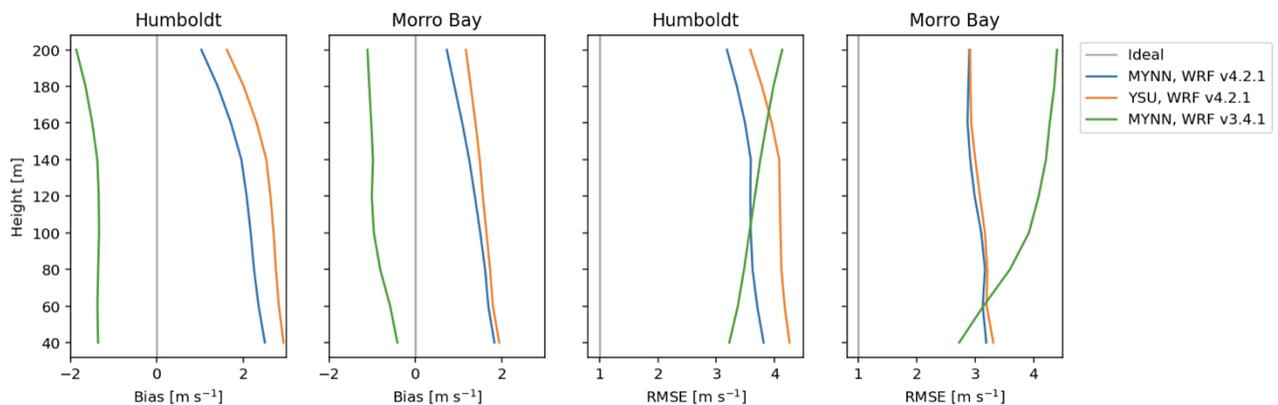


Figure R3: Same as Figure R1, except with a MYNN WRF v3.4.1 run.

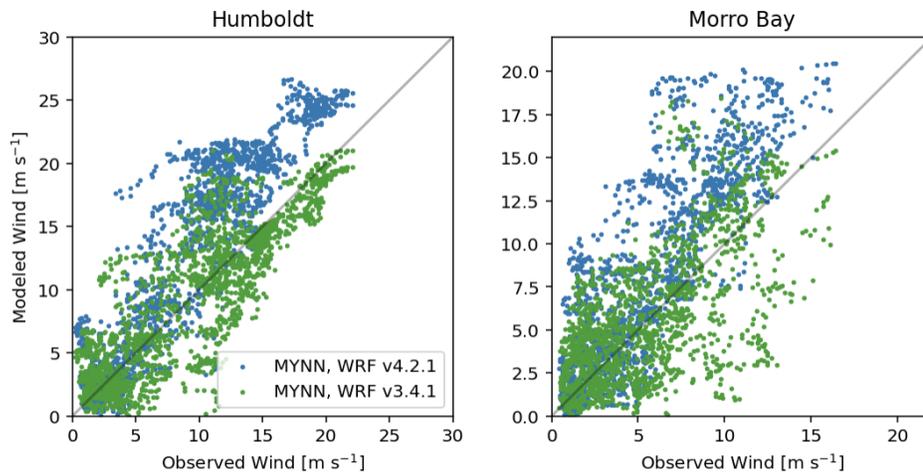


Figure R4: Comparison of instantaneous modeled and observed winds between MYNN WRF v4.2.1 and MYNN WRF v3.4.1.

We find that, indeed, MYNN in WRF v3.4.1 produces substantially different winds than those with MYNN and WRF v4.2.1 (Fig. R3). While wind profiles in WRF v4.2.1 show a positive bias, wind profiles in WRF v3.4.1 show a negative bias. The magnitude of the bias in WRF v3.4.1 is typically smaller than the bias in WRF v4.2.1, so based solely on bias, WRF v3.4.1 performs better in this comparison. The RSME results are less clear as to which model is better. At both locations, WRF v3.4.1 shows better RMSE values at lower heights, whereas WRF v4.2.1 shows better RMSE values aloft. Additionally, the comparison between pairs of observed and modeled winds (Fig. R4) shows that WRF v4.2.1 shows a pronounced bias at stronger observed wind speeds, whereas WRF v3.4.1 does not. While this limited comparison to observations is valuable, we do not believe that it fits within the scope of the CA20 vs. WIND Toolkit study, and we omit this analysis in the manuscript. However, due to the open review nature of this journal, this analysis is publicly available and citable, and we hope that it encourages future investigations.

- Low-level jet: I am not a specialist in the wind climate of North America, but the coastal low-level jet along the coast of California seems to be a well-known phenomenon. Could it be associated with the large differences in results seen during May – July? I understand that investigation into meteorological processes is beyond the scope of this paper, but the link to the low-level jet (or lack thereof) could help interpreting the results, especially, as the low-level jet is linked to upwelling, which is already linked to the strongly stable atmosphere by the authors (Line 176). Furthermore, the presence of low-level jets and understanding of its typical height can help with the interpretation of shear results (Figure 13).
- Thank you for encouraging us to examine the impact of LLJs on the wind resource. We have analyzed the impact of LLJs on wind speed and shear, and we detail our analysis below.

We define LLJs following the two criteria laid out in the North Sea analysis of Kalverla et al. (2017): the LLJ nose (the height of maximum wind speed) must be below the uppermost model height available, and the winds above the nose must decrease by at least 2 m s^{-1} . The decrease

above the nose of the jet characteristic is used in many key LLJ studies (Blackadar 1957, Bonner 1968, Baas et al. 2009), but because our datasets do not include winds above 200m, this constraint significantly limits the scope an LLJ analysis. LLJs off the coast of California have a typical height of 300-400 m (Parish 2000). However, CA20 and the WIND Toolkit only save data up to 200 m due to data constraints. (Upcoming offshore NREL-generated data sets save winds up to 500 m). Thus, our analysis only captures shallow LLJs that experience both a maximum wind speed as well as a 2 m s^{-1} fall-off within the lowest 200 m. The impact of deeper (and likely more frequent) LLJs is not possible to characterize with these data sets. Nevertheless, due to the reviewer's interest, we investigate two questions:

1. Are the large summertime differences (May-July, as requested by the reviewer) in monthly-averaged winds between CA20 and the WIND Toolkit linked to the presence of LLJs? This does not appear to be the case. First, shallow LLJs (that can be identified in these datasets) are somewhat uncommon at the three Call Areas. In the summertime months, LLJs appear most commonly at Diablo Canyon, approximately 50 hours per month in CA20, or about 7% of the total number of hours in a month (Fig. R5). LLJs appear even less frequently at the other sites.

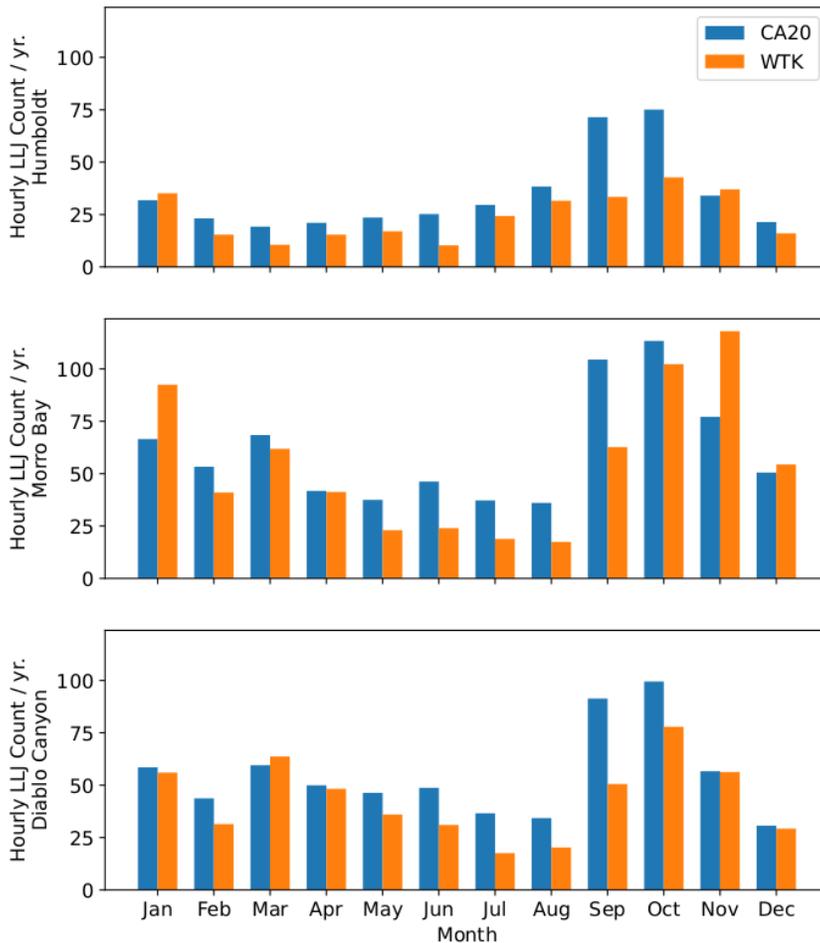


Figure R5: Average number of hours with LLJs present in each month.

Second, mean LLJ winds have a similar magnitude to typical winds, and at times, mean LLJ winds are actually weaker than the typical winds (Fig. R6). For example, mean 100-m winds in Diablo Canyon during LLJ periods for Jun-Aug are approximately 10 m s^{-1} . However, the average wind speed during all periods (irrespective of LLJ presence) is also approximately 10 m s^{-1} . Surprisingly, mean summertime 100-m winds are actually weaker than all-period-measured winds at Humboldt and Morro Bay. This counterintuitive behavior likely appears to occur because this analysis is restricted to shallow LLJs. Stronger LLJs with noses at 400 m may indeed drive summertime discrepancies between CA20 and the WIND Toolkit, but we do not have access to data with which to conduct that analysis. Based on this analysis, we believe that factors other than the LLJ drive the strong summertime wind speed discrepancy between CA20 and the WIND Toolkit.

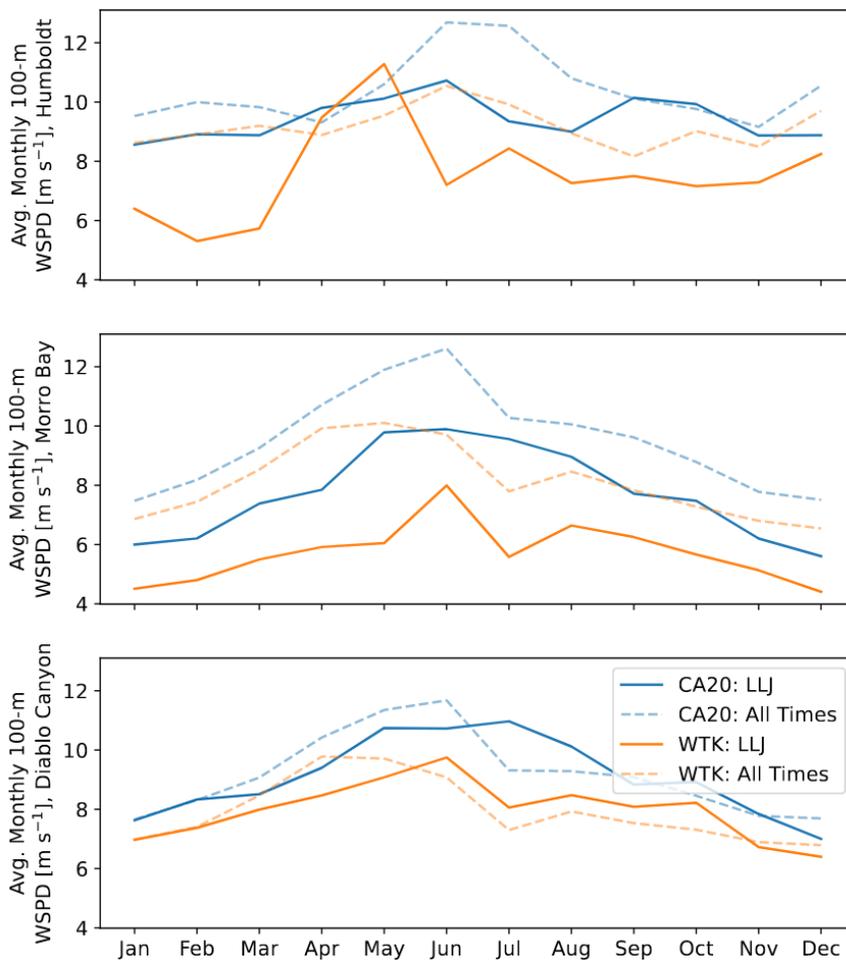


Figure R6: Average 100-m wind speed by month. Winds are averaged for periods with LLJs and additionally all timesteps.

2. Shear shows a sensitivity to the choice in lower height wind (10 m vs. 40 m). Do LLJs drive this height-dependence of shear? As a reminder, the distribution of the shear parameter is

sensitive to whether 10 m or 40 m is used as the lower height (Fig. 13 / R7). A high degree of sensitivity is observed at Humboldt and Morro Bay, whereas less sensitivity is observed at Diablo Canyon.

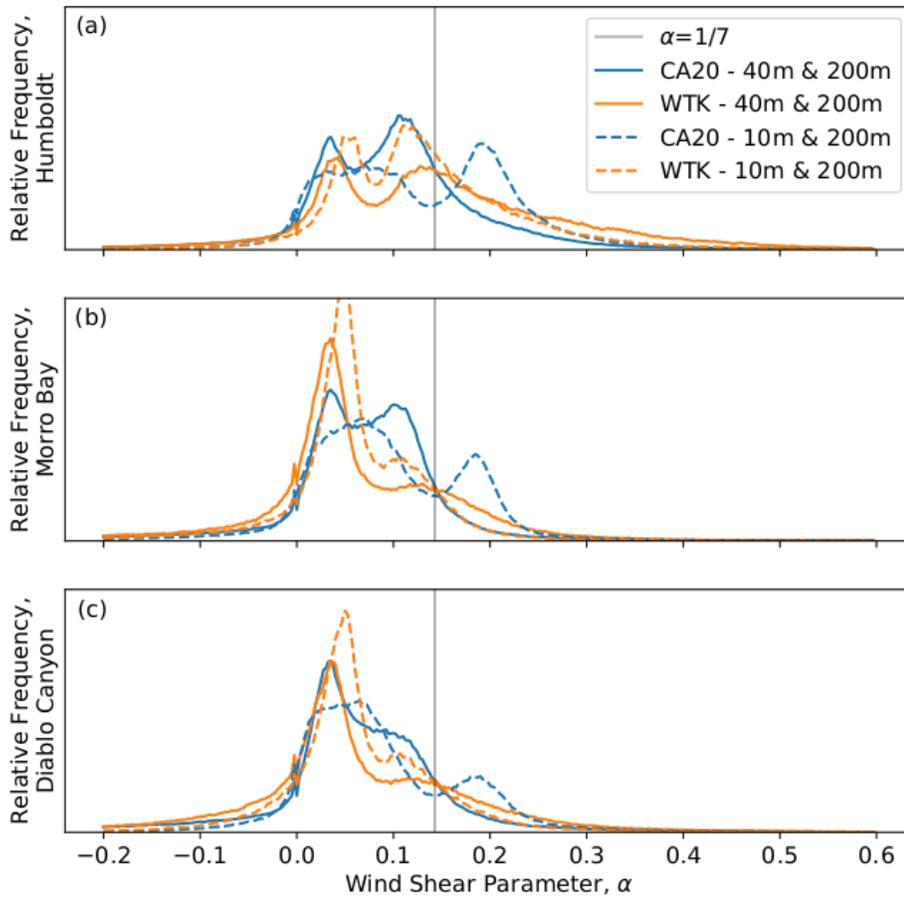


Figure R7: Figure 13 from the manuscript.

From a kinematic perspective, this sensitivity to lower height largely implies that 10-m and 40-m winds have different wind speed distributions from one another. Indeed, the distributions show similar shapes (Fig. R8), but the 40-m distributions more frequently show stronger winds ($>12.5 \text{ m s}^{-1}$) than the 10-m distributions, as would be expected.

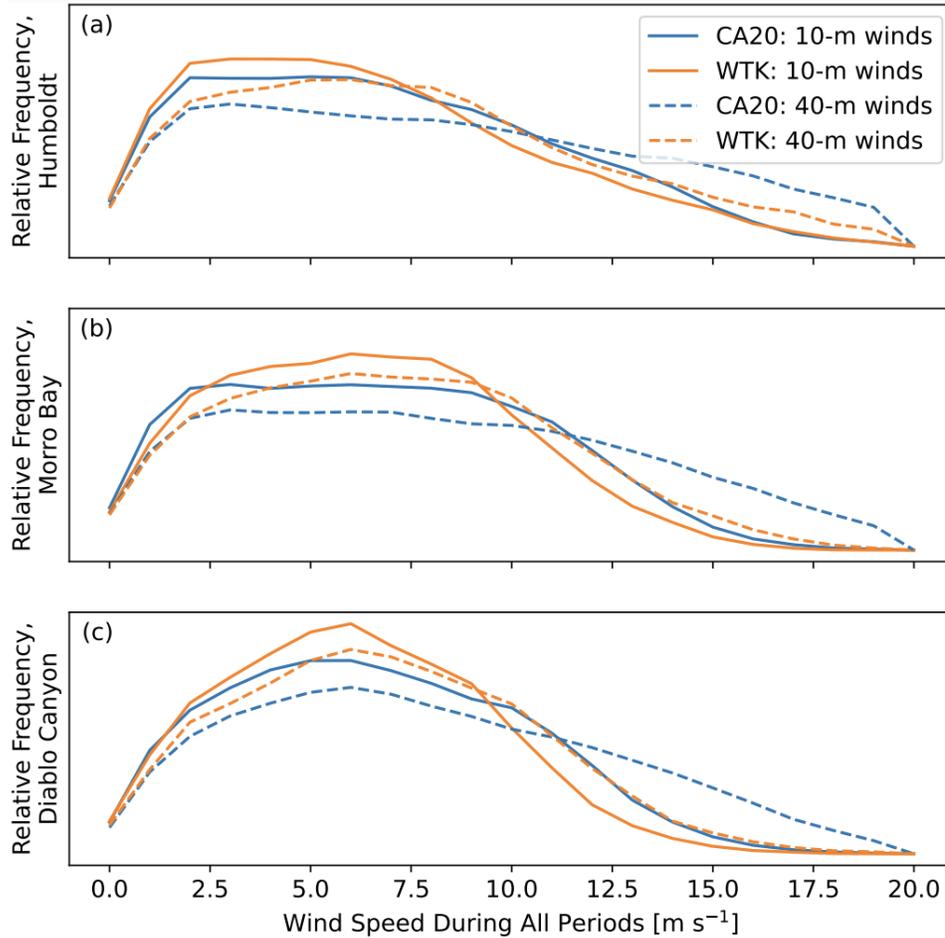


Figure R8: Distributions of 10-m and 40-m wind speeds across the full CA20 and WIND Toolkit data sets.

Thus, we examine the shape of 10-m versus 40-m distributions of wind speed during LLJs (Fig. R9). Specifically, do these distributions during LLJ periods have qualitatively distinct behavior from the “all winds” distribution? We find that they do not. At all Call Areas, the 10-m and 40-m distributions share a similar shape, but the 40-m distributions contain stronger winds slightly more frequently. This same pattern was observed for the 10-m and 40-m distributions of wind during all periods. As such, we do not believe that LLJs are driving the height-dependence of shear.

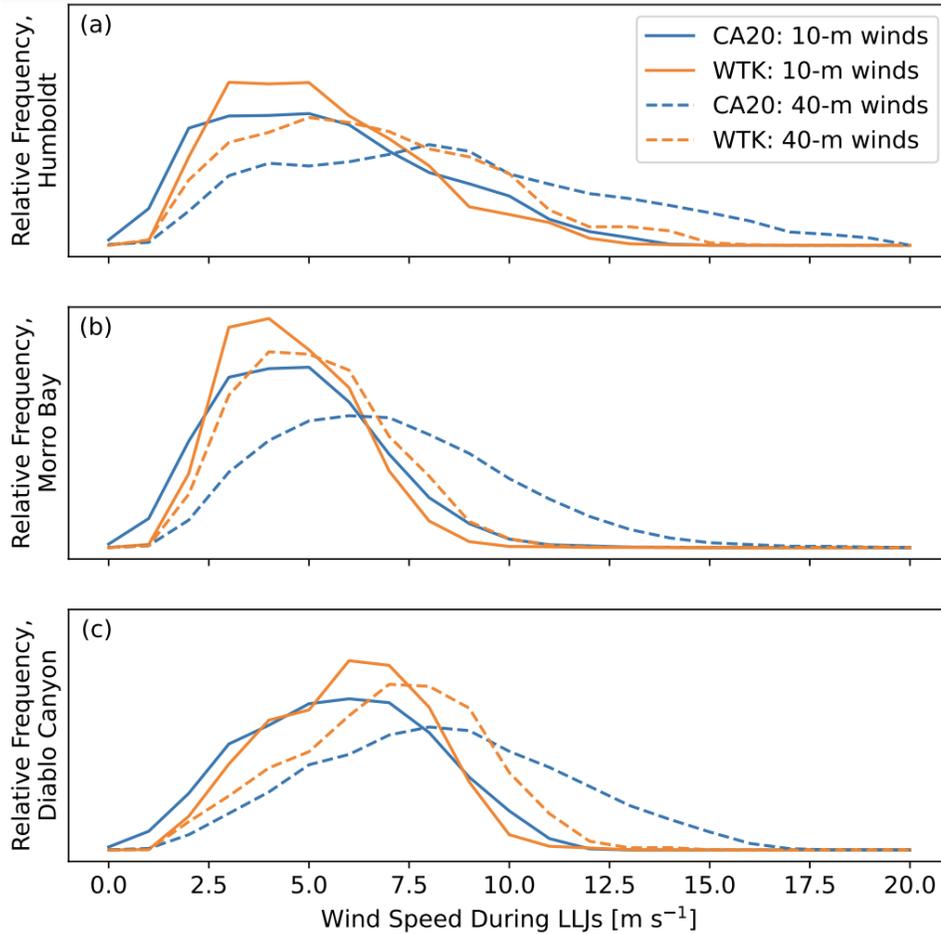


Figure R9: Distributions of 10-m and 40-m wind speeds during LLJs for both the CA20 and WIND Toolkit data sets.

Additionally, as requested, we examined the typical nose height, calculated by taking the mode over individual hours when LLJs were present (Fig. R10). We were ultimately able to find any clear correlations between nose height and the height-dependence of shear. We believe that the above “wind distribution” analysis helped us better examine the correlation between LLJs and shear.

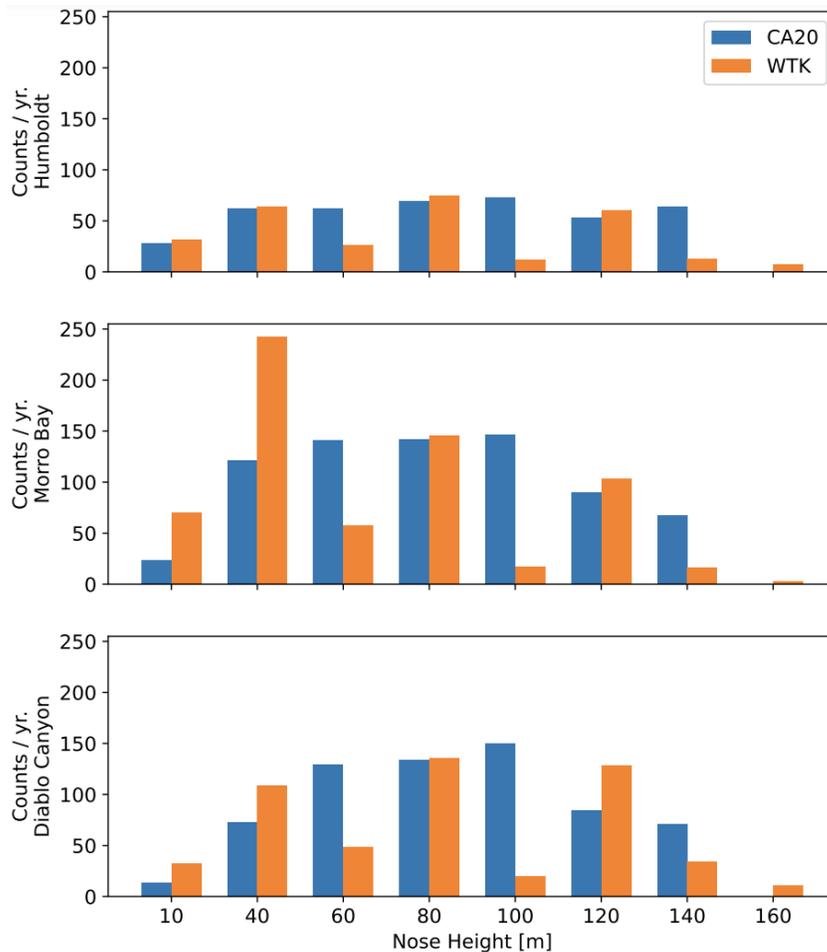


Figure R10: Typical nose heights within CA20 and the WIND Toolkit.

Overall, our analysis suggests that LLJs do not significantly impact summertime differences in hub-height wind speed as well as the height-dependence of shear. However, our analysis is fundamentally limited because we do not have access to winds above 200 m, and coastal LLJs in California typically extend up to 400 m. Due to our null results and the limited nature of our analysis, we have opted to omit this analysis from the manuscript.

Specific comments (minor):

- Figures 2-5 show 100m winds. Figure 6 speaks about hub-height winds. Does “hub height” mean “100m” in Figure 6?
- Thank you for catching this inconsistency. The caption in Figure 6 now reads “100-m wind mean winds” instead of “hub-height mean winds”.
- “At all three sites, the relative frequency distribution of hub-height wind speeds bears resemblance to the Weibull distribution (Fig. 10)” (line 251). I would argue that these distributions, especially those seen in Figure 10a are very different from the Weibull distribution. The fact that the distributions differ from the Weibull distribution is not bad, that is just the feature of the region, but if the authors would like to claim closeness to the Weibull

distribution, then I would ask them to fit the data to the Weibull distribution, estimate the coefficients, and show the fitted distribution in the figure.

- We have updated Figure 10 to include fitted Weibull distributions, and we have included the distribution coefficients in the figure caption (Fig. R11).

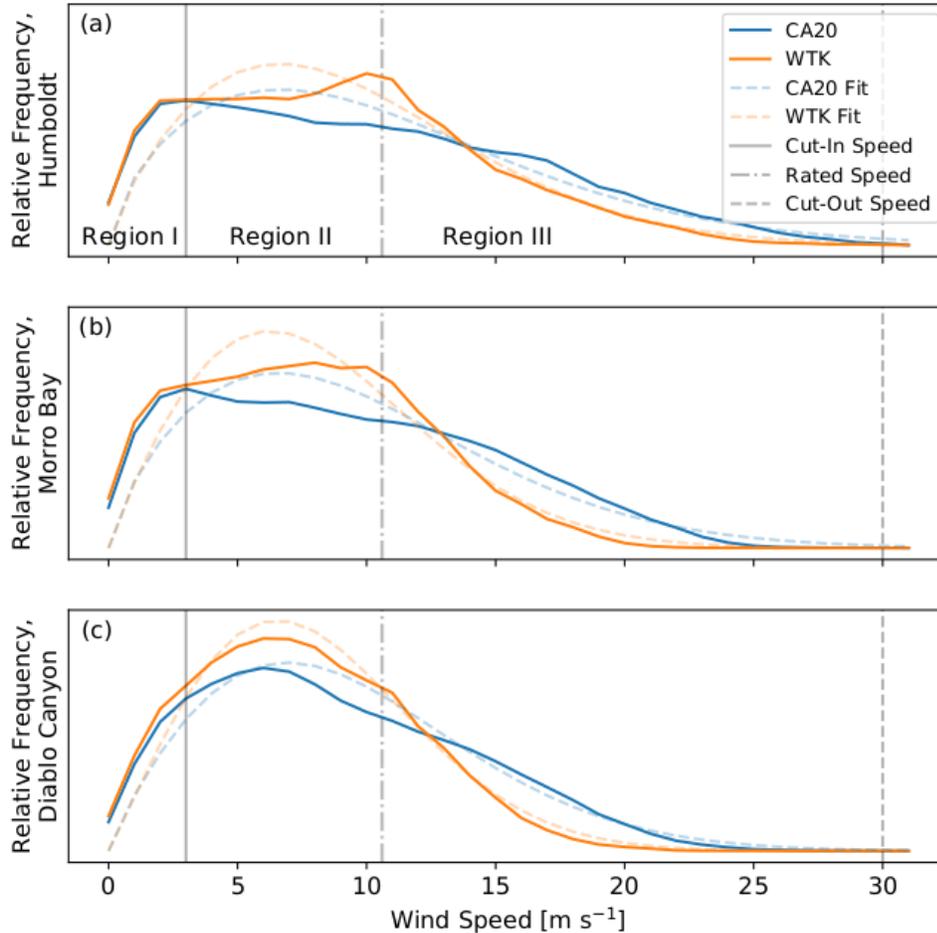


Figure R11: An updated version of Figure 10 that includes the Weibull distribution fit. The CA20 Weibull distribution fit parameters (shape factor, scale factor) are: (1.64, 11.88) at Humboldt, (1.73, 10.83) at Morro Bay, and (1.86, 10.48) at Diablo Canyon. Similarly, they are (1.78, 10.60) at Humboldt, (1.91, 9.23) at Morro Bay, and (2.04, 9.08) at Diablo Canyon for the WIND Toolkit fit.

- Figure 14 is very hard to interpret because the eye is drawn to the distribution of wind directions (wind rose) and it is hard to distinguish between α values inside each sector. Maybe the α distributions for only for certain key sectors can be shown, plotting them the same way as in Figure 13?
- We have explored several approaches to visualize the wind roses for shear, but we ultimately were unable to identify a cleaner method. It was challenging to come up with key sectors. We plotted winds from land vs. winds from open water in the style of Figure 13, but the figure was less informative. We think that these wind roses are difficult to visualize because there is not a dominant wind direction (in contrast to other locations, e.g. Bodini et al. 2019). We have added two vertical bars to help frame the subplots and to help the eye focus (Fig. R12).

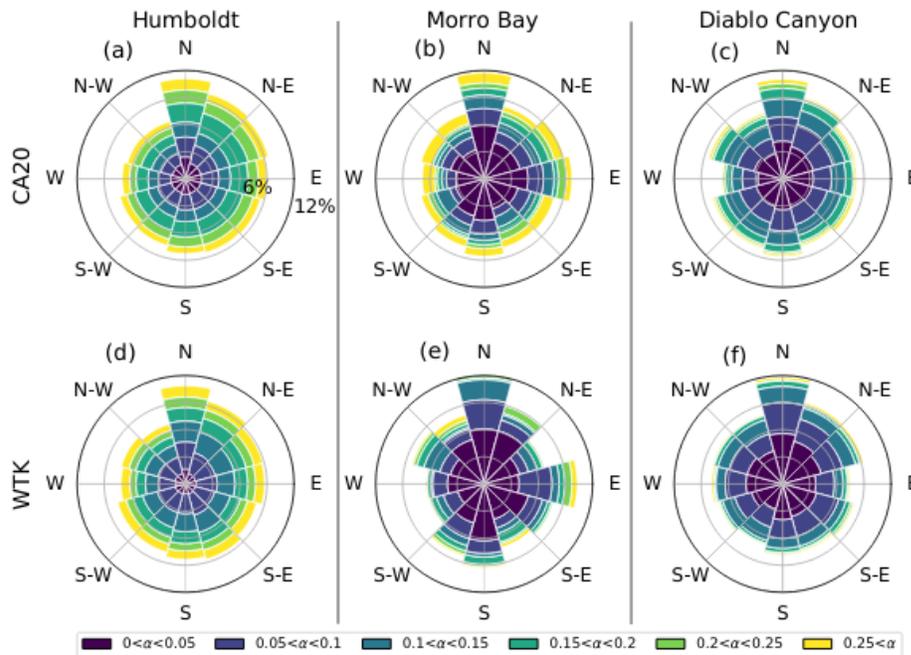


Figure R12: An updated version of Figure 14 with vertical bars.

- The results for the wind drought, especially in Humboldt, is quite counterintuitive. CA20 shows much higher windspeeds on average, but the number of wind droughts also seems larger, at least for droughts that are 6 – 12h long. Maybe the authors would like to comment on this?
- Thank you for drawing attention to this counterintuitive behavior (stronger wind resource, but more common droughts). This behavior appears because we require wind droughts to be at least 6 hours long (for reference, Ohlendorf and Schill (2020) use 5 hours as their minimum threshold). If we relax this requirement and instead wind droughts to be arbitrarily short, we find that the WIND Toolkit produces more wind droughts (Fig. R13), which would be expected for a data set with weaker winds. If we drop the 6-hour requirement however, the longer wind droughts are no longer visible in the figure, and as such, we have opted to retain the original figure in the manuscript.

We have clarified this behavior in the manuscript: “Somewhat counterintuitively, CA20 shows more wind droughts that are 6-9 hours long, even though this data set has stronger overall resource. This behavior likely appears due to randomness in the dynamical system, and it does not appear to have physical meaning. If the 6-hour minimum threshold is relaxed, the WIND Toolkit shows more 0-3 hour wind droughts than the WIND Toolkit (e.g. 246 counts per year in CA20 and 378 counts per year in the WIND Toolkit) as expected.” (L 359-363)

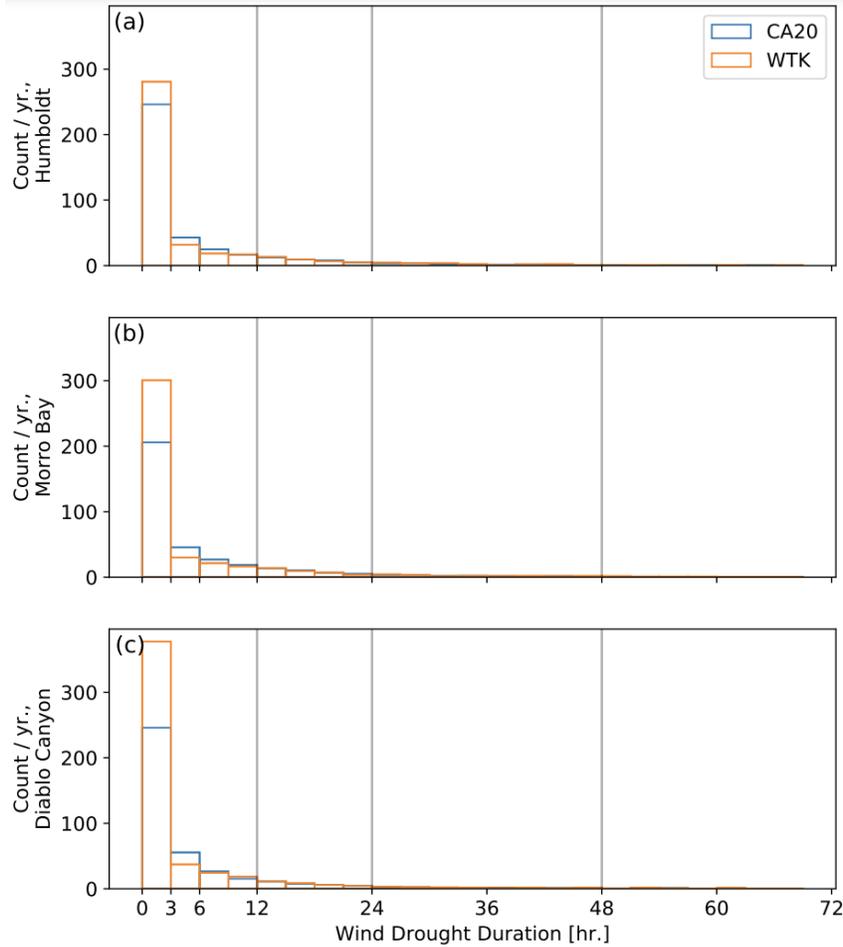


Figure R13: Figure 16 in the manuscript, except the minimum value of the x-axis has moved from 6 hours to 0 hours.

- If the authors would like to stress the differences in model performance between different regions (description of Table A1), I would suggest plotting the biases on a map using a larger circle, colored according to the bias, for each station. That would help with comprehending of the results.
- We have added a figure (Fig. A1 / R14) to Appendix A that highlights the regional dependence of bias and RMSE. We experimented with a map-style figure, but we found it more difficult to interpret than the attached figure. From the below figure, it is easier to discern the spatial nature of the statistics. For example, in Southern CA, the WIND Toolkit shows a typical bias of approximately 0.5 m s^{-1} , whereas CA20 shows a bias that is closer to 0 m s^{-1} .

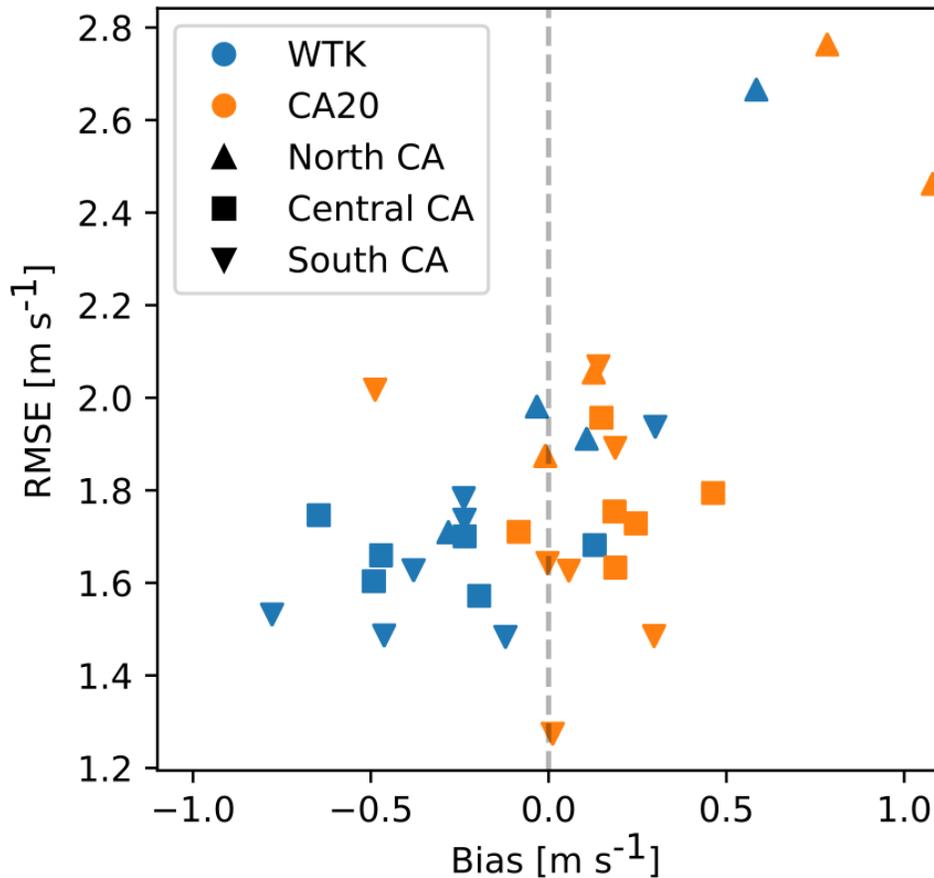


Figure R14: Bias and RMSE relative to buoy observations, binned by region.

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