Response to reviewers

21st of June 2021

1 General comment to reviewer # 2

We would like to express our gratitude to anonymous referee #2 for his/her time and effort revising the manuscript with the working title of “Norwegian hindcast archive (NORA3) - A validation of offshore wind resources in the North Sea and Norwegian Sea”. With the comments from referee 2 we strongly believe that the manuscript now is better and more precise. Please see our response to the comments below (new text added to the paper is in italic font).

2 Respons to major comments from reviewer # 2

RC1 FINO1 results: The FINO1 results differ strongly from the other sites. A quick online search could have given the authors the answer why this is the case. Since 2010 the wind farm alpha ventus started operating only about 400m east of the mast. Since 2015 the mast is located in the center of a large wind farm cluster. This change in time is by the way nicely reflected in Figure 6c. The deviations discussed in the manuscript thus mainly originate from the fact that FINO1 is in most of the years investigated here not measuring free wind conditions but winds that are strongly impacted by the turbines surrounding the mast.

AC1: Thank you very much for pointing out the close proximity of Alpha Ventus wind farm to the FINO1 met mast. The commissioning of Alpha Ventus explains why the observation-based capacity factor (CF) strongly deviates form the modeled CF after 2009 (Alpha ventus was operational from August 2009), and generally why the validation results for FINO1 are odd. To cope with this we will only use FINO1 data between 2004 and 2009 (until August) in the validation of NORA3 for FINO1. The excluding of the year 2010-2018 in the Fino1 time series results in a delta-pdf (Fig 2) more similar to the other delta-pdf for the five remaining sites. In other words, NORA3 overestimates (underestimate) the occurrence of wind speed events below (above) a typical rated wind speed limit (11-13 m/s). In addition, the number of zero events Fino1 is reduced (Fig. 8 and Fig. 9). Figures changed due to the shorter time series of FINO1 are: Fig 2b, Fig 6-10. Also Figures in appendix are influenced: Fig A1 and Fig B1. In addition, the following tables have changes: Tables 2-4, and Tables 6-8. The discussion of the affected figures and tables are rewritten accordingly.

RC2: Comparison to other data sets: In the introduction several other data sets are discussed but no comparison is made, not even to the ERA5 data. Thus, it is not even evaluated if the NORA3 is at all an improvement over ERA5. Thus, the study in my opinion does not show that NORA3 really is a suitable data set for wind energy applications in comparison to all the other data products that are available.

AC2: Thanks for addressing this relevant and important issue regarding comparison of NORA3 against the host data set (ERA5) and other wind resource data sets. NORA3 are extensively validated towards observations and compared against the host data set in the paper of [3]. Nevertheless, we have now performed a validation of NORA3 and ERA5 towards observations. A quantile-quantile plot (qqplot) for each of the six sites is generated and will be added to the paper to compare the wind speed distribution between the three data sets (obs, NORA3 and ERA5). The qqplots show that NORA3 performs better than ERA5 for almost all wind speed percentiles, especially for the high wind speeds. In addition, a seasonal validation is performed, showing the mean values and standard deviations (std) for the three data sets for the four seasons (DJF, MAM, JJA, SON). The seasonal analysis show that both mean and std values from NORA3 are closer to the observed mean and std values for all six sites. Two tables will be added to the paper, one for the mean values and one for the std. Hence, NORA3 wind sped are closer to observed values for all six sites. As several new wind resource data set are becoming available a model comparison is indeed of great interest and something we will pursue in future work. However, given the page limitations and the fact that this is the first paper to evaluate the wind resource estimates from this data set we have prioritized to put the focus on a detailed comparison against observations instead of introducing a second objective to the paper.

The following section will be added to the paper:

Comparison of NORA3 and ERA-5

The NORA3 wind estimates in 10 masl are extensively validated against observations and compared against the ERA-5 reanalysis in Haakenstad2021NORA3:Sea. Nevertheless, we compare the performance of NORA3 and ERA5 towards the observed wind speed climatology in the six wind sensor heights (68-140 masl).

The observed seasonal average and standard deviation of the wind speed are shown in Table 3 and Table 4, respectively. In addition, the relative difference between the observations and NORA3 (n3 (%)) and the observations and ERA5 (e5 (%)) are also shown. Table 3 shows that the modeled average seasonal wind speed from NORA3 are consistently closer to the observed values for all the seasons. The standard deviation (std) is here a measure of the variability in the wind speed. The seasonal variability is shown in Table 4. Compared to ERA5, *NORA3 is consistently closer to the observed seasonal std for all the six sites.*

Figure 3 shows the quantile-quantile plot (qq-plot) between the observed wind speed and modeled wind speed by NORA3 and ERA5. The qq-plot determines if the two data sets are drawn from the same sample distribution. If the circles lie on the reference line the data sets comes from the same data distribution. For all the six sites the models perform best for the lowest wind speeds ($u \leq 10ms^{-1}$). For both models the deviation from the reference line ("ref line") increases with increasing wind speed percentile. Nevertheless, NORA3 is consistently closer to the reference line compared to ERA5, and especially for wind speed exceeding a typical cut-off wind speed. A technical feature called "high wind ride through" enables the turbine to exploit more of the very strong wind speeds ($u \geq u_{co}$). In offshore areas higher winds is happening more frequently. Therefor, the importance for a NWP model to estimate these strong wind events correctly increases. NORA3 outperforms ERA5 for these high wind speeds ($u \geq u_{co}$).

As illustrated in Fig 3, the largest difference between the observations, NORA3 and ERA-5 is found for wind speeds exceeding a typical cut-out limit of 25 ms^{-1} ($u \geq u_{co}$). Since the power production is terminated or at least reduced when $u \geq u_{co}$ we calculate the wind power capacity factors (CF) for the three data sets. This is done to see how the the models perform in terms of power production where the strongest wind speeds not influence the result due the production cut-out limit. Table 4 contains the CF for the observed data, NORA3, and ERA-5 for the six sites. NORA3 performs consistently better than ERA5 for all the six sites. For the six sites used in this study, NORA3 is 1.8 percentage point closer to the observed average CF-value compared to ERA-5.

The validation of wind climatology in NORA3 and ERA5 show that the downscaling of ERA5 in the process of creating NORA3 has resulted in an improved wind resource data set. The remainder of this study will focus on the validation of NORA3 towards observed wind climatology.

RC3: Novelty of NORA3: After reading the whole manuscript, I have not understood what the novelty and improvement of NORA3 data are. The resolution in space is similar to NEWA, the resolution in time of 1 hour is poor. The wind industry would benefit from 30 min or even 10min resolutions. Doesn't this would also have an impact on the extremes discussed in the study? A mesoscale model does provide sub-hourly fluctuations and could improve the ramping. Is the novelty just the fact that NORA3 will be available for the time period from 1979 and further continued?

AC3: Thank you for pointing this out. The novelty of NORA3 over other similar data sets is that NORA3 is created by another numerical weather prediction model (HARMONIE-AROME, Cy 40h1.2, which in contrast to WRF has spectral dynamics and very different physical schemes (turbulence, radiation etc.)). Currently all other wind resource data sets are created by the Weather Reasearch and Forecasting model (WRF). The creation of NORA3 by a different NWP model will contribute to a diversity in the available wind resource data sets. When a multi-model ensemble of these data sets are considered for wind power planning the wind resource uncertainty can be quantified and reduced in regions like offshore which often have very few and short time in situ observational references. We know from inter-comparison of numerical weather prediction models, that there is no such ting as a overall "best" model. Quality depends strongly on which spatial and temporal scales are of interest, geography, the selected measure of quality and the application the data will be used for. Thus, the usefulness of multi model ensembles has become increasingly clear over the last few decades in research field such as weather prediction and climate change. We also see this slowly trickling down into wind resource research community. In addition, this study contains novel validation measures not seen in the assessment of other wind resource data sets covering the North Sea, Norwegian Sea and Barents Sea. Finally, we tend to agree that papers focusing on verification of new simulations seldom are extremely novel. However, they fill a very important role by documenting quality. This is a prerequisite to ensure a sound and critical use of the simulations by stakeholders and fellow researchers.

The introduction will be rewritten accordingly to clarify the intention of the study.

RC4: Wind Speed Interpolation: The wind speed interpolation is done using a power law relation. This is an empirical method with deficiencies in unstable conditions. I suggest to use a logarithmic interpolation here.

AC4: Thanks for your comment. Both logarithmic wind profile (log law) and power law wind profile (power law) assumes neutral atmospheric stability of the atmosphere and will have deficiencies in stable and unstable conditions. [2] reviewed different extrapolation methods (logarithmic models, Deaves and Harris, and power law) for 96 different locations worldwide. He concluded that the power law was the most reliable and widely most used extrapolation method. In addition, according [4] the usage of log-law is most suited near the surface. Despite the aforementioned results from Gualitieri and Sill we have compared the performance of the log law and the power law (with time varying power exponent) for the six offshore sites used in this study. For the majority of the sites, interpolating NORA3 wind speed to the sensor height using the two different methods (log-law and power law) we see that the model bias using log law is larger than using the power law method for the majority of the sites. Therefor, we stick to the power law method with a time dependent power exponent when wind speed interpolating is conducted.

The following text is added to section 2.2 (added text in italic):

Wind speed interpolation

To avoid introducing additional uncertainties into the observational data set, we verify the wind variables from NORA3 at the wind sensor heights, ranging from 68-140 m.a.s.l., for each site (see "WSH" in Table 2 for the sensor heights). By contrast, the wind power verification is performed at a typical hub-height, at 100 m.a.s.l., to ensure the production estimate are comparable between sites.

The interpolation of wind speed data to another height is usually done by either logarithmic law, Heaves and Davis, or power law. [2] reviewed the three aforementioned methods for 96 different locations worldwide. He concluded that *the power law was the most reliable and also the method most frequently used extrapolation method. In addition, according [4] the usage of log-law is most suited near the surface. Despite the aforementioned results from Gualitieri and Sill we have compared the performance of the log law and the power law (with time varying power exponent) for the six offshore sites. For the majority of the sites the model bias using log law is larger than using the power law method.* Therefor, the interpolation of wind speed data to sensor height or hub-height is done using the power law relation [1]. The interpolated wind speed is sensitive to the choice of the power law exponent α. Usually, α is assigned based on assumptions about atmospheric stability and surface roughness, both of which can introduce erroneous results. However, the data from NORA3 allows us to calculate α for each time step (i). Rearranging the power law relation, we get the following expression for the power law exponent α: ...

3 Response to minor comments from reviewer # 1

RC1: Line 80: 31 x 31 km → I think you mean 3x3km here.

AC1:: Thanks for noticing the error, and you are totally right. I have now changed it to 3x3km.

RC2: Line 83: ... and research by many European countries ... → I think European weather services and research institutes is better suited here.

AC2: Done.

RC3: Line 108: ... are hourly wind observations ... → I think it is better to write something like "10 min average values provided at every hour" directly in the text than with the footnote

AC3: Done.

RC4: Line 139: ... the turbine park ... → "wind farm" fits much better here.

AC4: Done.

RC5: Line 181: ... exploting NORA3 as a planning tool ... → How is NORA3 a planning tool. Isn't this just a dataset and a wind farm planning tool could make use of these data?

AC5: Thanks for commenting on this badly formulated sentence. You are complete right. The sentence will be rewritten.

RC6: Table 3: Weibull parameters are much more commonly abbreviated by lambda and k than b and a

AC6: a and b are changed to λ and k.

RC7: Line 230: ... wind park configuration and internal position... → better: wind farm layout

AC7: Done.

RC8: Line 242: But we cannot rule out... → better: "conclude"

AC8: I changed the sentence to the following: "But, we cannot exclude the possibility that the platform design at Sleipner affects the flow field more than the design of the other platforms."

RC9: Section 3.4: I would rather put this section as 2.2.1

AC9: Thank you for your suggestion. As section 3.4 is a part of the results and not a method-section we would like to keep the section where it is placed today.

RC10: Line 283: ... an hour-to-hour variability typically 7%-9% (Table 7) of the installed capacity → ... variability OF typically ...

AC10: Done

RC11: Line 377-378: The general picture is that the NORA3 data is rather well suited for wind power estimates in the absence of in situ data → afterwards all deficiencies are discussed. This conclusion does not fit to the sentences before.

AC11: Thanks for pointing this out. I have now rewritten the sentence in the following way: "Nevertheless, there is a tendency towards the modeled generating slightly conservative estimates, and the results are summarized below."

RC12: References: Please add availability for ALL publications that are not books

AC12: Unfortunately, we do not understand what the reviewer mean by RC12.

References

[1] S. Emeis. *Wind Energy Meteorology.* Springer, 2 edition, 2018.

[2] G. Gualtieri. A comprehensive review on wind resource extrapolation models applied in wind energy. *Renewable and Sustainable Energy Reviews*, 102:215–233, 2019.

[3] H. Haakenstad, Ø. Breivik, B. R. Furevik, M. Reistad, P. Bohlinger, and O. J. Aarsnes. NORA3: A non-hydrostatic high-resolution hindcast for the North Sea, the Norwegian Sea and the Barents Sea. *Submitted to Journal of Applied Meteorology and Climatology*, 2021.

[4] B. L. Sill. Turbulent boundary layer profiles over uniform rough surfaces. *Journal of wind engineering and industrial aerodynamics*, 31:147–163, 1988.