

# Answer to reviewer comments

December 19, 2023

## 1 Summary of the updates

Dear reviewers, we would like to thank you for the constructive and concrete feedback on our manuscript. We highly appreciate your input. Based on your comments we revised our manuscript. Major updates are made, including:

1. We revised the definition of the eyewall and rainband section.
2. We include profiles of shear and veer.
3. We include a short description of the IEC extreme wind speed model.
4. We update the introduction part on subgrid scale parametrization.
5. We update the description of the boundary layer schemes.
6. We elaborate on differences between different storm sectors.
7. We highlight limitations on the generally low wind shear and veer encountered in our simulations.

In the following, we respond point-by-point to your comments and refer to the updates in the manuscript.

## 2 Reviewer comments from the first referee

### 2.1 Summary

The authors perform a study evaluating how different boundary layer parameterizations in WRF modify mean wind characteristics relevant for offshore wind energy. The authors simulate typhoon Megi using the YSU, MYJ, and MYNN boundary layer schemes. The simulation results are validated using best-track estimates, surface wind speed observations, and synthetic aperture radar data. After validation, wind speed, wind speed shear, and wind veer are estimated over the turbine rotor layer of a hypothetical 14MW wind turbine in the eyewall against mean wind characteristics in the boundary layer for each boundary layer scheme. Wind speed in the rotor layer varies with boundary layer parameterization, especially near the eyewall. Wind shear and veer also vary, but to a lesser extent. In general, the authors report low wind veer in the turbine rotor layer and shear that agrees with turbine design standards.

Thank you for this summary.

### 2.2 Major comments:

1. Velocity fields are averaged azimuthally: The velocity fields in cyclones have distinct characteristics depending on the azimuthal location (Ren et al., 2019). For instance, the height of the tangential wind speed maxima and the height of the inflow varies azimuthally. Therefore, it is possible that by performing this azimuthal averaging, these characteristics are being lost, and shear and veer are being underestimated.

Thank you for raising this point. Based on your comment, we looked into the asymmetries over the tropical cyclone azimuth in detail. We address the variability between different sectors now in the results and discussion sections. We further changed the definition of the eyewall region, as described in the answer to your second comment. The new eyewall definition is no longer based on axisymmetry. With this new definition, the difference in the wind speed, shear, and veer between the storm quadrants is reduced in the eyewall region.

We now report on differences between the quadrants as follows (Please refer to the manuscript for Table 3):

**In the result section:** To further assess the horizontal asymmetry, wind speed, shear, and veer are analyzed in four quadrants relative to the storm motion. Median values are listed for the MYJ simulation in each quadrant in Table 3. Note, that the MYJ simulation resulted in the most severe wind speed, shear, and veer. In the Eyewall wind speed, shear and veer show less variation between the quadrants than between the different simulations. However, the asymmetry of the wind field reflects in the area forming the eyewall region in each quadrant. The two right quadrants have a larger eyewall area than the two left quadrants. The difference in the area is 65 % between the larger eyewall area in the back right quadrant and the smaller eyewall area in the front left quadrant. Different from the eyewall region, in the outer cyclone wind speed shear and veer show clear variations between the quadrants. Wind speed and wind shear are larger in the right quadrants than in the left quadrants. The difference in the median wind speed is  $4.3 \text{ ms}^{-1}$  between the front left and the back right quadrant. For  $\alpha$  the difference is  $8.6 \times 10^{-3}$  between the two right sectors and the back left sector. In the back right sector, 27.3 % of the profiles have  $\alpha$  values larger than 0.11. Different from wind shear, wind veer is larger in the two front quadrants than in the back quadrants. The largest median wind veer, in the front right quadrant, is  $1.3 \times 10^{-2}$ .

**In discussion:** Wind veer and wind shear vary between the different sectors. Using the extreme wind speed model the difference in median  $\alpha$  between the four quadrants leads to differences in the wind speed at above and below the hub height. For example, with a  $z_{\text{hub}}$  of 140 m and a  $V_{\text{ref}}$  of  $57 \text{ ms}^{-1}$ , the difference at 180 m between the quadrants in the MYJ simulation is  $0.2 \text{ ms}^{-1}$ .

2. **Radial locations in analysis:** The radial distance that defines the eyewall regions is very large (60 km), thus the most extreme wind conditions that occur in the vicinity of the radius of maximum winds might be eclipsed by slower winds inside the eyewall. How is the 60 km to 120 km range chosen to define this as the eyewall region? Furthermore, given that the different PBL schemes result in different storm sizes, the radial distances might not be entirely equivalent for the different storms.

This is a valid point. We decided to redefine the eyewall region and base the definition now on wind speed. The new criteria are described as follows in the method section (please refer to Fig. 2 in the manuscript):

*The eyewall and outer cyclone regions are analyzed separately. With that, we can account for and characterize differences between the two storm regions. To avoid, that the position of the simulation domain relative to the cyclone center influences the analysis, we use only grid points within a distance to the cyclone center ( $R$ ) smaller than 350 km. The definitions of the eyewall and outer region are illustrated in Fig. 2 and summarized in Eq. 4 and 5. We define the eyewall as a high wind speed regime. Our definition is based on the simulated wind speed at 10 m ( $WS_{10}$ ) at each simulation time step. Grid points are assigned to the eyewall region if two criteria are fulfilled: 1.)  $WS_{10}$  is greater than or equal to the 80th percentile of  $WS_{10}$  ( $P_{80}(WS_{10})$ ), and 2.)  $R$  is less than 250 km. The selected eyewall area is 76000  $\text{km}^2$ . The thickness of the eyewall is not symmetrical over the azimuth and can be zero. Note also, that the area includes gaps, where the wind speed is lower than  $P_{80}(WS_{10})$ . The outer region includes all grid points that are not part of the eyewall and the eye. To distinguish between the outer region and the eye, we define a critical radius  $R_{E_{ye}}$  in Eq. 5. Here,  $R_{E_{ye}}$  is taken as the 10th percentile of  $R$  of the eyewall grid points ( $P_{10}(R_{E_{eyewall}})$ ). Thus*

$$\text{Region} = \begin{cases} \text{Eyewall:} & \text{if } WS_{10} \geq P_{80}(WS_{10}) \text{ and } R < 250 \text{ km,} \\ \text{Outer cyclone:} & \text{if not Eyewall and } R > R_{E_{ye}} \end{cases} \quad (1)$$

where

$$R_{E_{ye}} = P_{10}(R_{E_{eyewall}}) \quad (2)$$

*The outer region is not homogeneous. It includes both the rainbands and the non-convective moat areas. These areas have different properties. However, we do not separate them, to prevent the analysis from becoming sensitive to the selection criteria.*

3. **Context:** The authors do not acknowledge the role of large-scale turbulence structures that form in tropical cyclones and the limitation of their simulations in resolving these structures. Please clarify that your simulations do not accurately resolve structures smaller than 15 km in wavelength due to the employed grid resolution. As a result, small- and large-scale variability in the boundary layer relevant for wind turbine design (such as large-scale vortices) are not captured.

Good point - our arguments on this are somewhat hidden in the original version. We now highlight them at several locations in the manuscript.

**In the introduction:** Typically they can only resolve wind speed variability on scales in the order of seven times the horizontal grid spacing (Skamarock, 2004). Smaller scale structures resolved in LES simulations, such as roll vortices, cannot be adequately resolved in mesoscale simulations (Li et al., 2021).

**In the discussion:** *The analysis is based on mesoscale simulation and cannot resolve scales smaller than 15 km. With that structures such as large-scale vortices are not resolved. Such unresolved structures may contribute to enhanced shear and veer.*

4. A brief description of wind turbine design standards should be provided. The authors should include a brief explanation of the extreme wind speed models used for design load cases 6.1-6.4 in the IEC 61400-3 standard.

Good point. A brief description of the IEC standard is added to the introduction. **New:** *To ensure the structural integrity of wind turbines, turbine design standards are defined in the International Electrotechnical Commission’s standard (IEC) for onshore and offshore turbines (IEC, 2019a,b). The standards are based on site-specific wind speed classes and turbulence classes. The ability of wind turbines to withstand wind conditions within the turbine class is tested in design load cases (DLC). Different DLCs assess the loads acting on wind turbines during power production, and at stand-still. In and close to the eyewall wind speeds typically exceed the turbine-specific cutoff wind speed. In this case, turbines are parked to minimize loads. However, further away from the cyclone center, turbines may still be operating. Either way, the wind conditions tested in the DLCs consist of a mean wind profile combined with either a deterministic gust profile or turbulence. A power-law model is used for the wind profile with an associated hub height wind speed and wind shear over the rotor plane. A constant wind shear is suggested for load simulations of operating and parked turbines. Such a simplified wind shear model has an influence on turbine loading (Dimitrov et al., 2015). Wind veer, the change in wind direction with height is not accounted for in the IEC standards.*

**Old:** *The wind input for aeroelastic wind turbine models consists of a wind profile with an associated hub height wind speed and wind shear over the rotor plane. In the International Electrotechnical Commission’s standard (IEC), a universal constant wind shear is suggested for load simulations (IEC, 2019a). Such a simplified wind shear model has an influence on turbine loading (Dimitrov et al., 2015). Wind veer, the change in wind direction with height is not accounted for in the IEC standards.*

In the Methods section, the extreme wind speed models are described. **New:** *The analysis of wind shear is performed, such that a comparison to the IEC standard is straightforward. For the assessment of extreme wind conditions, the IEC assumes a wind profile according to the extreme wind speed model:*

$$V_{50} = V_{ref} * \left(\frac{z}{z_{hub}}\right)^\alpha \quad (3)$$

Here  $V_{50}$  is the extreme wind speed with a return period of 50 years, averaged over a ten minute interval. For areas affected by tropical cyclones, the reference wind speed  $V_{ref}$  is  $57 \text{ ms}^{-1}$ . The height is given by  $z$ , and the hub height by  $z_{hub}$ . The wind shear exponent  $\alpha$  is a measure of vertical wind shear. Strong wind shear is associated with larger  $\alpha$  values. For extreme wind conditions, the IEC uses a constant  $\alpha$  of 0.11 (IEC, 2019a). Under normal wind conditions offshore,  $\alpha$  is set to 0.14 (IEC, 2019b).

**Old:** *In the IEC, wind shear is mostly expressed as shear exponent  $\alpha$ , which describes a power-law wind profile (IEC, 2019a):*

### 2.3 Minor comments:

1. Please review English writing throughout the manuscript. Some examples include: - Line 48: Hyphen in large-eddy simulations. - Line 70: Capitalize Weather Research and Forecasting model.

Thank you, the corrections are made.

2. Line 22: Please include the role of large-eddy simulations, which can resolve large- and small-scale turbulence structures (e.g., mesovortices) relevant for loads in wind turbines.

The sentence is updated as follows: *Further research incorporating mesoscale **and micro-scale** numerical models into aeroelastic wind turbine models is necessary to achieve reliable structural analysis of wind turbines in tropical cyclone conditions (Li et al., 2022).*

3. Line 48: depending on the grid resolution (e.g., 2 km),mesoscale simulations might not resolve scales smaller than 10 km either.

We reformulate as follows: **New:** *Typically they can only resolve wind speed variability on scales in the order of seven times the horizontal grid spacing (Skamarock, 2004). Smaller scale structures resolved in LES simulations, such as roll vortices, cannot be adequately resolved in mesoscale simulations (Li et al., 2021).* **Old:** *Mesoscale atmospheric simulations use larger grid spacing than large eddy simulations and cannot resolve sub-kilometerscale variability (Skamarock, 2004).*

4. Line 117: Is the timestep the same for all domains? A 45 second timestep for the 2 km domain seems too long, especially for such intense storm. I am happy you have spotted this. The sentence is updated: *The three domains are run with a 45, 15, and 5 s timestep.*

5. Section 2: Please mention vertical grid resolution in the lowest levels.  
The domain heights are added as follows: *All domains use 70 vertical layers. The lowest model levels have a mean height of 8, 26, 47, 72, 102, 139, 183, 234, 297, and 372 m.*

6. Line 74: Please clarify the spinup time for each domain. Is it 12 h for domain 1, or are all domains initialized at the same time?  
The spin-up time is clarified as follows: *All three domains are initialized at 00 UTC on 25 September. The first 12 h are used as spin-up time. The following 36-hour simulations starting at 12 UTC on 25 September are used for the analysis.*

7. Line 125: Please clarify that veer is the shortest rotational path of the wind vector and, as such, is restricted to  $|V_{\text{veer}}| \leq 180^\circ$ .  
The definition of wind veer is updated. We now decided to use a linear fit of the wind directions over all heights within the rotorplane instead of using only two heights. We chose to do this for two reasons: 1.) We would like to keep the definition of wind shear and wind veer similar (see point 9). 2.) We want to reduce the sensitivity of wind veer to the chosen model levels. We are aware that wind veer changes non-linearly with height. This limitation is discussed in the results and discussion sections. **New:** *Wind veer is defined as the shortest rotational path between the wind direction (WD) at different heights, which is maximal  $180^\circ$ . It is defined such that positive (negative) veer values describe clockwise (counterclockwise) rotation with increasing height. With that, a decreasing (increasing) inflow angle with height is associated with positive (negative) veer values. In this study we normalize wind veer by the vertical distance between two used heights. Veer is calculated as follows:*

$$V_{\text{veer}} = \frac{\min(WD_2 - WD_1)}{z_2 - z_1} \quad (4)$$

Here, *WD* is defined at the model heights  $z_1$  and  $z_2$ . Similar to the analysis of  $\alpha$ , wind veer is analyzed between consecutive model levels at different heights, as well as over the rotor plane. For the latter, we use a least square fit between *WD* and  $z$ . All model levels between the rotor bottom and the rotor top are used for the fit.

8. Line 139: Note that the averaging period is very different between Kapoor et al. (2020) and your simulations. Therefore, wind veer is expected to differ.  
We decided not to comment on the assumption of a monotonic increase of shear and veer with height, and don't show the text passage. We decided this for two reasons: 1.) we now calculate wind shear using a linear fit, and 2.) we analyze the profile of  $\alpha$  in the results section.

9. Section 2.2: Is there a reason for restricting the shear analysis to two heights only? Did the authors consider fitting wind speed at all model heights within the rotor layer to the power-law wind profile to estimate  $\alpha$ ?  
The difference between using two heights and a linear fit were small. We decided anyways to follow your comment and use a linear fit for the calculation. We further analyze the change of  $\alpha$  with height in the result section. The definition is updated as follows: *In this study  $\alpha$  is calculated using Eq. 2.*

$$\alpha = \frac{\ln(u_2/u_1)}{\ln(z_2/z_1)} \quad (5)$$

Here,  $u_1$  and  $u_2$  are the wind speeds at heights  $z_1$  and  $z_2$  respectively. While  $\alpha$  depends on height, the IEC assumes a constant  $\alpha$  over the rotor plane. We analyze both  $\alpha$  between consecutive model levels at different heights and the total  $\alpha$  over the rotor plane. For the latter, we use a least square fit between  $\ln(u)$  and  $\ln(z)$ . All model levels between the rotor bottom and the rotor top are used for the fit.

10. Section 3.2: Please report the mean radius of maximum winds for each boundary layer scheme.  
The radius is added: *Additionally, the distance between the eye and the maximal wind speed in the eyewall is larger in the MYNN (104 km) simulation than in the YSU (92 km) and the MYJ (94 km) simulations.*

11. Line 206: Minimum SLP and maximum wind speed are shown in Figure 4.  
The reference to Figure 5 is added (the number of the figures increased by 1): *Megi's track and intensity in terms of minimal SLP and maximal wind speed from 25 September onward are shown in Fig. 4 and 5.*

12. **Caption Figure 4: The 0.93 factor converts from 1-min to 10-min averaged winds and not the other way around.**  
The error is corrected: *Black crosses show the JTWC values multiplied by 0.93, as recommended by Harper et al. (2010) to convert one-minute sustained wind speeds to ten-minute sustained wind speeds in tropical cyclones over the sea.*
13. **Figure 5: Consider moving panels d,e,f to a new figure farther down in the manuscript. The authors only comment on these panels in line 255, after referring to Figure 6, 7, and 8.**  
Thank you for the comment, the panels are moved.
14. **Figures 1, 2, 3, 4, 5, 8: Please include axes and color bar labels where needed.**  
We updated all Figures to include Labels, unless axes are shared between subplots.
15. **Lines 221-225: Please comment on the limitations of comparing instantaneous velocities from the mesoscale domains with 1-min and 10-min observational averages. These are not entirely comparable and the instantaneous velocity fields are grid dependent.**  
We commented as follows: *The comparison between the maximal wind speed and minimal SLP in the simulations and the best track data has shortcomings, especially since the two sizes depend on the spatial and temporal resolution of the simulation. Nevertheless, the comparison is widely used and helpful to qualitatively evaluate the simulated intensity (Rajeswari et al., 2020; Shenoy et al., 2021; Zhu et al., 2014).*
16. **Line 231: Please clarify what you mean with symmetric wind component. Is this the tangential wind speed?**  
We agree that the word symmetric is not precise enough. We rewrite as follows: **New:** *Larger wind speeds are evident in the back right quadrant, northeastward of the eye. Here, wind speeds are around  $4 \text{ m s}^{-1}$  larger than in the back left quadrant, southwestward of the eye. Nevertheless, the wind speed changes similarly with increasing distance to the cyclone center in all quadrants.*  
**Old:** *Larger wind speeds are evident in the top right quadrant, northwestward of the eye. Nevertheless, the symmetric wind speed component dominates over asymmetric features.*
17. **Line 235: Units for  $12 \text{ m s}^{-1}$ .**  
Thank you, we corrected it.
18. **Line 253: Consider relocating numbers in sentence for clarity.**  
We reformulate as follows. **New:** *The larger slope in the MYJ wind speed profile with respect to YSU reflects in a  $2.7 \times 10^{-2}$  to  $2.8 \times 10^{-2}$  larger median shear exponent.*  
**Old:** *The larger slope in the MYJ simulation with respect to the YSU reflects in  $2.4 \times 10^{-2}$  ( $3.0 \times 10^{-2}$ ) larger shear exponent in the exponent in the eyewall (rainband) region.*
19. **Line 257: Please rephrase for clarity. Perhaps break down into two sentences.**  
The sentence is broken down into smaller sentences as follows. **New:** *The MYJ simulation has a  $1.9 \text{ m s}^{-1}$  larger eyewall wind speed at hub height than the YSU simulation (see Table 3). Note, that this is different at 10 m, where the two simulations have similar wind speeds in the eyewall. The difference between the two heights is a direct result of the larger shear exponent in the MYJ simulation with respect to the YSU simulation.*  
**Old:** *With the larger gradient in wind speed with height, the MYJ simulation has a  $1.9 \text{ m s}^{-1}$  larger eyewall wind speed at hub height than the YSU scheme, while having a similar wind speed at 10 m (see Fig. 8 and Table 2).*
20. **Line 269: Please clarify that the simulations only resolve large-scale variability of atmospheric variables.**  
The sentence is adjusted as follows: *Apart from the **Typhoon-scale** structure, the simulations also produce **mesoscale** variability in the wind field. **Mesoscale** wind fluctuations can be seen in all simulations within and outside of the eyewall in Fig. 9.*
21. **Section 4: Please comment on the limitations of estimating veer from these simulations given that the depth and intensity of the radial inflow varies with grid resolution (Xu et al., 2021; Ren et al., 2022).**  
Thank you for the comment. We saw that Li et al. (2021) address the inflow layer depth and its sensitivity on grid resolution more directly than Xu et al. (2021). We add the following: *In fact, Li et al. (2021) and Ren et al. (2022) find that the inflow layer was shallower and stronger in LES simulation compared to mesoscale simulations. Such a stronger, shallower inflow layer directly leads to a larger mean wind veer.*
22. **Line 312: Please soften the language in this sentence. Shear in the tropical cyclone boundary layer has been shown to be different in LES and mesoscale simulations (Ren et al., 2022; Xu et al., 2021; Li et al., 2021).**

We admit that this sentence was ambitious. We soften the language slightly and list the limitations directly below.

**New:** *This supports the conclusion, that the current IEC standard **may be** sufficiently similar in terms of wind shear and veer during tropical cyclones. **However, there are clear limitations to this conclusion as discussed in the following.***

- (a) *Larger values for  $\alpha$  and veer are found in LES simulations over open water. Gomez et al. (2023) find in LES simulations, that the mean  $\alpha$  is about 0.2 near the eyewall. Both Kapoor et al. (2020) and Gomez et al. (2023) find significant wind veer in LES simulations. Concretely, Gomez et al. (2023) report a mean wind veer between  $5.3 \times 10^{-2} \text{ }^\circ \text{ m}^{-1}$  and  $6.9 \times 10^{-2} \text{ }^\circ \text{ m}^{-1}$ . The differences between the study from Gomez et al. (2023) and the simulated wind veer in our simulations can come from higher resolved wind veer variability in LES simulations or an overall shifted wind veer distribution due to differences in the mean wind field. In fact, Li et al. (2021) and Ren et al. (2022) find that the inflow layer was shallower and stronger in LES simulation compared to mesoscale simulations. Such a stronger, shallower inflow layer directly leads to a larger mean wind veer.*
- (b) *The analysis is based on mesoscale simulation and cannot resolve scales smaller than 15 km. With that structures such as large-scale vortices are not resolved. Such unresolved structures may contribute to enhanced shear and veer.*
- (c) *The study analyzes a typhoon case over the open ocean, before being affected significantly by land. In contrast to our simulations over the open ocean, He et al. (2016) and Tse et al. (2013) use wind observations in coastal areas. Both studies find wind shear larger than in the current IEC standard during typhoon conditions. He et al. (2016) find  $\alpha$  in the range of 0.152 to 0.175 for profiles with marine exposures during 22 typhoons over Hong Kong. Tse et al. (2013) find  $\alpha$  values of 0.14 to 0.25 during typhoon Fengshen and Molave for profiles with marine exposure. The larger wind shear in these two studies could be a suggestion that wind shear may increase during the landfall of a tropical cyclone. Further studies are needed to understand how wind shear and veer evolve during landfall. Similarly, He et al. (2016) finds wind veer in the order of  $2.8 \times 10^{-2} \text{ }^\circ \text{ m}^{-1}$  from the surface to the height of maximal wind speed from wind direction measurements with an open water fetch over a coastal area. This is around  $0.003 \text{ }^\circ \text{ m}^{-1}$  larger than the wind shear in the YSU and MYJ simulation between the surface and 800 m (the height of simulated maximal wind speed) and around  $0.01 \text{ }^\circ \text{ m}^{-1}$  larger than in the MYNN simulation. The difference between the studies may originate from the different locations with respect to land.*
- (d) *The fraction of profiles with  $\alpha$  larger than 0.11 is substantial in the MYJ simulation. In the eyewall region of the MYJ simulation, 43.6 % of the  $\alpha$  values are larger than 0.11. Values up to 0.15 are reached in 0.7 % of the eyewall and 4.1 % outer cyclone region. In the outer cyclone region, 1.0 % of the  $\alpha$  values are larger than 0.2. Such large  $\alpha$  values in the tails of the distribution impact the wind speed above and below  $z_{\text{hub}}$  in the extreme wind speed model (Eq. 3). As an example, we take the extreme wind speed model with a  $z_{\text{hub}}$  of 140 m, and a  $V_{\text{ref}}$  of  $57 \text{ m s}^{-1}$ . The wind speed from the extreme wind speed model at 180 m is  $0.6 \text{ m s}^{-1}$  ( $1.3 \text{ m s}^{-1}$ ) larger with an  $\alpha$  of 0.15 (0.20) than with an  $\alpha$  of 0.11.*
- (e) *The analysis of the shear and veer distribution is sensitive to the definition of the eyewall and outer cyclone region. At the inner edge of the eyewall and along the rainbands larger  $\alpha$  and veer values are simulated.*
- (f) *Wind veer and wind shear vary between the different sectors. Using the extreme wind speed model the difference in median  $\alpha$  between the four quadrants leads to differences in the wind speed at above and below the hub height. For example, with a  $z_{\text{hub}}$  of 140 m and a  $V_{\text{ref}}$  of  $57 \text{ m s}^{-1}$ , the difference at 180 m between the quadrants in the MYJ simulation is  $0.2 \text{ m s}^{-1}$ .*
- (g) *Veer and  $\alpha$  are larger close to the surface. In particular, wind veer is up to 18 % larger at the rotor bottom than at hub height in the MYJ simulation. In the extreme wind speed model  $\alpha$  is assumed to be constant. Using two different  $\alpha$  values below and above the hub height instead of assuming a constant  $\alpha$ , the median wind speed at the rotor bottom varies up to  $0.5 \text{ m s}^{-1}$  in the eyewall region. In the outer cyclone region, the median difference is up to  $1.5 \text{ m s}^{-1}$ .*

23. *Line 312: This conclusion is drawn based on median wind characteristics. What about wind characteristics that are near the tail of the distribution (e.g., 0.75 percentile)?*

We now comment on the fraction of  $\alpha$  larger than 0.11 as follows: *The fraction of profiles with  $\alpha$  larger than 0.11 is substantial in the MYJ simulation. In the eyewall region of the MYJ simulation, 43.6 % of the  $\alpha$  values are larger than 0.11. Values up to 0.15 are reached in 0.7 % of the eyewall and 4.1 % outer cyclone region. In the*

outer cyclone region, 1.0 % of the  $\alpha$  values are larger than 0.2. Such large  $\alpha$  values in the tails of the distribution impact the wind speed above and below  $z_{hub}$  in the extreme wind speed model (Eq. 3). As an example, we take the extreme wind speed model with a  $z_{hub}$  of 140 m, and a  $V_{ref}$  of  $57 \text{ ms}^{-1}$ . The wind speed from the extreme wind speed model at 180 m is  $0.6 \text{ ms}^{-1}$  ( $1.3 \text{ ms}^{-1}$ ) larger with an  $\alpha$  of 0.15 (0.20) than with an  $\alpha$  of 0.11.

**Old:** This supports the conclusion, that the current IEC standard is sufficiently similar in terms of wind shear during tropical cyclones.

24. Figure 7, Figure 8, and Table 2: The wind profiles representing the 0.75 percentile in Figure 7 display much larger shear than the median wind profiles. This is also evident in the inter quartile range for  $\alpha$  reported in Table 2 and in the distribution of  $\alpha$  in Figure 8. Please comment on the percentage of wind profiles with shear exponent larger than 0.11. Based on Table 2, it seems about 25% of wind profiles may display shear larger than 0.11. We now include the percentage in the table and comment on the fraction in the method section: *For wind shear, it is of interest how the simulated  $\alpha$  differ from 0.11, which is used in the IEC maximal wind speed model. While the IQR of the  $\alpha$  values varies little between the different simulations, the percentage of  $\alpha$  values larger than 0.11 depends on the simulation, as well as the specific parts of a tropical cyclone. For the YSU simulation,  $\alpha$  is mostly smaller than 0.11 for the analyzed scenes, namely before being affected significantly by land. Only 3.8 % (0.9 %) of the values are larger than 0.11 in the outer cyclone (eyewall) in the YSU simulation. The fraction is larger for the MYNN simulation. MYNN produces 10.4 % of the  $\alpha$  values larger than 0.11 in the outer cyclone region. For MYJ with the largest median  $\alpha$ , a large fraction of  $\alpha$  exceeds 0.11: the percentages larger than 0.11 are 43.6 % in the eyewall and 22.3 % in the outer cyclone region. The tails of the  $\alpha$  distribution include values larger than 0.11. In the eyewall of the MYJ simulation, 14.2 % of the  $\alpha$  values are larger than 0.12, and 0.7 % are larger than 0.15. In the outer cyclone region, 12.6 % of the  $\alpha$  values are larger than 0.12, 4.1 % are larger than 0.15, and 1.0 % are larger than 0.2.*
25. Figure 8: Why are the y-axis tick labels for shear and veer larger than 1 if this is a plot of probability density? The pdf is defined such that its integral equals one. The probability for a value to be within the interval  $x_1$  and  $x_2$  is given by Eq. 6. If for example 90 % of the shear values are between 0 and 0.2 the left-hand side of Eq. 6 equals to  $P(0 < X \leq 0.2) = 0.9$ . In order for the right-hand side of Eq. 6 to be 0.9, the maximum of the pdf needs to be at least  $(0.2 - 0.0)/0.9 = 4.5$ .

$$P(x_1 < X \leq x_2) = \int_{x_1}^{x_2} \text{pdf}(x) dx \quad (6)$$

## 2.4 References

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## 3 Reviewer comments from the second referee

### 3.1 General comments

This manuscript presents a study of examining the sensitivity of low-level wind speed, shear, and veer of typhoon Megi simulated by WRF to three PBL schemes. The goal is to assess how tropical cyclone (TC) force winds affect the wind loading of turbines. The research is interesting and valuable to coastal wind engineering. The topic is suitable for Wind Energy Science. The manuscript overall is well written and easy to follow. However, I have a few comments about the manuscript. The manuscript may be published after major revision.

Thank you for the constructive feedback.

### 3.2 Specific comments

1. How PBL schemes affect TC simulations is an old topic. It has been extensively investigated in the past. The three PBL schemes, namely, YSU, MYJ, and MYNN schemes, investigated in this study has been evaluated previously by other studies. For example, Zhu et al. (2013) investigated how these three schemes affect eyewall asymmetric structure and mesovortices of TCs. Recently, Ye et al. (2023) and Ye et al. (2023) also investigated the impact of vertical turbulent mixing parameterization on TC intensification. Although this manuscript focuses on the issues from the wind engineering perspective different from previous studies, it is important for the authors to do a thorough literature review on this topic, so that the readers know the background of this research and what's new of this manuscript.
  - Zhu, P., K. Menelaou, Z.-D. Zhu, 2013: Impact of sub-grid scale vertical turbulent mixing on eyewall asymmetric structures and mesovortices of hurricanes Quart. J. Roy. Meteor. Soc.,140, 416-438. DOI:10.1002/qj.2147.
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  - Ye, G., Zhang X., and H. Yu, 2023: Modifications to Three-Dimensional Turbulence Parameterization for Tropical Cyclone Simulation at Convection Permitting Resolution, J. Adv. Mod. Earth Sys., 15(4), <https://doi.org/10.1029/2022MS003530>.

Thank you for the additional literature. We have now included them in the new version. We are aware of the large body of existing literature addressing the influence of SGS turbulent fluxes on tropical cyclones. The following two paragraphs have been extended with the suggested literature.

**New:** *The impact of SGS turbulent fluxes on tropical cyclone simulations has been widely investigated. Ye et al. (2023a) show how the spatial distribution of SGS turbulent fluxes depends on the boundary layer closure and how the SGS fluxes affect the tropical cyclone wind field. It has been shown, that the choice of the boundary layer scheme affects the tropical cyclone intensity (Gopalakrishnan et al., 2013; Rai and Pattnaik, 2018; Rajeswari et al., 2020; Zhang et al., 2020; Ye et al., 2023b), the storm radius (Gopalakrishnan et al., 2013; Ye et al., 2023b), the boundary layer inflow strength (Gopalakrishnan et al., 2013; Rajeswari et al., 2020; Zhang et al., 2020) and the inflow layer depth (Rai and Pattnaik, 2018; Gopalakrishnan et al., 2013; Chen, 2022). This suggests, that for tropical cyclones, the three parameters, namely, mean wind speed, wind shear, and veer can be sensitive to the surface and boundary layer parametrization.*

**Old:** *It has been shown, that the choice of the boundary layer scheme affects the tropical cyclone intensity (Gopalakrishnan et al., 2013; Rai and Pattnaik, 2018; Rajeswari et al., 2020; Zhang et al., 2020), the storm radius (Gopalakrishnan et al., 2013), the boundary layer inflow strength (Gopalakrishnan et al., 2013; Rajeswari et al., 2020; Zhang et al., 2020) and the inflow layer depth (Rai and Pattnaik, 2018; Gopalakrishnan et al., 2013; Chen, 2022).*

*In Nolan et al. (2009) the boundary layer parametrization parameters are affected if eyewall vorticity maxima are developed in mesoscale simulations. This suggests, that the boundary layer parametrization affects wind speed variability in tropical cyclones.*

2. This manuscript aims to address the impact of TC force winds on the wind loading of turbines. Yet, the simulations and the analyses presented in the manuscript focus on the TC winds on the open ocean. One would wonder, why winds on the open ocean can affect the wind turbines on shore? It is the winds at landfall that matter to the turbines. But TC force winds at the open ocean and landfall can be substantially different because of the complicated surface conditions at the coast (e.g., land-ocean contrast, surface roughness, topography, etc.). In this regard, more justification is needed to explain why the open ocean wind matters to turbines on



shore.

Offshore wind turbines are increasingly planned in regions affected by tropical cyclones (4Coffshore, 2023). These turbines are located over the ocean, although mostly in close proximity to land. Clearly, nearby land modifies the tropical cyclone wind field. Yet, most model studies on the tropical cyclone wind structure address tropical cyclones over the open ocean. For wind energy a number of studies focus on idealized LES simulation over water (Worsnop et al., 2017; Kapoor et al., 2020; Ren et al., 2022; Gomez et al., 2023). The comparison with these studies is simplified by focusing on the period where the tropical cyclone is over the open ocean. How wind shear and wind veer change upon landfall will be assessed in further studies. We now include the following in the manuscript: *Even though offshore wind projects are mostly limited to coastal regions, we chose to focus on the cyclone intensification stage over open water before the typhoon makes landfall. This stage is chosen for two reasons: 1.) Temporal and spatial averaging of the wind field is only reasonably applicable in the absence of abrupt surface changes. 2.) The comparison to literature is simplified, as the majority of model studies addressing the tropical cyclone wind structure focus on tropical cyclones over the open ocean. How the wind field over land and in close proximity to land differs from the open ocean should be addressed in further studies, where our study can serve as a baseline.*

**Old:** *To reduce the complexity related to friction over land, we chose to focus on the cyclone intensification stage over open water, before the typhoon makes landfall.*

3. The similarity and difference among the three PBL schemes, YSU, MYJ, and MYNN, are not well summarized. Vertical turbulent mixing schemes can be grouped into three categories in terms of order of closure, local/non-local mixing, and consideration of dry/moist thermodynamics. YSU is a first-order K-closure “dry” scheme that is formulated using thermodynamic variables (e.g., potential temperature, water vapor mixing ratio) that are not conserved for moist reversible adiabatic processes. But it considers non-local mixing. MYJ is a 1.5-order local Turbulent kinetic energy (TKE) “dry” scheme that is also formulated using thermodynamic variables that are not conserved for moist reversible adiabatic processes. Like MYJ, MYNN is a 1.5-order local TKE scheme, but it is formulated with thermodynamic variables that are conserved for moist reversible adiabatic processes. Therefore, it includes the cloud effects on the TKE buoyancy production.

Thank you for including your summary. We have rewritten the paragraph. We closely follow your recommendation, which is similar to Zhu et al. (2014):

**New:** *The three schemes use different ways to calculate SGS turbulent fluxes. The YSU scheme uses a non-local first-order K-closure. The MYJ and MYNN schemes use a 1.5 order local Turbulent kinetic energy (TKE) closure. MYNN is formulated based on variables conserved for moist reversible adiabatic processes and is therefore often called a “moist” scheme (Zhu et al., 2014). Differently, YSU and MYJ are “dry” schemes. The three schemes are widely used in WRF. Due to its non-local closure, YSU is a popular choice to simulate tropical cyclones. Many studies analyze tropical cyclones simulated with the MYJ scheme (Nolan et al., 2009; Sparks et al., 2019; Rajeswari et al., 2020; Shenoy et al., 2021), partly because it was one of only two boundary layer options in the earlier version of WRF (V2.2). The MYNN scheme is an important option for wind resource assessment in the presence of wind farm effects, because wind turbine parametrizations are available for the scheme (Fitch et al., 2012; Volker et al., 2015).*

**Old:** *The YSU scheme is a first-order non-local scheme. Its eddy viscosity is described by a parabolic profile, which is itself a function of boundary layer height. As a non-local scheme, YSU considers that turbulence can be regarded as surface-driven (Kepert, 2012). More precisely, in the YSU scheme, the turbulent tendencies at each vertical level are related to the heat and temperature profile throughout the boundary layer (Nolan et al., 2009). This scheme is however sensitive to the definition of the boundary layer height (Kepert, 2012), while dynamic and thermodynamic definitions of the boundary layer height lead to different results (Zhang et al., 2011). Most studies find, that YSU performs well for tropical cyclones (Rajeswari et al., 2020). In contrast to the YSU scheme, MYJ and MYNN are local schemes. Their eddy viscosity is defined as a function of the turbulent kinetic energy, which is calculated independently at all model height levels. Many studies analyze tropical cyclones simulated with the MYJ scheme (Nolan et al., 2009; Sparks et al., 2019; Rajeswari et al., 2020; Shenoy et al., 2021), partly because it was one of only two boundary layer options in the earlier version of WRF (V2.2). The MYNN scheme is an important option for wind resource assessment in the presence of wind farm effects because wind turbine parametrizations are available for the scheme (Fitch et al., 2012; Volker et al., 2015).*

4. To evaluate the impact of TC winds on turbine wind loading, the authors divided the TC winds into two regimes, eyewall and rainband based on the radii to the storm center. It is unclear why the eyewall region is defined from 60 to 120 km in radius and rainband region is defined from 200 to 400 km. In fact, such definitions can cause problems in wind analyses performed in this study. As shown in Figure 6, the winds at the inner edge of the

defined eyewall are much weaker ( 15 – 25 m/s) than those at the outer edge of the eyewall. The former is in the same range as that of the rainband region. But according to the authors, the eyewall region is considered to be a high wind regime, then, what is purpose to include these low winds in a high wind regime? It does not address the problem raised in the paper but only creates a large spread for the eyewall regime (Fig. 7). The definition of rainband regime also has problems. As shown in Figures 5d, 5e, and 5f, the width of rainbands is actually very narrow. In-between the eyewall and rainbands are the non-convective moat, which has different characteristics from the convective eyewall and rainbands. The current definition of rainband region mixes up the convective rainbands and non-convective moat. Such mix-up will have a significant impact on the wind shear and veer analyses as it clearly shows in Figures 5e and 5f that the wind shear and veer in the convective rainbands are substantially different from those in the moat.

Here are my suggestions. Since the authors are interested in the winds in the lower part of the boundary layer, it's better to classify the TC winds into three regimes: eyewall, moat, and rainbands. For the eyewall region, the authors may consider defining it based on the maximum wind speed and the associated radius of the maximum wind (RMW), say, [RMW-R1, RMW+R2] where winds are greater than 80% of maximum wind speed. As for the rainband region, the authors may consider defining it based on either vertical velocity or hydrometeor mixing ratio, i.e.,  $|w| > w_{crit}$  or  $qh > q_{crit}$ . The rest area in the TC inner core can be grouped into the moat region.

Thank you for the concrete suggestion. We tried to follow your suggestions. We could closely follow your suggestion for the definition of the eyewall region. However, we used the 80 percentile of the 10 m wind speed as a critical value. We decided to use the percentile instead of the maximal wind speed because the maximal wind speed fluctuates strongly over time. This would lead to strong changes in the selected eyewall area over time. The percentile is more stable over time, and with that the size selected area.

We tested different criteria for the rainbands. Using the vertical winds or the rainwater content resulted in areas that did not align well with the maximal shear and veer values. We came up with a selection criteria based on convective inhibition instead. However, the analyzed statistics of all variables are sensitive to the definition of the eyewall. This includes two aspects: 1.) The size of the area and 2.) how well the area overlays with the outliers of shear and veer. Both aspects may differ between different simulations. This makes it hard to assess the sensitivity of the boundary layer schemes on wind speed, shear, and veer in the rainband and moat area. Therefore, we decided not to separate the two areas in the analysis. We however comment on the different characteristics of rainbands and non-conductive moat. In order to avoid confusion, we further decided to refer to the region combining moat and rainbands as the "outer cyclone region".

In the manuscript we explain the new selection criteria as follows (please refer to the manuscript for Fig. 2): *The eyewall and outer cyclone regions are analyzed separately. With that, we can account for and characterize differences between the two storm regions. To avoid, that the position of the simulation domain relative to the cyclone center influences the analysis, we use only grid points within a distance to the cyclone center ( $R$ ) smaller than 350 km. The definitions of the eyewall and outer region are illustrated in Fig. 2 and summarized in Eq. 4 and 5. We define the eyewall as a high wind speed regime. Our definition is based on the simulated wind speed at 10 m ( $WS_{10}$ ) at each simulation time step. Grid points are assigned to the eyewall region if two criteria are fulfilled: 1.)  $WS_{10}$  is greater than or equal to the 80th percentile of  $WS_{10}$  ( $P_{80}(WS_{10})$ ), and 2.)  $R$  is less than 250 km. The selected eyewall area is 76000 km<sup>2</sup>. The thickness of the eyewall is not symmetrical over the azimuth and can be zero. Note also, that the area includes gaps, where the wind speed is lower than  $P_{80}(WS_{10})$ . The outer region includes all grid points that are not part of the eyewall and the eye. To distinguish between the outer region and the eye, we define a critical radius  $R_{Eye}$  in Eq. 5. Here,  $R_{Eye}$  is taken as the 10th percentile of  $R$  of the eyewall grid points ( $P_{10}(R_{Eyewall})$ ). Thus*

$$Region = \begin{cases} \text{Eyewall:} & \text{if } WS_{10} \geq P_{80}(WS_{10}) \text{ and } R < 250 \text{ km,} \\ \text{Outer cyclone:} & \text{if not Eyewall and } R > R_{Eye} \end{cases} \quad (7)$$

where

$$R_{Eye} = P_{10}(R_{Eyewall}) \quad (8)$$

*The outer region is not homogeneous. It includes both the rainbands and the non-convective moat areas. These areas have different properties. However, we do not separate them, to prevent the analysis from becoming sensitive to the selection criteria.*

We further comment on differences along the rainband various times. We include here three passages:

- (a) *Yet, along the spiraling rainbands,  $\alpha$  increases around  $3 \times 10^{-2}$  between the hub height and the rotor top (not shown).*

(b) In the outer cyclone region, the maximal values of shear and veer are found along the spiraling rainbands (Fig. 6). Along the rainbands, there is a zone of lower horizontal wind speed. Within this zone, local maxima and minima of wind shear are alternating. The wind veer changes from positive values (inflow angle decreasing with height) on the radially inward side of the rainbands to negative values (inflow angle increasing with height) on the outside.

(c) At the inner edge of the eyewall and along the rainbands larger  $\alpha$  and veer values are simulated.

5. The authors argue that in addition to the wind speed, wind shear and veer are also important to turbine wind loading. But only the vertical profiles of wind speed in the defined eyewall and rainband regions are shown (Fig. 7). Then, what about the wind shear and veer. In fact, vertical profiles of wind speed in TCs have been shown in many papers, but not the shear and veer. So, it would be interesting to see what the vertical profiles of wind shear and veer in different regimes of a TC look like.

Thank you for the suggestion. We now include profiles of wind veer and wind shear in Fig. 8 and Fig. 9. In the result section we refer to the shear and veer profiles as follows:

*To analyze how  $\alpha$  varies with height, profiles of  $\alpha$  are shown in panels c and d of Fig. 8. According to Vickery's wind speed model (Eq. 6),  $\alpha$  decreases monotonically with height. This is different in the simulations. The YSU and MYJ simulations show a similar behavior of  $\alpha$  with height. In these simulations,  $\alpha$  decreases with height only below the hub height. Between the hub height and the rotor top the median  $\alpha$  changes less with height. Yet, along the spiraling rainbands,  $\alpha$  increases around  $3 \times 10^{-2}$  between the hub height and the rotor top (not shown). The MYNN simulation produces a pronounced change in wind speed between the first and second model levels. This results in an enhanced  $\alpha$  between these levels. Above the second model level  $\alpha$  increases slightly. Over the rotor diameter the increase in  $\alpha$  is  $7 \times 10^{-3}$  ( $2 \times 10^{-3}$ ) in the outer cyclone (eyewall) region.*

*Similar to our analysis of  $\alpha$ , we analyze the change in wind veer over the rotor diameter in Fig. 9 c and d. Wind veer is maximal close to the surface. Below the hub height veer generally decreases with height. The difference in wind veer between rotor bottom and hub height is 18 % in the MYJ simulation and around 8 % in the MYNN and YSU simulations. Above the hub height wind veer is nearly constant for the MYJ and slightly increases with height for the YSU and MYNN simulations. MYNN produces strongly enhanced wind veer between the lowest two model levels.*

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