

RESEARCH LETTER

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Key Points:

- Large-eddy simulations quantify hurricane gusts, gust factors, and wind direction shifts
- Category 5 hurricane mean wind speed, gusts, and gust factor in eyewall exceed current design thresholds
- Inclusion of veer in turbine load calculations is recommended

Correspondence to:

R. P. Worsnop,
rochelle.worsnop@colorado.edu

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Gusts and shear within hurricane eyewalls can exceed offshore wind turbine design standards

Rochelle P. Worsnop¹ , Julie K. Lundquist^{1,2} , George H. Bryan³ , Rick Damiani², and Walt Musial²
¹Department of Atmospheric and Oceanic Sciences, University of Colorado Boulder, Boulder, Colorado, USA, ²National Renewable Energy Laboratory, Golden, Colorado, USA, ³National Center for Atmospheric Research, Boulder, Colorado, USA

Abstract Offshore wind energy development is underway in the U.S., with proposed sites located in hurricane-prone regions. Turbine design criteria outlined by the International Electrotechnical Commission do not encompass the extreme wind speeds and directional shifts of hurricanes stronger than category 2. We examine a hurricane's turbulent eyewall using large-eddy simulations with Cloud Model 1. Gusts and mean wind speeds near the eyewall of a category 5 hurricane exceed the current Class I turbine design threshold of 50 m s^{-1} mean wind and 70 m s^{-1} gusts. Largest gust factors occur at the eye-eyewall interface. Further, shifts in wind direction suggest that turbines must rotate or yaw faster than current practice. Although current design standards omit mention of wind direction change across the rotor layer, large values ($15\text{--}50^\circ$) suggest that veer should be considered.

1. Introduction

Offshore wind energy generation in the U.S. began with a 20 m tall, 20 kW turbine deployed $\approx 4 \text{ km}$ off Maine's coast [Russo, 2014]. The first utility-scale wind farm, off the coast of Block Island, Rhode Island, can generate 30 MW [Gillis, 2016]. Offshore wind farm sites are proposed in regions with hurricane return periods less than the 20 year expected lifetime of a wind farm [Keim *et al.*, 2007; Russo, 2014]. According to the National Hurricane Center, a return period of a major hurricane (1 min sustained winds $\geq 49 \text{ m s}^{-1}$ at 10 m elevation) is as short as 16 years along the North Carolina coast [National Hurricane Center, 2016]. Three second gusts exceeding this wind speed threshold can occur even more frequently [Neumann, 1991]. Hurricane winds pose a substantial risk to turbines deployed in hurricane-prone regions, as demonstrated by the destruction of turbines during Typhoons Maemi (2003) and Usagi (2013) [Chen and Xu, 2016]. Therefore, hurricane-tolerant turbine designs are now being considered to address this risk [U.S. Department of Energy, 2015].

Current design standards for offshore wind turbines do not provide design parameters accounting for extreme winds associated with tropical cyclones. The International Electrotechnical Commission (IEC) offers a special class of wind turbines, Class S, for conditions outside of Classes I–III specifications, as in hurricanes [International Electrotechnical Commission (IEC), 2007]. However, the values of extreme wind speeds and directions must be specified by the turbine manufacturer, because design parameters specifically for hurricanes have not yet been issued by IEC. Further, the standard is silent on the issue of veer for all turbine classes. To provide design guidance, we compare our results to values provided by the IEC for the strongest class of turbines outside of tropical conditions (Class I). We demonstrate that mean wind speed, 3 s gusts, gust factor, and wind direction shifts can exceed current Class I design criteria, suggesting that modifications are required. Because the current classes of turbines in the IEC standard are not intended for tropical storm environments [IEC, 2007], a well-defined special design class may be needed for turbines in hurricane-prone regions.

The lack of adequate turbulence measurements at turbine heights undermines the understanding of how wind conditions in the hurricane boundary layer (HBL) affect wind turbines in the path of major hurricanes. Profiles of mean horizontal wind speed within the HBL are approximately logarithmic from $\approx 20 \text{ m}$ to 300 m above sea level (asl) [Powell *et al.*, 2003; Vickery *et al.*, 2009], consistent with the IEC's standard logarithmic profile. Vickery and Skerlj [2005] found that the IEC's gust factor can represent hurricane gust factors at 10 m elevation, for wind speeds $\leq 60 \text{ m s}^{-1}$. They did not examine hub height gust factors, which are needed to determine the loads that turbines experience. Worsnop *et al.* [2017] assessed turbulence spectra and spatial coherence for a theoretical wind turbine within a simulated HBL. Their results showed greater horizontal coherence along with a shift in peak spectra to higher frequencies than those in the IEC standard, suggesting

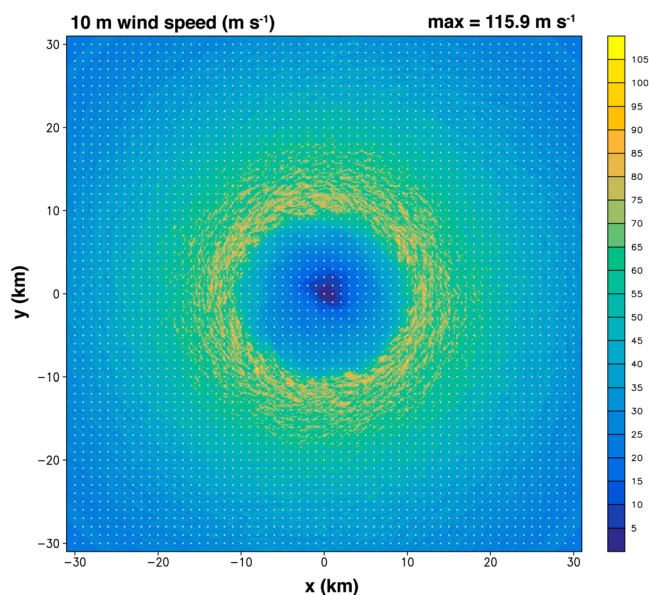


Figure 1. Instantaneous snapshot of the 10 m wind field produced by the CM1 model ($\Delta x = \Delta y = 31.25$ m). Locations of the virtual towers and thus data output are shown as the gray dots.

ited within the storm and unlikely to sample the most extreme winds [Stern *et al.*, 2016]. However, large-eddy simulations (LESs) can provide simulated winds within the eyewall at turbine heights with high spatial (≈ 30 m) and temporal (≈ 0.2 s) resolution. We can also examine the radial dependence of wind speed and direction to determine the most problematic regions within the hurricane. These data could provide further design guidance for upcoming hurricane-resilient turbine standards, which will appear in IEC 61400-1 edition 4.

Herein, we use LES to provide critical data to revise offshore wind turbine design standards. In section 2, we discuss the model configuration and data aggregation methods. In section 3, we quantify gusts and gust factors at a range of radii. We discuss shifts in wind direction at hub height in section 4 and veer across the rotor layer in section 5. Lastly, we summarize findings and offer suggestions to modify design standards in section 6.

2. LES of a Hurricane

We simulate an idealized Category 5 hurricane, a worst-case scenario for wind turbines: damage increases exponentially with wind speed [Landsea, 1993]. We use the 3-D, nonhydrostatic, time-dependent numerical model Cloud Model 1 (CM1) [Bryan and Rotunno, 2009; Bryan *et al.*, 2017]. This idealized simulation is based on a Category 5 hurricane, Felix (2007). The simulation's outer domain ($3000 \text{ km} \times 3000 \text{ km} \times 25 \text{ km}$) encompasses the entire hurricane (eye, eyewall, and rainbands). Within this outer domain, a fine-mesh LES domain ($80 \text{ km} \times 80 \text{ km} \times 3 \text{ km}$) with horizontal (vertical) grid spacing of 31.25 m (15.625 m) resolves the turbulent winds within the inner core, including the eye and eyewall. We output data every 0.1875 s time step at virtual towers located every kilometer in x and y (Figure 1) and at every model level from 7.81 m to 507.81 m asl.

This simulation is initialized from an axisymmetric model simulation of the hurricane, plus random perturbations, as in Richter *et al.* [2016] and Worsnop *et al.* [2017]. The simulation reaches steady state after 4 h. We analyze wind fields from a subsequent 10 min period, the averaging period used in the IEC standard and recommended by the World Meteorological Organization [Harper *et al.*, 2010]. LESs are computationally expensive; this simulation required more than 500,000 core hours (1 week of wall clock time using 4096 cores). Worsnop *et al.* [2017] present validation of CM1 compared to hurricane observations. This configuration is identical to the "Complex" simulation of Worsnop *et al.* [2017]; here we double the temporal and spatial resolution.

that unique wind characteristics within the HBL may exceed current design standards and may intensify aerodynamic loading effects.

To study the most extreme wind conditions, data are required from the strongest winds in the eyewall, the turbulent region surrounding the eye of the hurricane [Powell and Cocke, 2012]. The radius of maximum winds (RMWs), within the eyewall, is typically ≈ 20 km for a Category 5 hurricane [Kimball and Mulekar, 2004; Stern *et al.*, 2015]. Offshore hurricane wind data at turbine heights (below 200 m asl) are extremely limited. Reconnaissance flights are normally flown at 1.5–3 km asl [French *et al.*, 2007; Cione *et al.*, 2016], offshore towers are sparse [Archer *et al.*, 2013] and usually incur damage from direct hurricane hits, and dropsonde data are spatially lim-

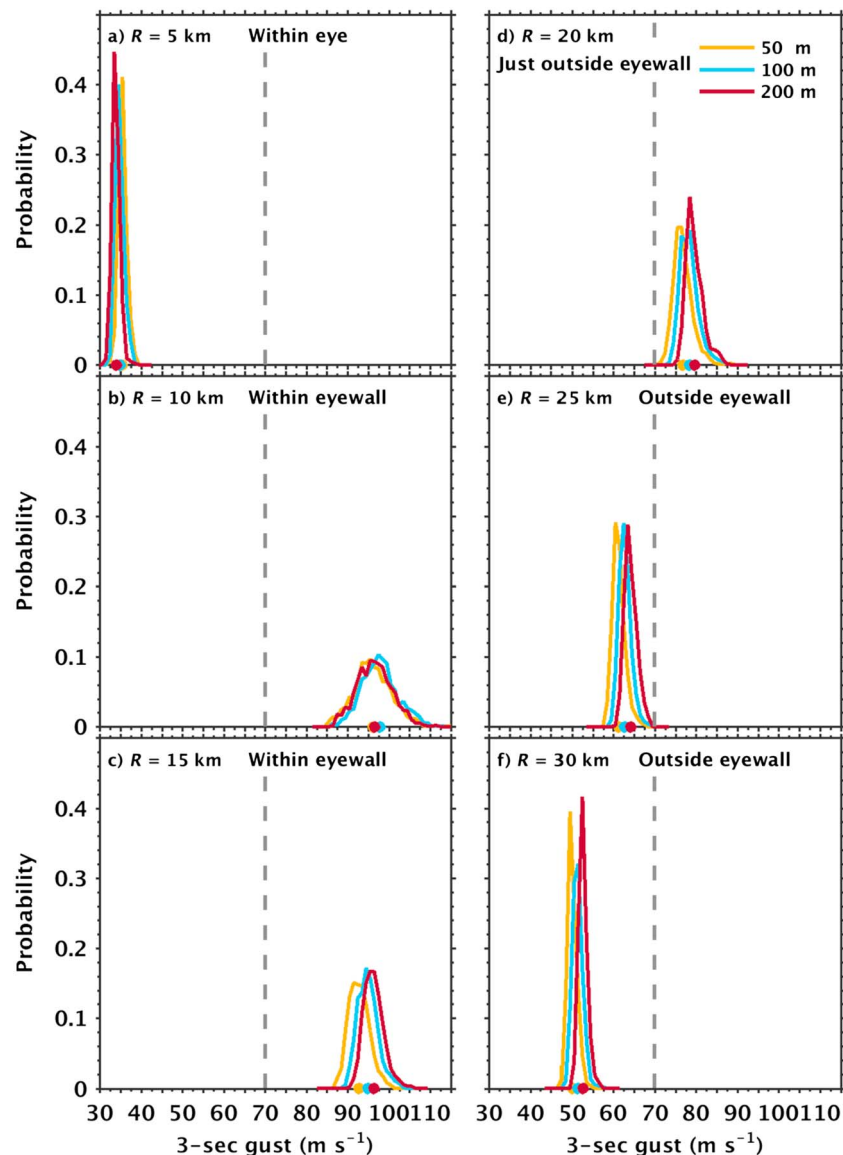


Figure 2. Histograms of the 3 s gusts at different locations within the hurricane: (a) eye (in this case, $R = 5$ km), (b and c) eyewall (in this case, $R = 10$ and 15 km), (d) just outside of the eyewall (in this case, $R = 20$ km), and (e and f) outside of the eyewall (in this case, $R = 25$ and 30 km). Probabilities are shown for gusts at 50 m (gold), 100 m (blue), and 200 m (brown) asl. Means of the distributions are shown as the gold, blue, and brown dots. For reference, the 70 m s^{-1} gust threshold is also shown (gray dashed).

We calculate 10 min mean wind speeds, 3 s gusts, gust factors, directional shifts at hub height (≈ 100 m), and veer at each virtual tower location shown in Figure 1. We then aggregate the towers into 1 km radial bins to obtain a representative sample at each radius. Finally, we take the maximum value of these variables at each radius to assess the strongest wind conditions a wind turbine would experience in a major hurricane.

3. Hurricane Gusts and Gust Factor

HBL flow is not homogeneous: greatest wind speeds occur within the eyewall. The peak 3 s gust quantifies the highest 3 s average wind speed observed within a longer interval, here 10 min [Harper et al., 2010], and is used to estimate loads. Gusts exceeding 70 m s^{-1} at altitudes across the rotor are problematic [IEC, 2007] and may cause significant damage; we find that these gusts occur within and just outside of the eyewall of major hurricanes (Figures 2b–2d). Some gusts exceed 100 m s^{-1} . These gusts could cause

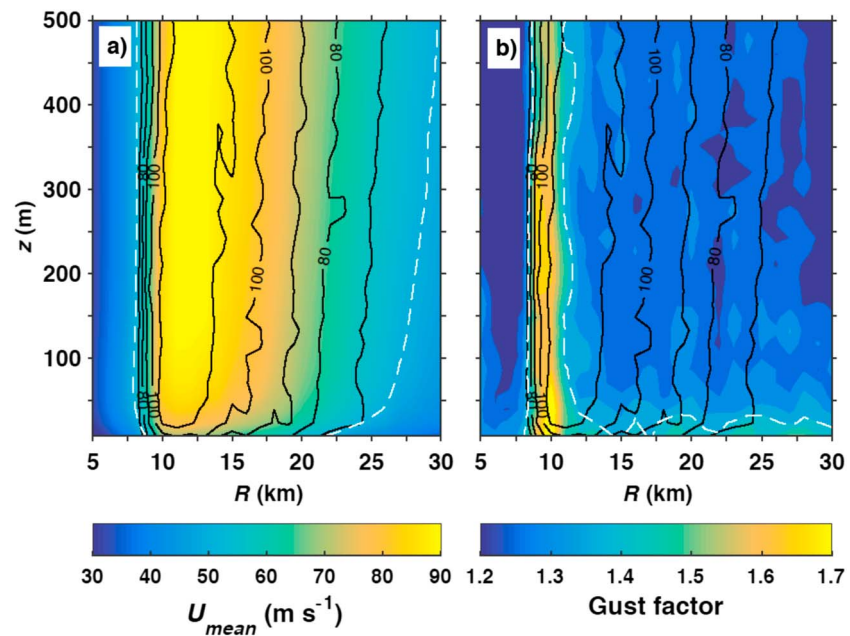


Figure 3. (a) Radius-height contours of the maximum 10 min mean wind speed (colored contours) at each radius and height overlaid with maximum 3 s gusts (black contours, only values exceeding 70 m s^{-1} are plotted). (b) Radius-height contours of the maximum gust factor (colored contours) during 10 min overlaid with maximum 3 s gusts (black contours, only values exceeding 70 m s^{-1} are plotted). Contours (white-dashed) of the 50 m s^{-1} 10 min mean wind threshold and a threshold gust factor of 1.4 are shown in Figures 3a and 3b, respectively.

extreme aerodynamic and structural loading on turbines, leading to damage/failure of turbine components and possibly component fatigue if the gusts reoccur. For this storm, this critical region spans $\approx 10 \text{ km}$ ($R = 10\text{--}20 \text{ km}$). These wind speeds agree with maximum observed speeds in an analysis of $\approx 12,000$ dropsondes from tropical cyclones [Stern *et al.*, 2016]; extreme horizontal wind speeds ($\geq 90 \text{ m s}^{-1}$) and updrafts ($\geq 10 \text{ m s}^{-1}$) can occur within the eyewall at altitudes as low as 100 m. Outside the simulated eyewall region, gusts fall below 70 m s^{-1} .

By considering maximum 10 min mean wind speed and 3 s gusts at each radius (Figure 3a), we identify regions where the wind speeds exceed current Class I design thresholds (50 m s^{-1} mean wind and 70 m s^{-1} peak gusts) and therefore where Class I wind turbines may fail. Even these thresholds may be too lenient: turbines along Japan's coast were severely damaged in mean wind speeds below this threshold ($\approx 38 \text{ m s}^{-1}$): the peak gust reached 74 m s^{-1} during Typhoon Maemi (2003) [Ishihara *et al.*, 2005]. Peak gusts (Figure 3, black lines) exceed 100 m s^{-1} over a range of $\approx 8 \text{ km}$, suggesting that in a direct strike, turbines should anticipate gusts higher than the current threshold (or that destruction should be assumed). Such an occurrence may be rare. However, mean wind speeds can exceed design thresholds even outside the eyewall (radii up to $\approx 32 \text{ km}$) (Figure 3a). A thorough investigation of return periods and likelihoods of eyewall conditions is needed to justify the expense of design modifications.

Gust factor, G_{t,T_0} , estimates the expected peak gust based on the mean wind speed, V_{T_0} ,

$$G_{t,T_0} = \frac{V_{\tau,T_0}}{V_{T_0}}, \quad (1)$$

where V_{τ,T_0} is the highest 3 s mean (gust) that occurs within 10 min ($\tau = 3 \text{ s}$, $T_0 = 600 \text{ s}$) [Harper *et al.*, 2010]. Gust factors for turbines should be representative of hub height winds. Vickery and Skerlj [2005] determined hurricane gust factors from onshore and offshore observations collected below 40 m and for wind speeds $\leq 60 \text{ m s}^{-1}$. Here we examine gust factors at turbine heights to highlight regions with the highest gust factors (Figure 3b).

The highest gust factors (≈ 1.7), outside of the quiescent eye, occur at the eye-eyewall interface (here $R = 9\text{--}11 \text{ km}$) inward of the peak gusts (we ignore gust factors within the eye because mean wind

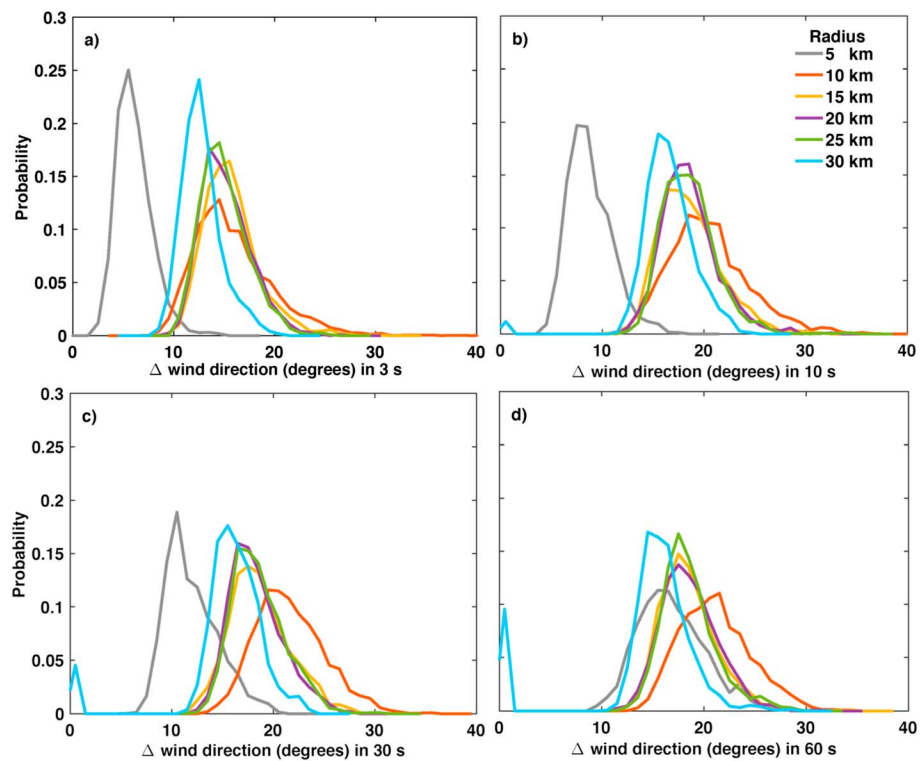


Figure 4. Histograms of the maximum change in wind direction over (a) 3, (b) 10, (c) 30, and (d) 60 s. Six hurricane radii are shown for each histogram: 5 km, 10 km, 15 km, 20 km, 25 km, and 30 km from the hurricane center.

speeds there are too weak to impact wind turbines). Additionally, gust factors ≥ 1.4 occur below 30 m asl, on average, just outside of the eye-eyewall interface ($R > 11$ km). Generally, the gust factor is ≤ 1.4 (the standard IEC value corresponding to mean wind speed of 50 m s^{-1} and gust of 70 m s^{-1}) outside of the eyewall (except below ≈ 30 m asl). This result is consistent with *Vickery and Skerlj* [2005] who showed that over the open water, gust factors ≤ 1.4 for wind speeds $\leq 60 \text{ m s}^{-1}$. However, we find that gust factors up to 1.7 occur in the eyewall, and values of 1.5 occur close to the surface even outside the eyewall. While a gust factor of 1.4 is adequate for most of the hurricane, it underestimates the eyewall region and regions outside of the eyewall below 30 m asl.

4. Yaw Misalignment

Wind direction can shift 180° during a hurricane passage over 0.5–1.5 h [*Clausen et al.*, 2007]. While turbines can slowly yaw, or rotate into the mean wind direction, abrupt changes in wind direction may affect turbine survival. Edgewise vibrations induced by yaw misalignment [*Fadaeinedjad et al.*, 2009] damage turbine blades and induce buckling of the tower. Yaw misalignment, possibly from yaw drives breaking, the system's inability to keep up with the changing wind direction, or loss of grid connection caused turbines to fail at a wind farm in China during passage of Typhoon Dujuan (2003), even when wind speeds were below the design speed [*Clausen et al.*, 2007].

Large shifts in wind direction occur at hub height (Figure 4). Largest shifts occur within the eyewall (here ≈ 10 km) perhaps due to coherent vortices ("mesovortices") [*Aberson et al.*, 2006]. Turbines typically yaw based on the recorded 10 min average change in wind direction. However, for higher wind speeds, a shorter averaging time and faster yaw response time are possible. The tails of the distributions (Figure 4) reveal that the wind direction can shift $10\text{--}30^\circ$ over durations < 10 min even outside the eyewall. Yaw misalignment could occur frequently if the yaw system were not designed to sense and respond to 1 min or less directional shifts. Near the eyewall, abrupt changes in wind direction at hub height suggest that a yaw response faster than 10 min may be needed.

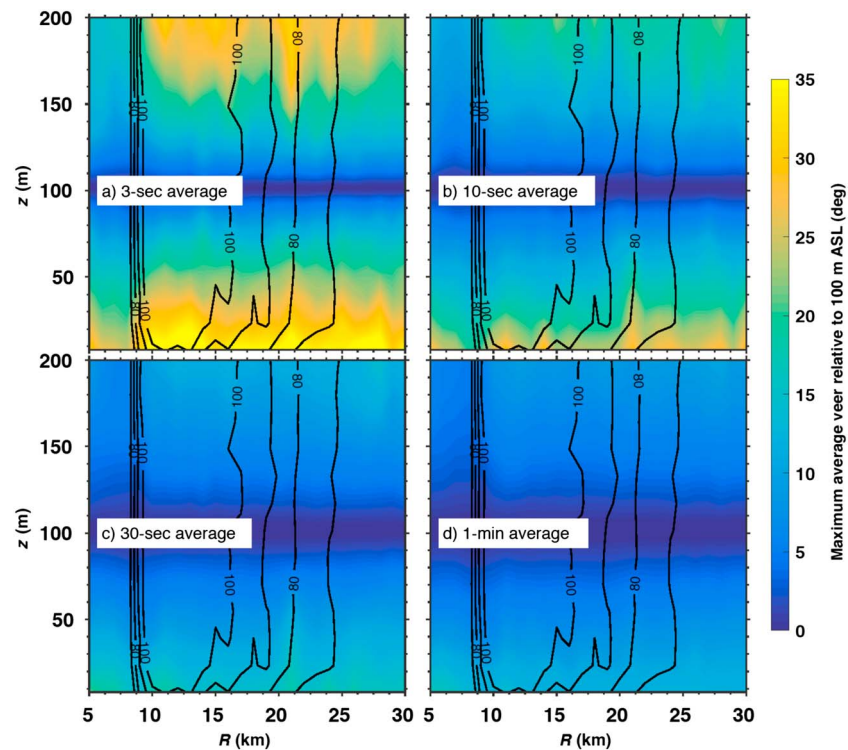


Figure 5. Radius-height contours of the maximum average veer relative to hub height (100 m asl) (colored contours) for averages calculated over (a) 3 s, (b) 10 s, (c) 30 s, and (d) 1 min. Overlaid are the maximum 3 s gusts (black contours, only values exceeding 70 m s^{-1} are plotted).

5. Wind Veer

Current design standards do not address veer, the change in wind direction across the vertical rotor layer, even though veer may affect turbine loads and has been shown to affect power production [Walter *et al.*, 2009; Vanderwende and Lundquist, 2012]. Varying wind direction can cause additional stress leading to mechanical failure. We calculate the average veer at each tower in each radius bin relative to hub height (100 m) over averaging periods from 3 s to 1 min (Figure 5) and then take the maximum value over all towers in that radius bin. Within 200 m asl, we find that the wind direction can change $>35^\circ$ (maximum of 55°) as compared to hub height for periods ≤ 10 s (Figures 5a and 5b). Veer ranges from 5 to 15° , particularly below 50 m for averaging periods of 30 s and 1 min (Figures 5c and 5d). This strong veer demonstrates that wind turbines will endure swift changes in wind direction, across the vertical rotor layer, on the order of 1 min or less during an eyewall passage. Testing the influence of an average veer of 15° in load simulators such as FAST (Fatigue, Aerodynamics, Structures, and Turbulence) [Jonkman and Buhl, 2005] would reveal how veer impacts turbine loads and whether manufacturers should include veer in the turbine design process.

6. Conclusion

We examined gusts, gust factor, and wind direction changes in the hurricane boundary layer (HBL) and compared these values to those in the IEC wind turbine design standard for Class I turbines. We represented the HBL with large-eddy simulations of an idealized Category 5 hurricane using Cloud Model 1 (CM1). Results indicate that conditions outside the design standards would be encountered by wind turbines experiencing the eyewall and near-eyewall regions of a Category 5 hurricane; turbines built to current design standards would incur structural damage.

Mean wind speed and 3 s gusts are greatest in the turbulent eyewall of the hurricane. Within and just outside of the eyewall, winds exceed the current turbine design thresholds of 50 m s^{-1} mean wind and 70 m s^{-1} peak gust. Mean wind speeds (gusts) can exceed 90 m s^{-1} (100 m s^{-1}) within the eyewall, consistent with

observations [Stern *et al.*, 2016], suggesting that either design standards or expected turbine lifetimes should be modified to account for extreme conditions within a hurricane, if the probability of a direct eyewall strike is deemed likely in the wind farm location.

We also analyzed gust factors at altitudes relevant for wind turbines (<200 m asl). Largest gust factors occur at the eye-eyewall interface, just inward of the peak gusts. While the majority of the hurricane gust factors outside the eyewall are similar to those previously reported [Vickery and Skerlj, 2005], gust factors exceed 1.7 within the eyewall. While the eyewall constitutes a small fraction of the total hurricane area, climatologies of Atlantic Category 5 hurricanes [Kimball and Mulekar, 2004, Figure 15; Stern *et al.*, 2015, Figure 10] show that the median RMW is ≈ 20 km, which could engulf a wind farm experiencing a direct strike. Additionally, for radii outside the eyewall and RMW, the gust factor is greatest at altitudes <50 m asl. At these locations, the gust factor can exceed 1.4, the value used in the IEC standard to convert a reference wind speed of 50 m s^{-1} to a 3 s gust. A value of 1.5 may be more accurate to estimate gusts at the lower reaches (≈ 30 m asl) of wind turbines outside the eyewall of a Category 5 hurricane.

Wind direction shifts in the HBL lead to significant yaw misalignment: wind directions can shift $10\text{--}30^\circ$ over durations <10 min. Turbines should be able to respond to directional shifts on these shorter time scales to avoid damaging loads. In quantifying the absolute average veer for a typical turbine, we found shifts of 35° or greater from the hub to the tip of the rotor layer for 3 and 10 s periods. For 30 s and 1 min periods, veer is weaker but can reach 15° . Veer across the turbine is not considered in current design standards, but these results suggest that its influence should be tested in load simulators to determine if veer should be an essential component of turbine load estimations.

These results can guide the design of robust offshore wind turbines for hurricane-prone regions and the quantification of financial risk for those offshore wind turbines. The results herein could inform the upcoming subclass T (typhoon/hurricane resilient) turbines, which will soon appear in IEC 61400-1 edition 4. Investigation of the actual turbine loads induced by the gusts, veer, and yaw misalignments discussed herein can help determine the modifications required to build turbines to withstand major hurricanes. Incorporating these LES into turbine load simulators as in Sim *et al.* [2012] and Park *et al.* [2015] and accounting for storm surge [Jordan and Clayson, 2008] and breaking waves [Suzuki *et al.*, 2014; Hara and Sullivan, 2015] near offshore wind turbines would be a viable next step.

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