

Modeling Offshore Wind Farm Performance in Coastal Low-Level Jets Using Coupled Mesoscale-Microscale Large Eddy Simulations

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Accurately predicting wind farm reliability under complex offshore atmospheric conditions remains a key challenge, particularly during noncanonical meteorological events such as coastal low-level jets (LLJs). LLJs, characterized by strong nonmonotonic vertical shear and directional veer, depart significantly from the simplified inflow assumptions embedded in conventional design standards, low-fidelity engineering models, and microscale large eddy simulations of the atmospheric boundary layer. In this work, we use the virtual wind farm framework—an exascale, graphics processing unit-accelerated large eddy simulation platform coupled with high-fidelity aeroservoelastic turbine models and advanced mesoscale-microscale coupling via the ExaWind software stack—to investigate turbine responses under realistic LLJ forcing. Simulations are performed over the U.S. North Atlantic offshore domain with the use of meteorological inputs from New York State Energy Research and Development Authority buoy data, focusing on a representative LLJ case impacting the International Energy Agency 15 MW reference turbine. Our results show that LLJs can cause up to 50% power deficits in downstream turbine rows and significantly amplify low-speed shaft and tower loads through nonlinear coupling between complex inflow characteristics and turbine structural dynamics. Two primary mechanisms drive these load amplifications: (1) unique LLJ inflow features—including veer and vertical/lateral shear—and (2) the downstream evolution of the flow under stable thermal stratification, which suppresses turbulence mixing and alters wake recovery. These mechanisms produce streamwise variations in turbine loading not captured by standard hub height-based metrics or existing design load case (DLC) definitions. This study highlights the critical role of rotor-scale flow gradients in driving fatigue and system-level aeroelastic responses, challenging current DLC and control strategies. We advocate the integration of full-flow field, environment-aware wind inputs into load modeling and control algorithms. By leveraging exascale computing to resolve mesoscale-microscale coupling, this work lays the groundwork for next-generation offshore wind turbine design and operation in meteorologically complex marine environments.

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I. INTRODUCTION

Over the last decade, wind energy research has made significant strides in phenomenological understanding to advance efficiency, reliability, and scalability. Advances in

atmospheric inflow characterization [1–4], aerodynamics [5–7], materials science, and control strategies [8,9] as well as novel grid integration strategies [10] have supported the development of larger, more efficient, and more reliable wind turbine design. In particular, the offshore wind sector powered by unencumbered and vast wind resources, viable floating wind technology [11], and gigantic rotor designs [12] has seen remarkable growth. Although offshore wind energy is more expensive [13] to generate than its onshore variant, the potential to scale to larger park sizes in deeper waters is attractive. Advancement in computer hardware, e.g., graphics processing units (GPUs), has enabled exascale computational fluid dynamics and

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data-driven artificial intelligence–based predictive models in the realm of turbine physics modeling. The fidelity of these simulations is approaching levels high enough to provide trustworthy insights into turbine performance to increase operational efficiency and reliability and improve wind forecasting and design grid integration strategies [14,15]. The technoeconomic viability of offshore wind energy is driven by reduction of the levelized cost of electricity—a metric that correlates overwhelmingly with turbine efficiency and reliability. The latter is usually critical as turbine design is often driven by extreme, low-likelihood loads, which invariably drive up cost. Especially critical is the lack of in-depth understanding of farm-level turbine reliability (fatigue and ultimate) driven by realistic atmospheric conditions from a system-level perspective. These limitations can be inherently tied to (1) *technology*—the limitations in the design process used today—and (2) *knowledge of offshore wind resource*—a limited fundamental understanding of the wind resources and their characterization in offshore sites. Farm reliability is quantified primarily through mechanical load assessment of isolated turbine systems with the use of design load cases (DLCs) with low-fidelity aeroelastic tools [16], with the use of canonical semiempirical International Electrotechnical Commission (IEC) standards representative of site-class/wind conditions and mean wind-resource information at farm sites. This process does not consider wake turbulence and turbine load interactions, or wind flow characterizations that are realistic representations of atmospheric boundary layers (ABLs), including potentially high risk unconventional events such as coastal low-level jets (LLJs) and hurricanes [17], which can have a detrimental impact on the reliability of the turbine system. Furthermore, the wind resource assessment of offshore sites has resulted in significant uncertainty owing to the limited instrumentation and scarcity of deployed projects. Analysis of the New York Bight data [18] has revealed the presence of unique shear tails in the distribution whose effects on turbine reliability have not been explored. In particular, the presence of strong negative shear and veer in unconventional wind events in offshore sites that may be in significant proportion can impact wind farm dynamics, and thereby, turbine design.

Traditionally, the research community has focused on the interaction between canonical equilibrium atmospheric inflow turbulent winds and wind turbines within a farm [19,20] comprising nominal monotonic shear and veer—phenomena that are likely to occur in neutral, moderately convective, and weakly stable conditions. The engineering community typically uses cheap, reduced-fidelity models (including mid-fidelity approaches such as the Reynolds-averaged Navier-Stokes equations) that are calibrated [21,22] by higher-fidelity research data [large eddy simulation (LES)] involving the interaction of turbines. These high-fidelity data usually include canonical

turbulent ABLs with monotonic shear ($\alpha \leq 0.2$) and low veer (approximately 5°). In addition to the idealization of atmospheric inflow, turbine representation in these studies is also simplified to consider only aerodynamic effects, leaving out critical elastic and controller impacts that influence field operation. Aeroservoelastic interaction is a critical driver for wind turbine reliability during both operational and nonoperational conditions, and is therefore highly valued by turbine manufacturers. In the engineering design process, this aeroservoelastic response is considered, but with the use of kinematic turbulence models [23] and usually in single turbine settings. Farm-level reliability assessment is hardly pursued at affordable fidelity with the use of wake models to assess control strategies [24]. Consequently, the resulting turbine design achieved with the use of less accurate models will incorporate conservatism to mitigate uncertainties in loading under realistic conditions. Specifically, the disconnect between simplified and realistic atmospheric inflow and its consequent two-way aeroservoelastic interaction with turbine designs has pushed the industry toward a purely fatigue-driven design process as against a combination of fatigue and unconventional extreme operational conditions.

As an attempt to bridge this technology gap in modeling fidelity, we consider the notion of virtual wind farms (VWFs)—an extreme-scale compute-enabled condition-aware wind farm system-level simulator with scientific complexity that can compare to field tests, but with the added advantage of being instrumented through hundreds of millions of sensors (as grid points) within the computational domain. This powerful combination enables VWFs to serve as virtual test beds that offer a microscopic view of the underlying flow physics. Specifically, each grid point in the simulation is a sensor generating unique insight into the flow physics in the vicinity of the turbine. Such high-resolution instrumentation is not feasible in field tests. The other unique aspect of VWFs is the level of detail that goes into turbine representation, where the aerodynamics and structural model of the turbine system along with the controller mimic realistic complexity. Such detailed turbine models are, in turn, coupled to the detailed flow-physics solver, which includes realistic atmospheric turbulence and wake turbulence from neighboring turbines. Thus, one has access to the complex end-to-end process of inflow turbulence-turbine-wake-rotor interactions within a wind farm, which allows causal exploration relating controller-aerodynamic-structural response and wake flow with an incoming turbulent wind event. The VWF concept in this work is exercised with the use of the GPU-accelerated ExaWind software stack [25], particularly AMR-Wind with OpenFAST to realize the atmospheric flow-turbine aeroelastic modeling environment. The wind turbine controllers are invoked via the Reference Open Source Controller (ROSCO) [26] framework. Prior work by the authors extended this capability to incorporate offline

mesoscale-microscale coupling algorithms for downscaling the mesoscale physics to the microscale within AMR-Wind [2]. Note, higher-fidelity online coupling methods such as Weather Research and Forecasting driven LES (WRF-LES) and three-dimensional or four-dimensional variational assimilations [27,28] exist, but are too computationally intensive for mesoscale-to-turbine-scale simulations. Additionally, while blade-resolved fluid-structure interaction tools (e.g., ExaWind) have emerged in the last few years [7], they remain largely intractable for large farms. The VWF concept thus offers a practical compromise by using actuator line models (ALMs) to approximate aeroelastic blade effects driven by mesoscale-microscale ABL turbulence without resolving blade boundary layers. VWF environments allow us to study morphologically unique nonstationary ABLs that are different from canonical ABLs and simplified kinematic representations used within turbine design cycles. In particular, we are interested in high-risk unconventional wind events in the offshore sites such as coastal LLJs that are driven by conspicuous nonstationarity, strong shear ($|\alpha| \gg 0.2$), and strong veer (40° or more across the turbine rotor) and how they can detrimentally impact the turbine-system-level load response. The mesoscale-microscale coupled atmospheric turbulence captures the nonstationary evolution of the mesoscale weather, including frontal events, coastal mixing, and baroclinicity [29,30] that underlie low-level jet formation, and transmits these tendencies into the evolution of the microscale atmospheric turbulence eddies that impact turbine performance.

Coastal LLJs represent meteorological events with implications for the broader atmospheric and wind energy community [31–34], and are driven by thermal and pressure gradients (mesoscale) across the coastline, resulting in strong baroclinicity, especially in the midlatitudes [29,30]. These low-altitude streams of narrow, fast-moving air occur intermittently over the year (between 2% and 7% of the time in a year [35] in the New York Bight region) and more frequently in the summer months (25% as per the NOW-WAKES dataset [30]), yielding nonmonotonic jetlike wind profiles with strong positive/negative shear around the jet nose. This, in turn, generates unique combinations of turbine pad-specific wind shear, veer, and turbulence intensities (TIs) [2] that are not achieved through simulation of equilibrium turbulent ABLs. More pertinently, these conditions are not accounted for in standard annual energy production (AEP) calculations and the mechanical load analysis part of the design mandates standardized by the IEC [36]. Therefore, it is of interest to understand the detailed turbine load response to such unconventional winds, especially in the nascent offshore wind industry. The study of jet-type inflow impacts on turbines has been explored by the use of idealized simulations—particularly, using equilibrium stable ABL surrogates [37,38] and simplified turbine models (actuator

disks [19,20]) that do not account for the combined aeroservoelastic responses. Such models are useful to assess power performance (AEP benefits) without considering reliability. Stieren *et al.* [39] improved the modeling of LLJs by introducing baroclinicity in the geostrophic wind layer that was used to study wind farm behavior. The negative shear in the geostrophic layer resulted in lower LLJ heights, increased turbulence from baroclinicity (inline with the mesoscale-driven LLJ event [2]), and potential AEP losses in wind farms due to reduction of hub-height wind speeds. A wind tunnel study [40] has also documented the influence of LLJ nose height on wind turbine power at different scales. However, in all these cases, the physics considered was inherently stationary, which differs in turbulence morphology from that of realistic low-level jets driven by nonstationary weather events [2]. Secondly, the realistic turbulence-turbine interaction from the aeroservoelastic perspective is lacking, which makes it hard to connect the inflow turbulence to loads and reliability. The current work aims to address these gaps in wind farm research by leveraging the complexity ingrained within the VWF; namely, (1) characterizing coastal LLJs with the help of mesoscale-microscale coupled LES [4,41] to generate the levels of shear, veer, lateral gradients, and turbulence intensity that cannot be created by canonical microscale LES [19,42] and (2) adopting a turbine representation that mimics realistic aerostructural impact on the turbine system (blades, hub/nacelle, and tower) for farm-level reliability assessment. In this work, we use the VWF to assess, characterize, and quantify the impact of a coastal LLJ observed in the marine ABL off the U.S. North Atlantic coast (New York Bight) as observed by floating lidar buoy measurements recorded by the New York State Energy Research and Development Authority (NYSERDA). This event was carefully selected from the year-long measurement campaign and chosen for the sustained low-level jet observed over a few hours. We leverage weather-scale replication of this particular event using the Weather Research and Forecasting (WRF) Model and downscale the observed tendencies using a mesoscale-to-microscale ABL model. This was done to replicate the observed atmospheric turbulence within the coastal LLJ with uncharacteristically strong shear and veer. The virtual wind farm consisting of International Energy Agency (IEA) 15 MW offshore reference wind turbines was designed to mimic current offshore wind farms in scale, spacing, and aeroservoelastic complexity. The wind farm performance was compared against that of its counterpart operating in a monotonically sheared (MS) ABL that matches the wind speed, rotor-averaged velocity and shear, and TI from the LLJ at turbine level. This is inspired by IEC-mandated design considerations where wind speed, shear, and TI (across the rotor disk) are often used as surrogates of the turbulent wind to determine the corresponding mean and fatigue turbine loads. Therefore, this study is one

of the first in-depth efforts to assess wind turbine system-level response to realistic inflow ABL turbulence, paving the way for causal analysis of observed load spikes, turbine vibrations, etc. as a possibility in the near future. This study complements ongoing experimental field campaigns, e.g., the RAAW and AWAKEN studies [43,44], and the corresponding efforts to validate simulation tools. From the results of this study, we observe that the multilayer shear, strong veer, and lateral velocity gradients detrimentally impact the fatigue life of a low-speed shaft and tower. The impact of these findings on direct drives and shaft reliability is significant for an industry struggling with higher leveled cost of energy and increasing reliability issues. These results call for mitigation strategies that include both environmental condition-aware high-fidelity turbine design and improved sensing of shear, veer, and lateral gradients resulting in better turbine control algorithms.

II. NUMERICAL METHOD

A. Computational framework

The VWF simulator framework is created with the use of state-of-the-art wind models driven by realistic atmospheric conditions coupled with aeroelastic models and a controller framework for the wind turbines. In particular, for weather-driven wind modeling pertaining to LLJs, we resort to mesoscale-microscale coupled LES with nested grids driven by realistic atmospheric conditions, e.g., the GPU-accelerated code AMR-Wind [25]. The mesoscale forcing for coastal LLJ ABL simulations is further calculated by WRF simulations as in Ref. [35]. The ocean waves are modeled as a lump roughness element for wall modeling in LES, and the wind-wave interactions are not considered in the present study. Because of the large spatial scales in the problem, the wind turbine blades and their boundary layers are not resolved but are rather modeled

with the use of an ALM [45]. The structural vibrations are calculated from prescribed one-dimensional mode shapes with the use of Euler-Bernoulli beam theory—e.g., via OpenFAST coupling. In a similar vein, the tower is modeled as an aeroelastic nonrotating actuator line. The aeroelastic model is simulated in a “still-water” environment, and the hydrodynamic forces are not calculated for the present work. Additionally, the turbine model is hooked to a realistic controller algorithm implemented with the use of ROSCO [26] integrated via two-way coupling with the aeroelastic module in OpenFAST. (The multiscale complexity of the simulations is highlighted in Fig. 1). The development of AMR-Wind is being led by the National Renewable Energy Laboratory through the Exascale Computing Project [46], while OpenFAST and ROSCO have been developed as separate initiatives by the National Renewable Energy Laboratory. WRF project development is led by the National Center of Atmospheric Research [47]. For more details about the LES solver, the aeroelastic solver, and the controller module, see Appendixes A and B.

B. Case setup

At a high-level, large eddy simulations for the wind farms are driven by inflow boundary conditions generated by offline precursor simulations. Two sets of precursor and wind farm simulations are carried out for (1) coastal mesoscale weather-driven LLJs [2,48] and (2) a canonical, convectively unstable boundary layer representative of daytime onshore conditions (baseline) for comparison. The reason for the choice of the baseline case will be clearer in Sec. III A. The precursor simulations are horizontally periodic, while the wind farm simulations involve inflow-outflow boundary conditions driven by the precursor data. Both the precursor and the wind farm domain

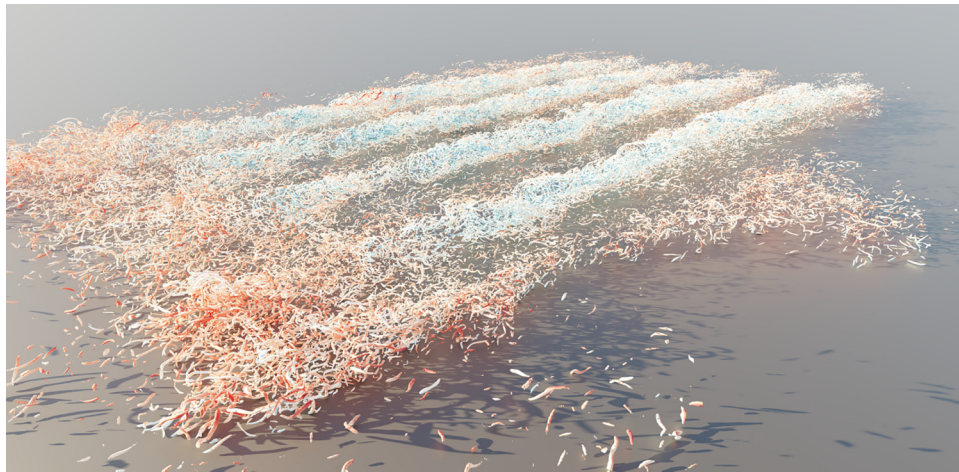


FIG. 1. Large-scale coherent structures (Q criterion) in a wind farm in a coastal LLJ environment. Figure created from a 5×4 layout high-fidelity wind farm simulation done by the authors.

TABLE I. Domain size and mesh count (millions of computational cells) of baseline MS and coastal LLJ simulations (precursor and wind farm). WT, wind turbine.

Case	Domain size (km ³)	Mesh count ($\times 10^6$)
MS (baseline, precursor)	$10 \times 5 \times 2$	67
MS (baseline, wind farm: 20 WTs)	$10 \times 10 \times 2$	1500
LLJ (precursor)	$10 \times 10 \times 1$	34
LLJ (wind farm: 20 WTs)	$10 \times 10 \times 1$	1400

extend to 10 km (approximately $40D$) in each horizontal direction to capture the large-scale structures of the ABL. The vertical extent of the unstable baseline case is greater than that of the stable LLJ case to allow for the buoyancy-driven growth of the boundary layer. The various domain sizes and the mesh counts are listed in Table I. The baseline resolution for the precursor simulations is 10 m (approximately $0.04D$). For the wind farm region, two successive layers of mesh refinement have been incorporated into the domain, resulting in a resolution of 2.5 m (approximately $0.01D$) at and near the turbine pads. These refinement regions extend $6D$ upstream and downstream of the farm layout. For the fine-scale stable LLJ configuration, the resolution of the precursor, while being coarse, is in line with the recommended prediction of approximately 6.25 m by Beare *et al.* (2006) [49] and 4 m by Momen [50], and is within the upper bound of resolving large eddies of approximately 30 m from the condition $L/\Delta z > 2$, where L is the Obukov length scale [51] (see Table II). Our precursor ABL simulations for the LLJ and MS cases capture approximately 90% and approximately 95%, respectively, of resolved turbulence in the rotor region (see Fig. 24 in Appendix A), which increases further to more than 95% of resolved turbulence for farm simulations in the near

wall region up to $z \sim 0.1\delta_{\text{ABL}}$, where δ_{ABL} is the boundary layer thickness. The vertical resolutions in the LLJ and MS cases for wind farm simulations are sufficiently resolved to capture the rotor loads and the loads on tower at various pad locations, and are consistent with the grid size recommendations from recent literature [52,53]. The 5×4 layout wind farm with interturbine spacing of $5D$ is aligned with the mean wind direction obtained from the precursor ABL. The along-wind interturbine distance is approximately 30% less than the standard offshore interturbine distances [54]. This was purposefully designed as a trade-off between reducing computational expense and amplifying the effect of wakes (especially coastal LLJs). All the simulations were done with the Summit supercomputer (now decommissioned) at Oak Ridge National Laboratory. The computational cost for collecting 20 min wind farm flow field and wind turbine system loads for each of the 20 turbine wind farm simulations is $276 \text{ nodes} \times 240 \text{ h} = 66\,240$ GPU hours. The number of GPUs was optimally selected to ensure that the simulations were run at a sweet spot of approximately 500 000 degrees of freedom per GPU obtained from the strong and weak scaling analysis.

III. RESULTS

A. Precursor ABL simulations

This section documents the statistics of the flow field observed in the mesoscale-driven coastal LLJ precursor simulation that was used to drive the wind farm computations. The mesoscale WRF simulations were validated against the NYSERDA buoy measurements (Fig. 2) recorded on May 15, 2020 (see Ref. [2]). The results indicate the presence of a strong noselike feature characteristic of an LLJ at approximately 100 m from the ground. The mesoscale simulations in WRF were done 48 h before the target date of May 15, 2020, to allow there to be warm-up simulations. Additionally, in the same spirit of removing

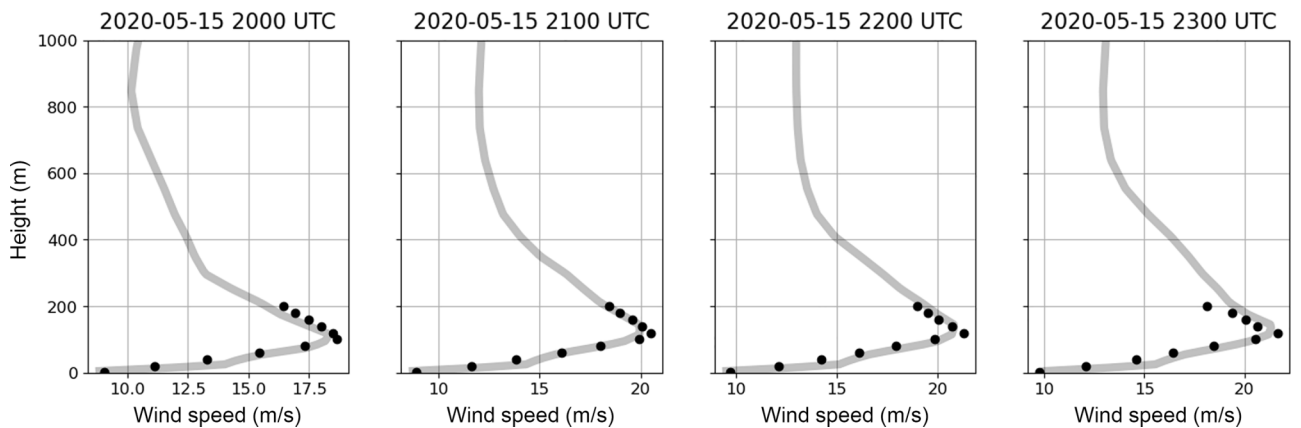


FIG. 2. Validation of horizontally and 10 min averaged WRF simulations (solid lines) depicting a coastal LLJ against 10 min averaged southeast floating lidar buoy (E06) measurement campaign (NYSERDA; symbols) in the New York Bight region on May 15, 2020. Uncertainty in measurements approximately 3.3% [35]. UTC, Coordinated Universal Time.

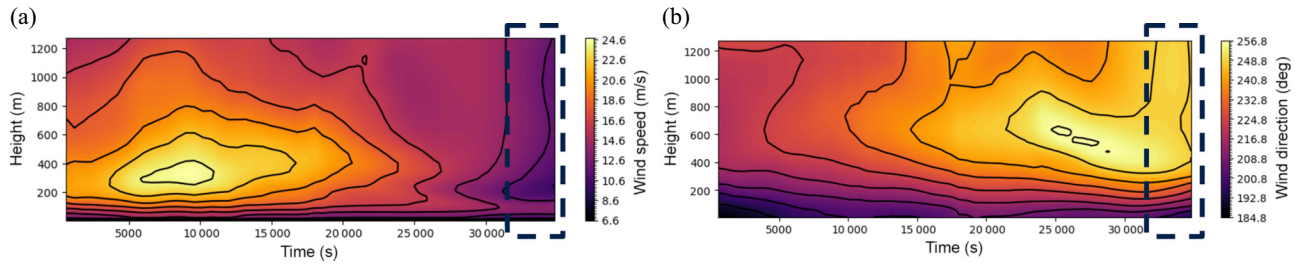


FIG. 3. Time-height contours of (a) wind speed and (b) wind direction in mesoscale forced LES of coastal LLJ simulations. The black-dashed box indicates the 30 min region of interest for wind farm simulations.

spurious transience, mesoscale forcing-driven LES was done 12 h ahead of the data collection region. Consequently, in the nonstationary time-varying flow field of the coastal LLJ, a 30 min window is chosen from the precursor LESs as in Fig. 3, where the averaged wind speed is relatively flat (time stationary) and is used to drive the wind farm simulation (see Appendix A). Figure 4 depicts 30 min time-averaged and horizontally averaged statistics profiles of the precursor ABL of the coastal LLJ compared against a convectively unstable boundary layer representative of the daytime onshore conditions (MS) [48]. The coefficient of variation of the statistics profiles for the LLJ and MS simulations in the 30 min region is less than 1% in both cases, and thus the flow can be considered stationary for all practical purposes. Note, the first 10 min of the wind farm simulations is ignored in the statistical wake, power, and load analysis to remove numerical

transience in the data. Moreover, the horizontally averaged WRF simulations (see Appendix A) have illustrated the detection of the LLJ jet nose at a spatial extent of approximately $O(100)$ km and on a timescale of 6 h; hence, it is physically well justified to assimilate horizontally averaged WRF data in a much smaller ($10 \times 10 \text{ km}^2$) fine-scale LES domain for analysis purposes.

To understand the turbine response to the unique features of the LLJ, namely, the triple shear structure and mean veer, a baseline case has been constructed that encapsulates the absence of these strong features for context. A monotonically sheared convectively unstable boundary layer with nominal shear (representative of the IEC-61400-3 standard for DLC simulations [36]) is a good candidate for that. Additionally, the precursor MS case was designed such that the free stream hub height and rotor-averaged velocity, hub-height wind direction, and hub-height TI are

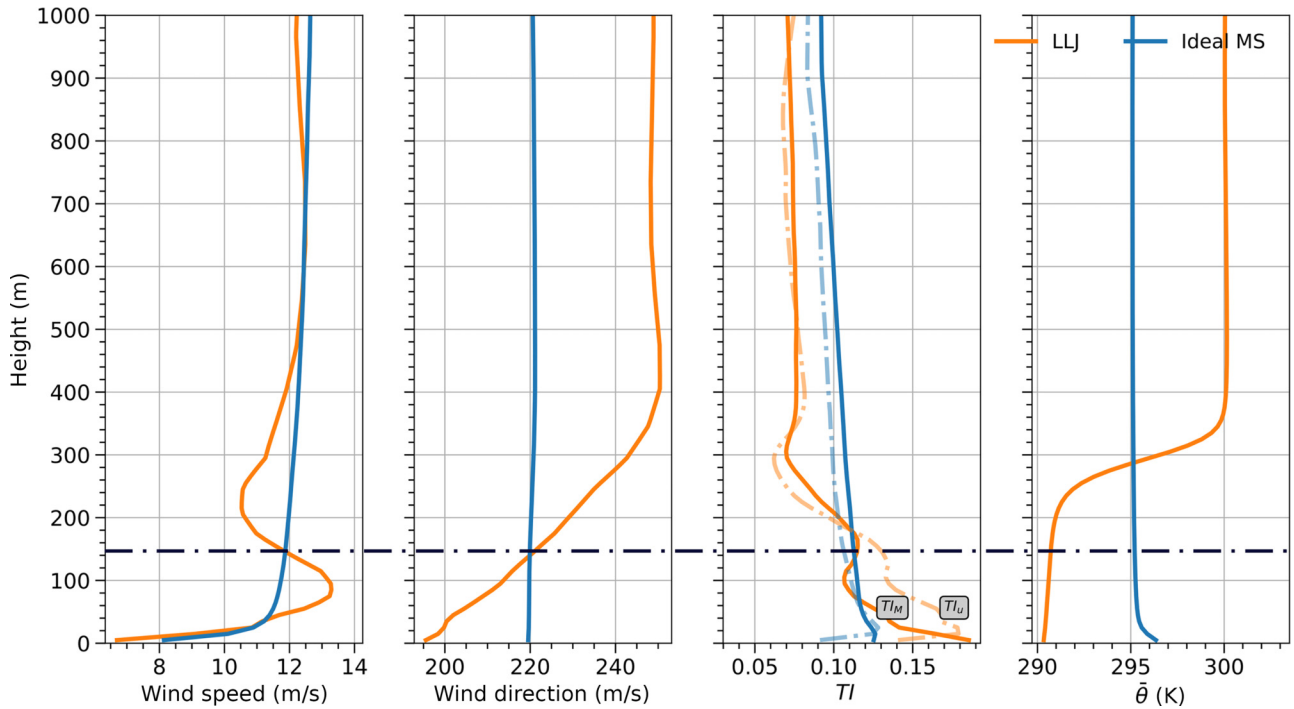


FIG. 4. Comparison of statistical profiles of wind speed, wind direction, turbulence intensity [TI_M (solid lines) and TI_u (dashed-dotted lines)], and potential temperature θ for the precursor ABL. The black-dashed line represents $z = z_h$ (hub height).

TABLE II. Comparison of time-averaged (20 min window) integrative quantities and hub-height winds of the baseline MS and coastal LLJ cases. Wind speed, wind direction, TI_M , and TI_u are defined at hub height $z = z_h = 150.0$ m.

Case	z_i (m)	Q (m K/s)	u_* (m/s)	w_* (m/s)	L (m)	Wind speed (m/s)	Wind direction (deg)	TI_M	TI_u
MS	1214.72	0.19	0.247	3.129	-66.66	11.86	219.93	11.2	9.58
LLJ	376.34	-0.01403	0.555	-0.07	77.14	11.75	220.50	13.07	13.07

same as in the LLJ case (see Table II) for comparison purposes. Note, in this process the rotor-averaged shear and lateral streamwise velocity gradients of the coastal LLJ are very similar to those in the baseline MS case (shown in Sec. III B). The choice of these metrics is driven by the fact that, per IEC standards, wind speed, shear, and turbulence intensity guide the fatigue load design (turbine life) of wind turbine components. This comparison gives us a great opportunity to respond to the following question: Given the free stream wind speeds and TI approaching the hub height remaining same, would an LLJ give a markedly different aerostructural response compared with the MS case? It turns out that the differences are conspicuous despite engineering wake models based on hub-height information [55] not being able to differentiate between the two flow cases. As we will see later, the loads can be primarily attributed to the unconventional shear, veer profile, and lateral gradients in the wind condition and the stable stratification of the ABL in the LLJ event (see Fig. 5). However, it is important to understand that the daytime onshore wind condition is not the only representative condition that can be compared against the coastal LLJ. Other canonical boundary layers, such as stably stratified offshore conditions with comparable shear and veer, can also be considered for differentiating an “LLJ” event from a “non-LLJ” event (e.g., differences in the TI behavior in the rotor and tower region). Additional efforts for comparison can also encompass matching rotor-averaged wind speeds in the first turbine row (decouples

the induction/blockage effect) or opening up more possibilities by matching LLJ jet-nose wind speeds, such that the wind turbines for the LLJ and MS cases can operate in different controller regimes. These comparisons would entail different free stream wind conditions approaching the wind turbines and hence a different nominal controller response in the first row of turbines. Some of these comparisons are envisioned to be done as part of the future effort with a smaller and computationally less demanding wind farm setting. We match the TI for the ABL at hub height, and have used the definition that is consistent with that used by the wind resource assessment community, or $TI_M = \sqrt{M'M'}|_T/\bar{M}$, where $M = \sqrt{u^2 + v^2}$ and $|_T$ denotes time average. We have also compared turbulence intensity based on streamwise velocity, $TI_u = \sigma_u/\bar{U}_{\text{hub}}$, as prominently used by the boundary layer community, for reference. However, in the subsequent sections we use the definition of TI as $TI_{AD} = \langle \sigma_u \rangle_{AD}/\bar{U}_{\text{hub}}$, which is also conventional within the wind turbine and wind farm community, and is henceforth used for qualitative correlation with the wind turbine loads. The $\langle \rangle_{AD}$ (actuator disk or rotor-averaged and time-averaged) quantity absorbs the variation in the rotor region and thus serves as a perfect flow metric for correlation with the load performance. σ_u is the standard deviation of the velocity component in the wind direction at each height z . We observe that shear $\alpha = dM/dz$, $M = \sqrt{u^2 + v^2}$, in the MS case is strictly positive within the entire boundary layer, while the LLJ manifests a strong triple shear structure in the rotor region (two sign changes of α). Additionally, owing to its strong stable nature of the ABL, the LLJ has high mean wind veer (more than 40°) across the rotor as opposed to less than approximately 5° in the MS case. Strong gradients of TI_u in the rotor region, accompanied by higher near-wall TI_u (approximately 15%), are also a characteristic feature of the mesoscale-driven LLJ, in line with what was observed with strong baroclinicity in stable boundary layers [39,50] but not observed in synthetic LLJ simulations [37]. Finally, the potential temperature profile indicates that the LLJ has a shallow capping inversion layer as compared with the MS case, where the capping inversion layer is pushed more than 1 km from the ground by the buoyant convective plumes. Table II compares the integrative quantities u_* (friction velocity), w_* (buoyancy velocity), z_i (inversion height), L (Monin Obukov length scale), and Q (kinematic heat flux), and the wind conditions at hub height ($z = z_h = 150$ m), including wind speed, direction, and

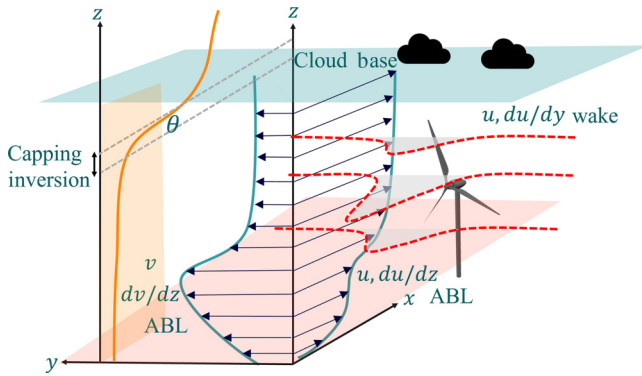


FIG. 5. Mean ABL inflow and wakes as it intercepts the wind turbine. u , dominant wind direction, v , cross-flow. θ , potential temperature.

TI. The inversion height is calculated as $z_i = z|_{\langle w'\theta' \rangle_T=0}$, where $\langle \# \rangle$ denotes horizontal average. Also, $u_* = \sqrt{\tau_w/\rho}$, where τ_w is the wall shear stress, ρ is air density, and $w_* = \text{sgn}(Q)((g/\theta_0)|Q|z_i)^{1/3}$, where $\text{sgn}(Q)$ is the sign of kinematic wall heat flux. For the coastal LLJ, $z_i/L = 5.25$, while for the MS case, $z_i/L = -22.27$. This indicates that the coastal LLJ is a weakly stable ABL, while the MS case is a strongly unstable ABL.

B. Wind farm simulations

We illustrate the flow field from the wind farm simulations in this section. For brevity, all the coordinate axes in the plots have been normalized by the turbine diameter D , the hub height z_h , and the first row turbine location x_{WTG0} as deemed necessary. Consequently, $(z - z_h)/D = 0$ corresponds to the hub height of the turbines and $(x - x_{\text{WTG0}})/D = 0, 5, 10, 15, 20$ are the five stream-wise pad location rows for each of the four array of wind turbines. Figure 6 shows the instantaneous x - z plane of the second turbine array and the rotor plane view of wind turbine wakes driven by coastal LLJ atmospheric conditions. We observe small-scale turbulence, deep wakes, and a highly skewed ellipsoidal wake structure (similar to what is seen with yaw-misaligned turbines) [56] in the LLJ case, where turbulence is dominated by stable stratification [56]. These structures are a demonstration of strong wind veer owing to Coriolis forces and were demonstrated earlier in field experiments [57] and simulations [58]. The coastal low-level jet also has high TI in the rotor region, unlike the canonical stable ABLs, and is primarily being augmented via down-fluxes from the atmospheric residual layer. A recent study [59] predicted the presence of low TI (less than approximately 5%) in extreme coastal LLJ events in the North Sea. However, the coastal LLJ simulations in the current work, validated against the NYSEDA

buoy observations (see Ref. [2]), are a clear testimony of a markedly different mesoscale phenomenon owing to its high hub-height turbulence intensity (greater than 10%). The wake structures and their evolution are also clearly distinguishable from the more canonical cases (e.g. near neutral cases) commonly used for wind resource assessment and AEP calculations in the wind energy industry. The evolution of the coastal LLJ wind profile is better understood in Fig. 7. The footprint of the “jet nose” seen in the induction region is only potentially recovered downstream of the farm, with embedded effects of “wake deficit” still persisting owing to stable stratification. While the literature has indicated complete elimination or upward shift of the LLJ nose in large farms [60], this was not observed in the current layout of finite size. Nonetheless, we have observed flow signatures indicating “weakening of stratification,” which are demonstrated later. Figure 8 captures the transverse wake structure evolution complementing Fig. 7 to illustrate the three-dimensional evolution of wakes. It clearly indicates the influence of “wake meandering” in the mean footprints for the MS case—illustrated by the drift of wake centers. The lack of meandering in the LLJ case is another feature complementing the “deep wake” effects that influences the strong power losses in the turbines. The horizontal wind speed is complemented by the vertical wind speed comparison at the streamwise locations. The plot illustrates that despite the stronger wake deficits in the coastal LLJ, the vertical wind speeds at hub height are not greater (compared with MS case). This is surprising, and points out that for mass conservation to be valid in the simulation domain, vertical velocity fluxes (in this case down-fluxes from the top of the farm) must play a critical role in the farm flow. Similar observations are also documented in Figure [37]. Another interesting angle is that Fig. 8 further illustrates the pressing need for analyzing rotor-averaged statistics for power and load

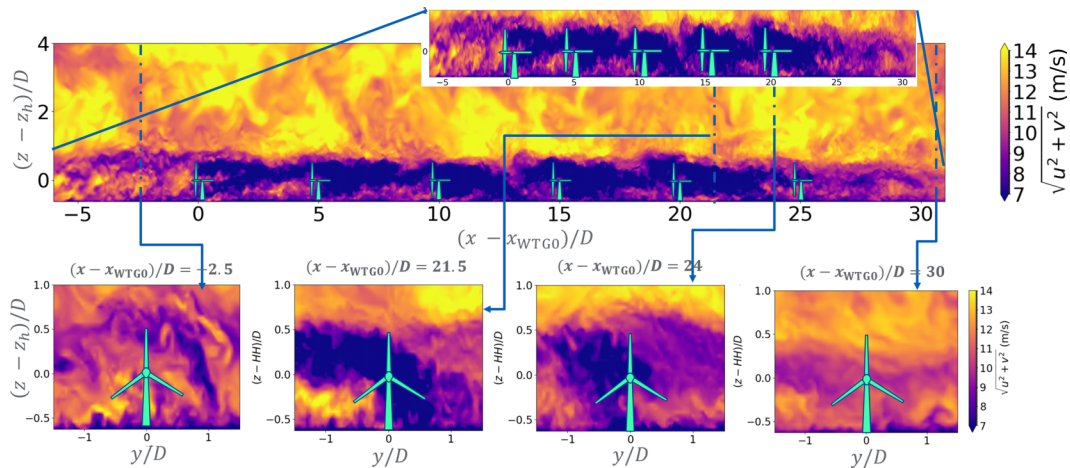


FIG. 6. Time snapshot of WRF-LES simulation of a coastal LLJ driving a 5×4 layout of a wind farm. Sideways or x - z plane and four y - z or upstream or downstream planes of rotor locations are shown. The x - z plane shows the LLJ velocity profile upstream of the turbine.

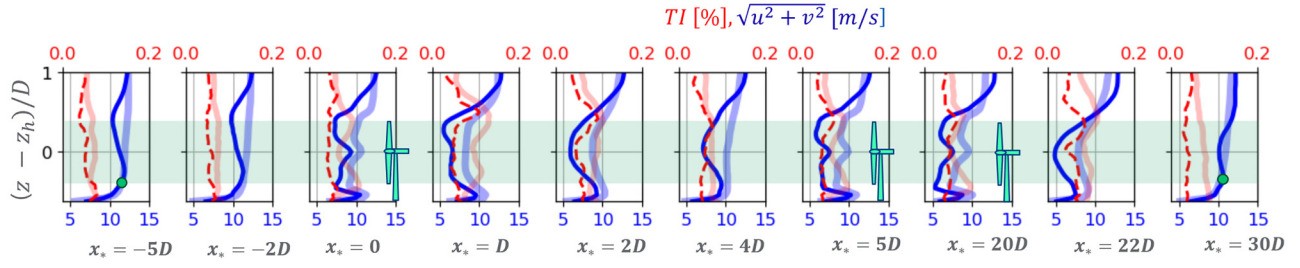


FIG. 7. Time and array averaged profiles of $\sqrt{u^2 + v^2}$ and TI at different streamwise stations: $x_* = (x - x_{WTG0}) = -5D, -2D, 0, D, 2D, 4D, 5D, 20D, 22D, 30D$. Green shaded areas correspond to the region of the rotor. Green turbines indicate the location of turbine rows. Green circles indicate the peak location of the coastal LLJ nose. Transparent blue lines represent the reference canonical MS (convectively unstable) velocity profile.

analysis, since the hub-height data “deceptively” do not contain footprints of velocity gradient information, which, we will see later, is critical for many turbine component loads. In this section we begin building a robust mathematical foundation of our analysis by defining certain flow features of the turbulent ABL that have a direct influence on the loads. For rotor/blade or hub loads, we define the rotor-averaged and temporally averaged velocity as $\langle U \rangle_{AD} = \left(\int_{z_h-D/2}^{z_h+D/2} \sqrt{u^2 + v^2}(x, y = y_c, z, t) dz \right) |_T [u, v \gg w$ (vertical velocity)], where $|_T$ denotes time-averaged data. The normalized shear is defined as $du_*/dz_* = \langle du/dz \rangle_{AD} D / \langle U \rangle_{AD}$ (u is the velocity in the dominant

wind direction). Similarly, the veer can be defined as $d\phi/dz_* = D \langle d\phi/dz \rangle_{AD}$, where ϕ is the angle the wind vector makes with the dominant wind direction. These definitions ensure that the variables shear and veer are mathematically not coupled and can be treated as independent contributors to turbine loads. Finally, we define $\langle TI \rangle_{AD} = \sqrt{u'^2} / \langle U \rangle_{AD}$, where $u'(x, y = y_c, z, t) = u(x, y = y_c, z, t) - \bar{u}(x, y = y_c, z) |_T$. From the flow-field data, we have established that the line-averaged data in the rotor region $(1/D) \int_{z_h-D/2}^{z_h+D/2} () dz$ are consistent with the conventional rotor-disk-averaged data $(4/\pi D^2) \iint_A () dA$, where A is the disk area corresponding to the region

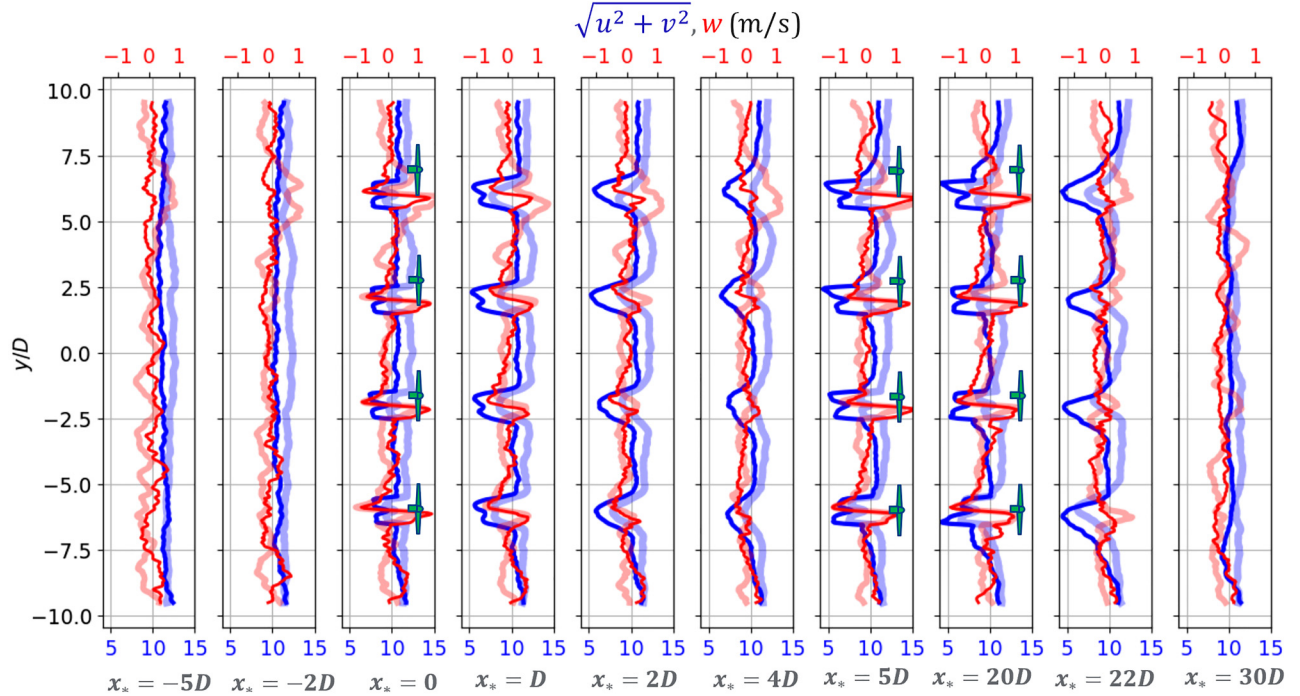


FIG. 8. Spanwise variation of time and array averaged horizontal wind speed $\sqrt{u^2 + v^2}$ and vertical velocity w at different streamwise stations: $x_* = (x - x_{WTG0}) = -5D, -2D, 0, D, 2D, 4D, 5D, 20D, 22D, 30D$. Green turbine indicate the location of turbine rows. Transparent blue lines represent the reference canonical MS (convectively unstable) velocity profile.

$(y - y_{\text{WTG}}^i)^2 + (z - z_h^i)^2 < 1$. Here x_{WTG}^i , y_{WTG}^i , and z_h^i are the pad locations of the turbines in the farm, where $x_{\text{WTG}}^0 = x_{\text{WTG}0}$ and $z_h^i = z_h = 150$ m for all $i = 0, \dots, 19$. The line-averaged surrogate of rotor-averaged data is particularly beneficial in terms of working with planar data in turbine pad locations instead of postprocessing three-dimensional data around the wind farms. Note for analysis of turbine tower loads, the definition remains the same, except the rotor-averaged entities would now be replaced with the tower average, $\langle \rangle_t = (1/z_h) \int_0^{z_h} () dz$. Figure 9 illustrates the rotor-averaged flow statistics for the coastal LLJ event, and they are compared against statistics for the MS case for reference. Coastal LLJs have strong induction regions and wake deficits in the rotor region (compared with the MS case), and stable stratification limits the augmentation of TI_{AD} in the downstream turbine pads. The presence of strong positive and negative shear profiles in the coastal low-level jets is translated to quasizero rotor-averaged shear along with strong “*negative rotor-averaged shear bursts*” due to rotor interception. Strong mean veer characteristics of the shallow boundary in the coastal LLJ is also prominent in the wind farm. Additionally, turbine rotor presence causes slight veer reduction (by approximately 15°) in the farm interior, indicating the local weakening of the stratification effect. We further document the standard deviation for fluctuations of the normalized shear and veer through the error bars in Fig. 9. As we will see later, the pad-location evolution of the shear and veer standard deviation dictates certain damaging fatigue loads to a great extent. Figure 10 shows statistical features in the tower-averaged sense. Strong velocity deficits are observed in

the LLJ similarly to those observed in the rotor-averaged cases, followed by augmentation in the turbulence intensity. The strengths of the deficits and augmentation are slightly lower than in the rotor-averaged cases owing to the lower “blockage effect” of the tower compared with the rotor. In the tower region, high positive shear is captured for the LLJ, since more than 60% of the tower is in the positive shear region of the LLJ wind. Additionally, even in the tower region, the LLJs demonstrate a significant amount of veer (approximately 25°). However, owing to the dominance of atmospheric surface layer turbulence, the unstable boundary layer (MS) near the ground has a very high standard deviation in the wind direction, despite zero mean veer. Note that the tower-averaged statistics have direct implications for the tower fore-aft and side-side mean fatigue loads.

IV. TURBINE POWER AND LOAD ANALYSIS

A. Statistical load analysis

In this section we perform statistical analysis of the generator power and control parameters as well as blade, hub, and tower loads of the different wind turbines in the farm layout. Although the large eddy simulation-coupled aeroelastic simulations generate time series from multiple load sensors for the entire turbine system, for the purpose of analysis we restrict ourselves to two representative bending loads each at the turbine rotor, hub, and tower. In particular, we have highlighted the fatigue [damage equivalent loads (DELs)] as well as the ultimate (maximum) loads for the turbines. While the mean loads are directly correlated with the wind flow characteristics, the DELs and the maximum loads are most

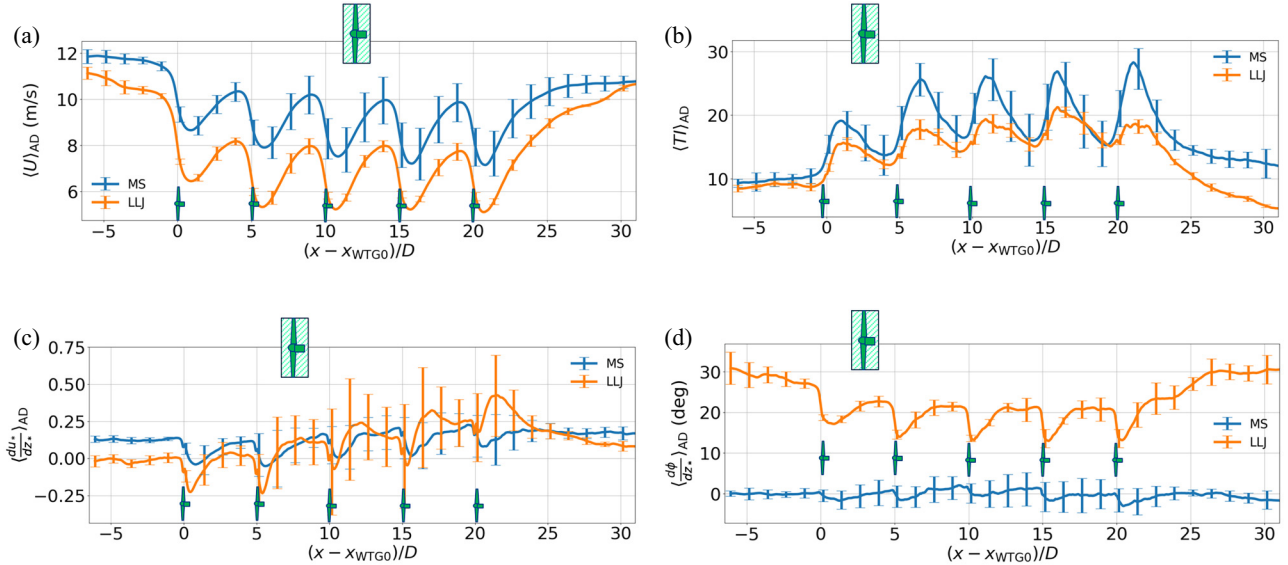


FIG. 9. Comparison of time, array-averaged and rotor averaged (a) wind speed, (b) TI, (c) normalized shear, and (d) normalized veer for LLJ and MS cases. Error bars represent the standard deviation in time. Turbine row locations: $(x - x_{\text{WTG}0})/D = 0, 5, 10, 15, 20$. $x = x_{\text{WTG}0}$ for the first row of turbines.

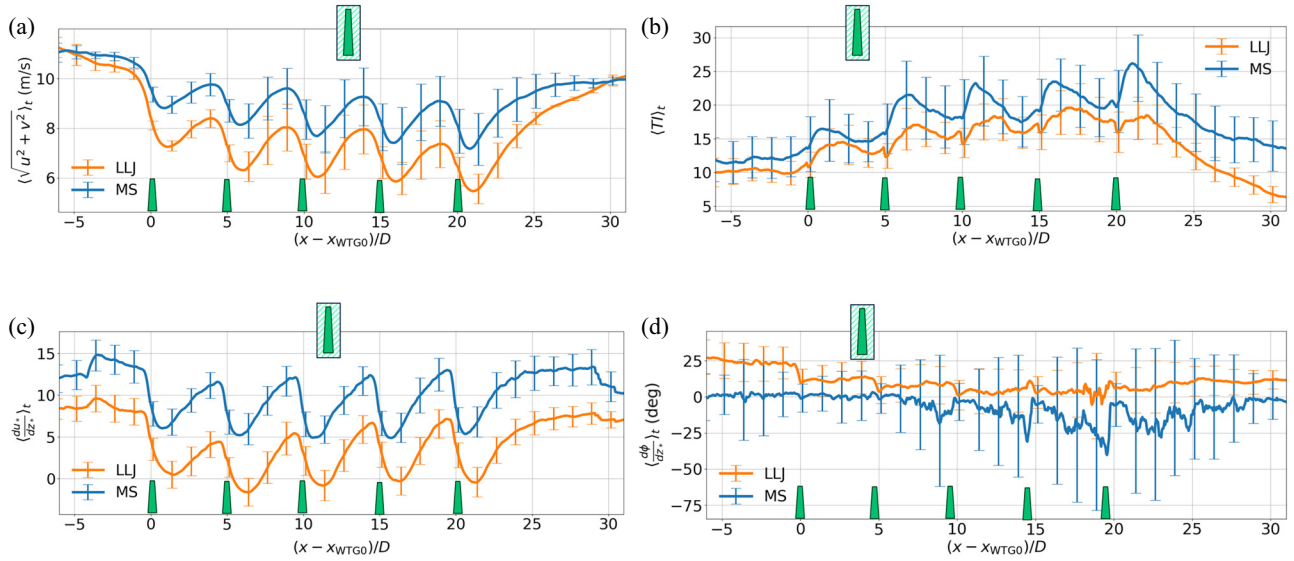


FIG. 10. Comparison of time and array-averaged hub-height and tower-averaged velocities for LLJ and MS cases. Error bars represent the standard deviation in time. Turbine tower row locations: $(x - x_{WTGO})/D = 0, 5, 10, 15, 20$. $x = x_{WTGO}$ for the first row of turbines.

relevant to the industry since they are directly tied to turbine damage (fatigue and ultimate stress failure). Figure 11 illustrates the deep-wake evolution of the farm driven by the coastal LLJ and the mean controller response at the turbine pads. Even though the wind speed in the first row is above the rated condition for the turbine and invokes pitch control ($\beta_m > 0^\circ$), the subsequent rows in the downstream face wind speeds significantly below the rated conditions. This results in the farm activating to torque control with the pitch at a fine-pitch setting ($\beta_m = 0^\circ$). The first-order effect due to “deep wakes” is on generator power and rotor thrust, as illustrated in 12. Because of deep wakes, the power drops to around 50% in the last row of turbines, accompanied by approximately 25% increase in power variability. In a similar spirit, the drop

in the rotor thrust documented is approximately 10% in the last row, with approximately 20% more variability. The variability in power and thrust downstream mainly comes from the augmented turbulence from the turbine pads with slower decay due to lack of wake mixing. A similar power drop at the farm level was also documented previously [37] for synthetic LLJs with jet nose lower than the hub height as in the current setting. The turbine load analysis is introduced in the current section by our first providing a schematic (Fig. 13) of how the different features of the wind affect the different turbine component loads. The schematic clearly indicates that while the wind speed pushes the wind turbine rotor and tower and hence contributes to the rotor flapwise and tower fore-aft loads, the vertical gradients d/dz in the velocity or velocity direction

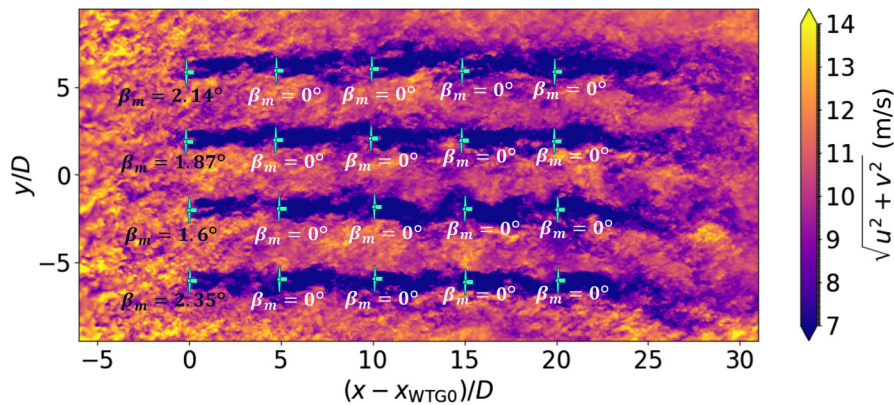


FIG. 11. Time snapshot planar view of wind turbine wakes driven by coastal low-level jets. Turbines are labeled by mean blade-pitch angle owing to the controller response.

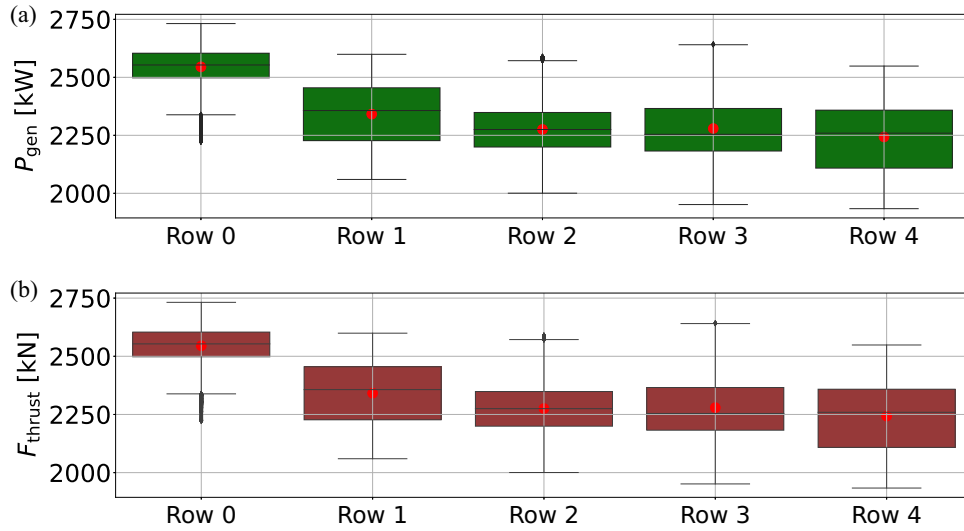


FIG. 12. (a) Categorical box-and-whiskers plots showing the variation of array-averaged (a) generator power and (b) rotor thrust vs the row number in the wind farm with a coastal LLJ.

are responsible for the rotor-imbalance loads as manifested in the low-speed shafts. It is also important to differentiate the load results by categorizing them into (a) loads in the *first row of turbines (effect of unique LLJ flow profile)* and (b) *loads in the subsequent rows (major effect of atmospheric/thermal stratification on the deep wakes)*. We identify that (a) is correlated only with the vertical gradients d/dz influenced primarily by the ABL evolution (as shown in the schematic), while (b) is correlated

with the spanwise/lateral gradients d/dy as well as vertical gradients d/dz caused primarily by “wake effects” downstream. Consequently, the wind turbine loads can be expressed as a function of several flow features across the rotor (and/or tower) and can be mathematically written as $\mathcal{L} = f(\langle U \rangle_{\text{AD}}, \langle du_* / d\eta_* \rangle, \langle d\phi / d\eta_* \rangle, \langle TI \rangle_{\text{AD}}, \langle \sigma_{du_* / d\eta_*} \rangle_{\text{AD}}, \langle \sigma_{d\phi / d\eta_*} \rangle_{\text{AD}})$, where $\eta = y, z$. Here $*$ denotes normalization, $u_* = u / \langle u(z = z_h) \rangle_{\text{AD}}$, and $z_* = z / D$. While $\langle U \rangle_{\text{AD}}$ is the primary driver for the mean loads $\mathcal{L}$, $\langle TI \rangle_{\text{AD}}$ contributes

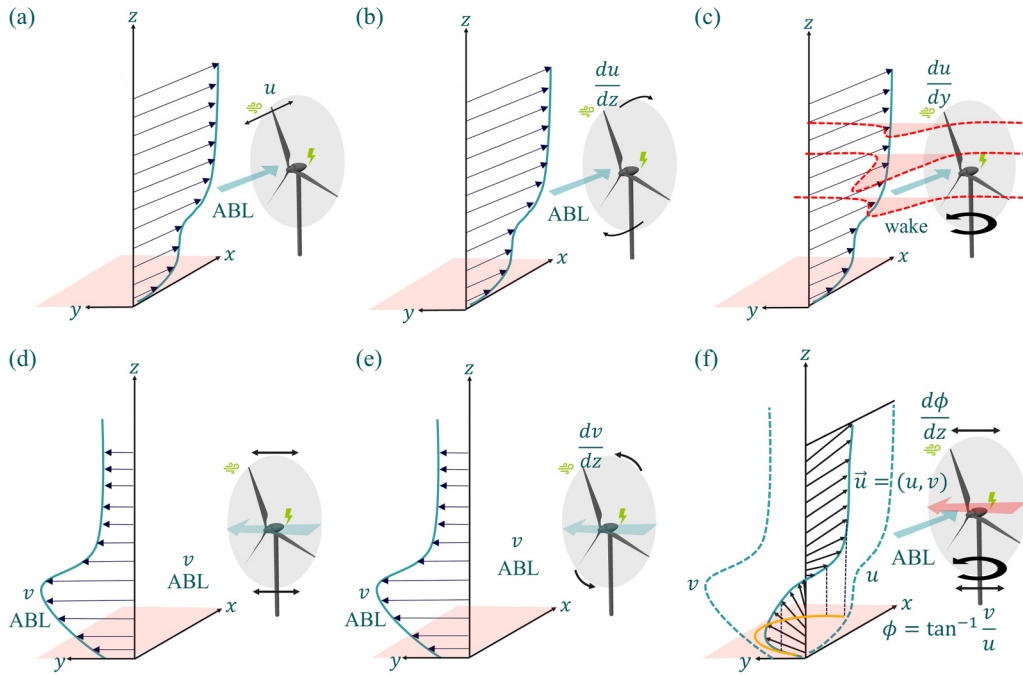


FIG. 13. Causality of the load response in wind turbines corresponding to the different flow characteristics in the coastal LLJ wind condition: (a) u , out-of-plane/flapwise vibrations; (b) du/dz , out-of-plane rotor imbalance/shaft bending; (c) du/dy , twist/torsion; (d) v , in plane/edgewise vibrations; (e) dv/dz , in plane/edgewise vibrations; (f) $d\phi/dz$, in plane/edgewise and twist/torsion.

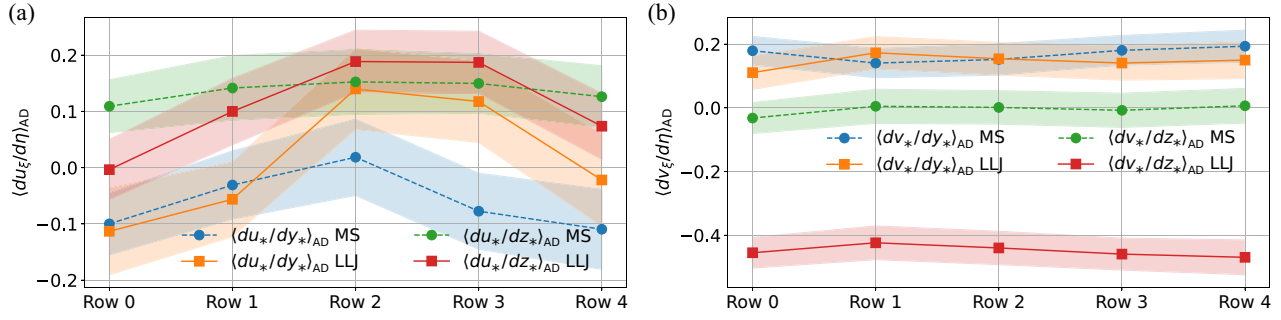


FIG. 14. Pad-level rotor-averaged velocity gradients for the coastal LLJ case and the convectively unstable MS case. (a) $\langle du_*/d\eta \rangle_{AD}$ and (b) $\langle dv_*/d\eta \rangle_{AD}$, where $\eta = y, z$. Colored regions correspond to $\pm \frac{1}{4}\sigma(\langle du_*/d\eta \rangle_{AD})$ and $\pm \frac{1}{4}\sigma(\langle dv_*/d\eta \rangle_{AD})$.

to the fluctuating loads $\mathcal{L}'$, which can cause fatigue damage to the turbine systems. Figure 14 shows a comparison of the pad-level rotor-averaged normalized vertical and lateral gradients of the velocity field d/dz_* , d/dy_* for the coastal LLJ and convectively unstable cases. The gradients $\langle du_*/dy_* \rangle_{AD}$, $\langle du_*/dz_* \rangle_{AD}$ of the dominant wind direction u show strong variations in the rowwise direction that demonstrate that u plays a dominant role in the streamwise variation of the loads due to wake effects. Similarly to what is observed in Fig. 9, the gradient plots for v also illustrate the effect of veer $\langle dv_*/dz_* \rangle_{AD}$ or lateral gradients $\langle dv_*/dy_* \rangle_{AD}$. These pad-level plots serve as a reminder that while the vertical gradients d/dz in the first row are unique to the ABL physics, the gradients d/dz and d/dy are inherently coupled and “modulate” each other in the downstream turbines. However, for the sake of load analysis, and correlation with flow features, we simplify the connection to loads with the velocity field and mostly the vertical gradients, which will contain enough information about the wake physics.

Figures 15–17 illustrate the standard deviation, DELs, and maximum loads of the turbine system for the coastal LLJ. The results are compared against the results for reference convectively unstable case for context. Additionally, we see that certain turbine system loads are also triggered by the shear (du_*/dz_*), the veer ($d\phi/dz_*$), and their fluctuations or standard deviations (σ_{du_*/dz_*} , $\sigma_{d\phi/dz_*}$). The turbine loads can be broadly categorized into the blade loads (edgewise, flapwise, and torsion), tower loads (fore-aft, side-side, and twist), and the hub loads (low-speed shaft and yaw-bearing system). For offshore turbines the low-speed shafts from the rotor hub are connected to the generator via a direct drive without the need for a gearbox. So, technically “low-speed shaft” and “high-speed shaft” refer to the same turbine element in the context of the IEA 15 MW turbine [61]. For this paper, we have focused on the standard deviation and maximum loads, standard deviation $\mathcal{L}$, max $\mathcal{L}$, as well as the DELs, which are crucial for understanding fatigue damage. Mathematically, the DEL

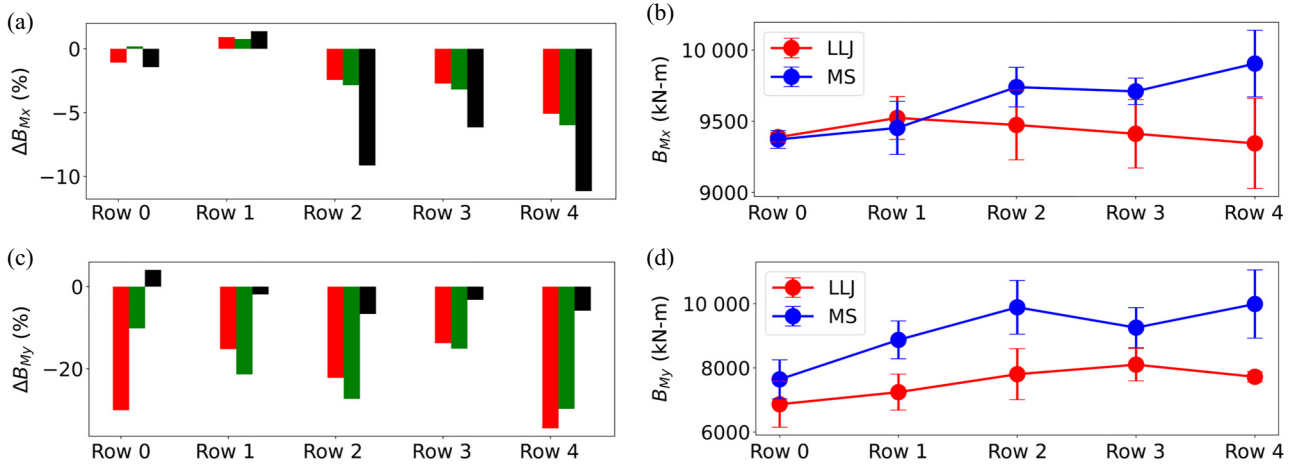


FIG. 15. Comparison of array-averaged relative load statistics (left) and array-averaged DEL statistics (right) of blades for the coastal LLJ and baseline MS cases for a 20 turbine farm layout. In (a),(c) red represents the standard deviation, green represents the DEL, and black represents the maximum load. Error bars in DELs represent the standard deviation of the DEL across four arrays (cross-wind direction). (a),(b) Blade edgewise moment and (c),(d) blade flapwise moment.

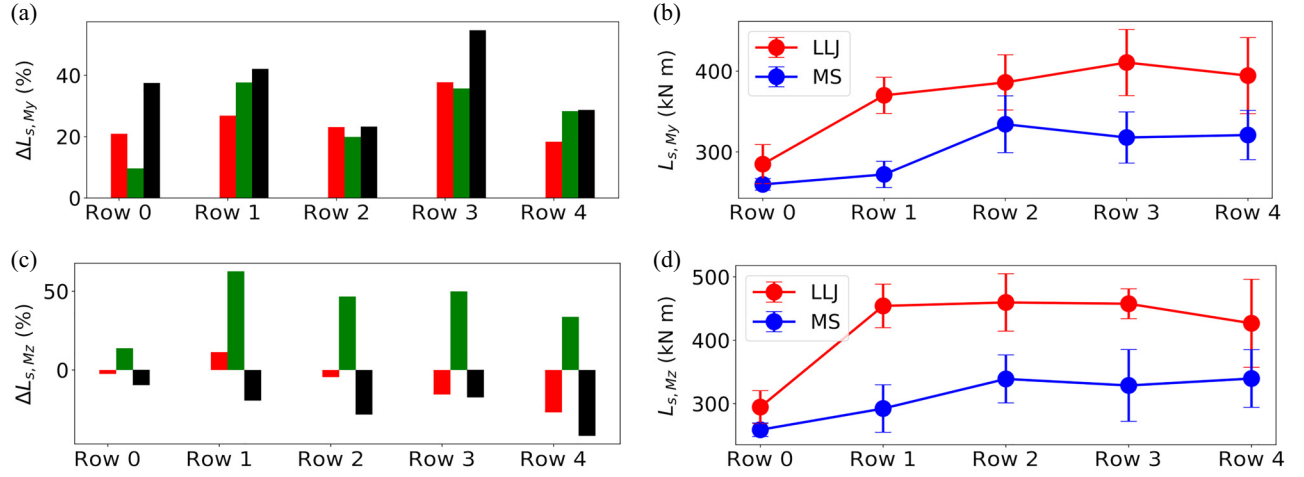


FIG. 16. Comparison of array-averaged relative load statistics (left) and array-averaged DEL statistics (right) of blades for the coastal LLJ and baseline MS cases. The colors in the bar chart and the error-bar definitions are same as in Fig. 15. (a),(b) Rotating low-speed shaft bending moment in the direction of gravity and (c),(d) rotating low-speed shaft bending moment in the direction of the ground.

is defined as

$$\mathcal{L}_{\text{DEL}} = \frac{(\sum_{i=0}^N n_i R_i (n_i)^m)^{1/m}}{n_{\text{eq}}}, \quad (1)$$

where a load is composed of several load ranges R_i for all $i \in 0, \dots, N$ and the corresponding number of cycles n_i to fatigue damage. The DEL in Eq. (1) is an equivalent load range corresponding to $n_{\text{eq}} = 10^6$ cycles, which would give the same fatigue damage as the actual load. The fatigue damage corresponding to load range R_i is $n_i R_i^m$, where m is the Wöhler exponent empirically obtained from the material's Wöhler curve [62]. For blades, $m = 12$, while for the hub and tower loads,

$m = 4$ is used for the DEL calculations reported herein [61].

Figure 15 shows the statistics of the blade root edge-wise (B_{Mx}) and flapwise (B_{My}) moments. While we have illustrated the root loads of one blade, the results are statistically similar for blades 2 and 3 and hence are not considered in the analysis for brevity. (Statistical and spectral analysis further indicates that the blade moments and the rotor thrusts are morphologically similar). Note that the bar chart depicts the relative difference between the loads for coastal LLJ and unstable MS conditions normalized by the loads of the first row of turbines in the coastal LLJ environment. The standard deviation, DELs, and the maximum loads have similar decreasing trends in

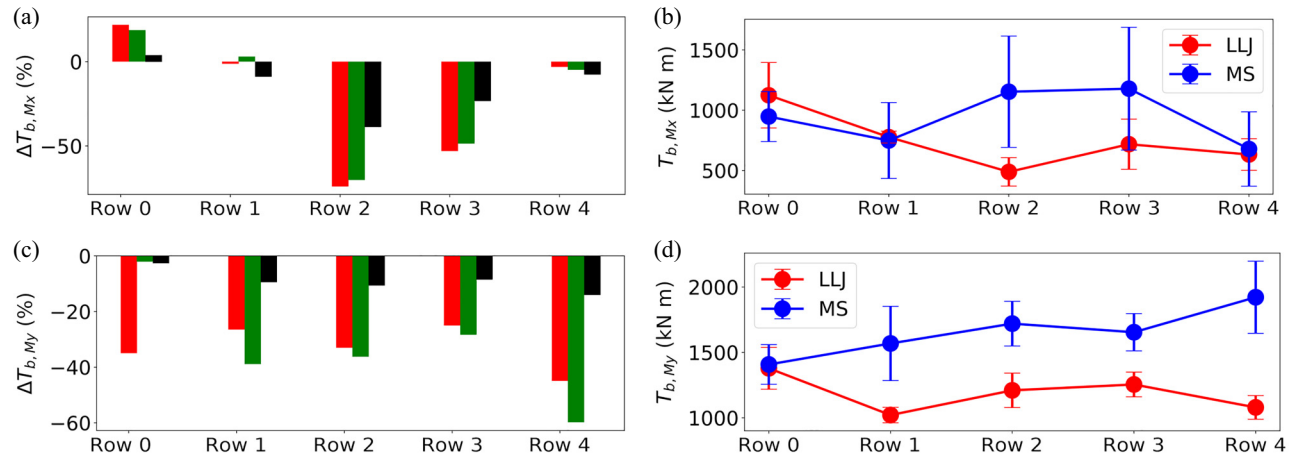


FIG. 17. Comparison of array-averaged relative load statistics (left) and array-averaged DEL statistics (right) of blades for the coastal LLJ and baseline MS cases. The colors in the bar chart and the error-bar definitions are the same as in Fig. 15. (a),(b) Tower side-side moment and (c),(d) tower fore-aft moment.)

the downstream rows for the edgewise case, and the loads are 10%–20% lower than in the MS case in the downstream farm direction. The flapwise root moments also indicate that the standard deviation and DELs due to the coastal LLJ are approximately 20% lower than in the MS cases in the downstream turbines. Note the maximum loads manifest similar trends with the standard deviation and DELs for flapwise moments. The streamwise variation of the DEL rotor flapwise loads for the LLJ case increases downstream owing to the augmentation of TI , but the loads are lower than in the MS cases owing to weaker augmentation of turbulence intensity due to the stable stratification of the atmosphere. The growth of DELs in the LLJ case for the edgewise moments is not so apparent, because more than TI , the structural participation of the blades (e.g., from periodic gravity loading and the effect of the cross-wind component) plays a dominant role in dictating the response. It must be noted that the lower standard deviation of veer (Fig. 9) also aids to some degree in the lower edgewise DELs. In Fig. 16 we illustrate the bending moments in the direct drive shaft of the turbine connected to the generator. The lateral bending moment $L_{s,My}$ causes the shaft to bend in the direction of gravity. The standard deviation, DELs and maximum loads manifest similar trends and show that the fatigue bending moments grow downstream by as much as approximately 40%. The bending moment is caused by the imbalance of the loads in the rotor region, and can thus be directly attributed to the “wind-shear” (du_*/dz_*) effect. In particular, strong variations in the shear at turbine-pad locations σ_{du_*/dz_*} for the coastal LLJ play a significant role in the high fatigue bending moment $L_{s,My}$ in the downstream turbines. For the bending moment $L_{s,Mz}$ (bending in the same plane as the ground), the wind farms in coastal low-level jets display higher DEL bending loads downstream in the farm. This is a surprising fact since the standard deviation and maximum loads show opposite trends for the coastal low-level jet scenario and are lower than in the MS case. Lower standard deviation loads can be tied to the lower standard deviation of veer (rotor region) in the farm compared with the MS case. However, despite low veer, higher DELs for the LLJ case can potentially be further actuated by the higher mean and standard deviation of du/dy , which gives a lateral rotation effect. This also speaks of the structural participation in some format that triggers higher DELs for $L_{s,Mz}$. Further in-depth analysis is required to understand if the presence of strong mean veer itself or du/dy coupled to mean veer acts as a trigger to the vibration signatures/DELs in $L_{s,Mz}$. After evaluating the time series (not shown for brevity), we recorded bursts of low-amplitude and high-amplitude signals in $L_{s,Mz}$, and the high-amplitude signals contribute to the amplification of DEL owing to the term $n_i R_i (n_i)^m$ ($m = 4$). In a similar spirit, the tower loads are shown in Fig. 17. The tower fore-aft ($T_{b,My}$) and side-side ($T_{b,Mx}$) moments both display overall lower standard deviation, DELs, and maximum

loads than in the MS case. Additionally, the standard deviation and the DELs appear to have similar trends as well. The presence of lower TI and its lower augmentation in the tower region (Fig. 10) results in the lower fore-aft moments in the LLJ case. The lower shear variation in the tower region also aids the generation of lower fore-aft DELs compared with the MS case. More than the lack of strong veer in the tower region, the side-side moment $T_{b,Mx}$ is impacted by triggers to structural vibrations (Fig. 10). This behavior is very similar to the rotor edgewise vibrations. We identify that higher lateral gradients du/dy in the rotor region for the coastal LLJ do not contribute to the side-side tower top vibrations, even though higher DELs of tower torsional loads are reported (statistically similar to $L_{s,Mz}$). The statistical analysis clearly indicates that out-of-plane loads (rotor flapwise, tower fore-aft, shaft bending in the direction of gravity) are influenced by the flow quantities from the atmospheric boundary layer, while for the in-plane loads (rotor edgewise, tower side-side, shaft bending in the direction of the ground) the structural response of the aerodynamic loads plays a definitive role. Figure 18 illustrates the load envelope of the IEA 15 MW turbine obtained with DLC simulations for the worst-case scenario (fatigue and maximum loads). The current load conditions observed in the coastal LLJ environment are well within the limits of the load envelope. However, shaft loading is not part of the DLC portfolio, because most DLC calculations are done with nominal shear and veer. The present study shows the important effect of unconventional velocity gradients, e.g., shear, veer, and lateral gradients, and their temporal variation in the contribution of shaft loads and why DLC simulations need to be redesigned with wind conditions with the requirement of shaft load envelope documentation. The load analysis is further bolstered by the categorical violin plots (probability distribution of the loads) of the turbine system loads in Fig. 19. The differences in the probability density function (PDF) distribution in the first row are due to the uniqueness of the LLJ profile wind distribution (velocity, TI , shear, veer, etc.), while the subsequent rows show how these wind characterizations evolve under atmospheric stratification. The PDF

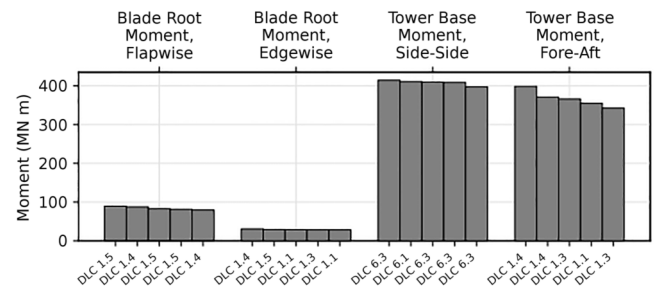


FIG. 18. Load envelopes obtained from design load simulations of the IEA 15 MW wind turbine [61].

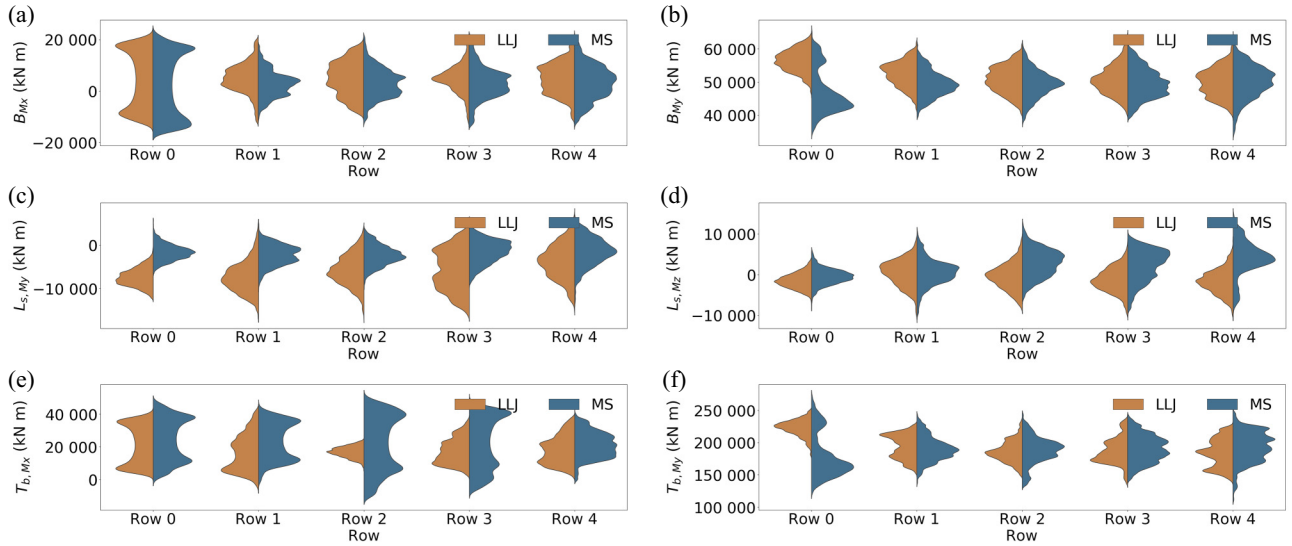


FIG. 19. Categorical violin plot depicting the probabilistic distribution of the loads for the coastal LLJ compared with the reference MS case. (a) Root edgewise moment, (b) root flapwise moment, (c) low-speed shaft bending moment y , (d) low-speed shaft bending moment z , (e) tower fore-aft bending moment, and (f) tower side-side bending moment.

distributions for blade flapwise and tower fore-aft loads in the *first row* are extremely similar (for the LLJ and MS cases) indicating how these loads are guided by the unique flow characteristics (wind-speed, TI). Additionally, since the wind speed and the TI are similar for the LLJ and MS cases, similar relative differences in the blade flapwise and tower fore-aft loads are also documented between these wind conditions. The root edgewise moment B_{Mx} , tower side-side bending moment $T_{b,Mx}$, and shaft bending moment $L_{s,Mz}$ clearly show a bimodal/unimodal distribution of the PDF in the first row, indicating the presence of oscillatory signals (vibrations). The downstream turbines deviate from modal characteristics of the loads to certain extents, indicating the importance of the flow variables (due to atmospheric conditions) as a guiding factor. With the increasing dominance of the structural response (mainly if the response is near resonance with the system's natural frequency), the effect of flow variables beyond wind speeds is not a decisive factor anymore.

B. Spectral load analysis

The load results are further analyzed in the spectral space, which provides valuable insights into the regions of turbulence-driven and structural-driven response. The importance of the spectral analysis is twofold: (1) it supplements the understanding from the statistical analysis of the loads and (2) it provide valuable insights that are critical toward designing load mitigation strategies in the controller [63,64]. All plots related to spectra have their y axis labeled as $\hat{F}(\text{load})$, where $\hat{F}$ denotes the fast Fourier transform (FFT) operation on the time series of loads. Figure 20 illustrates the spectral behavior of the

wind farms with the coastal LLJ environment for generator power. The results are compared with those in the MS case for context. For the generator power, in the turbulence-driven region, $-5/3$ scaling regime is increased in the downstream turbines—owing to the presence of wake turbulence, which surprisingly contributes to the generator power in the regime of frequency much less than approximately $O(10^{-1})$ Hz irrespective of the status of atmospheric stratification. The structural response provides unique signatures for the coastal LLJ, where we see high energetic content beyond “one per revolution” (1P) ($1P \sim \Omega_{\text{rotor}}/2\pi$ Hz), especially at the tower's first mode natural frequency of approximately 0.18 Hz, which indicates the “LLJ small-scale turbulence-driven” aerodynamic torque can potentially trigger resonant vibrations in the turbine tower. This brings us to the high-level message demonstrated in Fig. 21, which reiterates the need to understand the importance of intersection of atmospheric, structural, and controller features that dictates power and loads at the farm level, moving away from the design

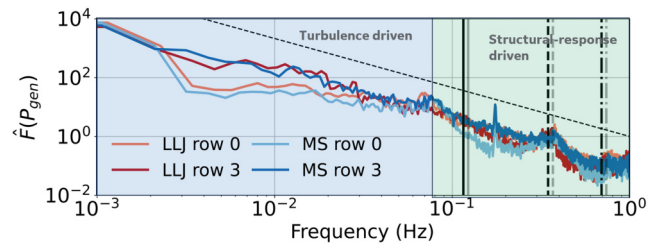


FIG. 20. FFT spectra of generator power for the first and penultimate rows of turbines. The dashed line corresponds to $f^{-5/3}$.

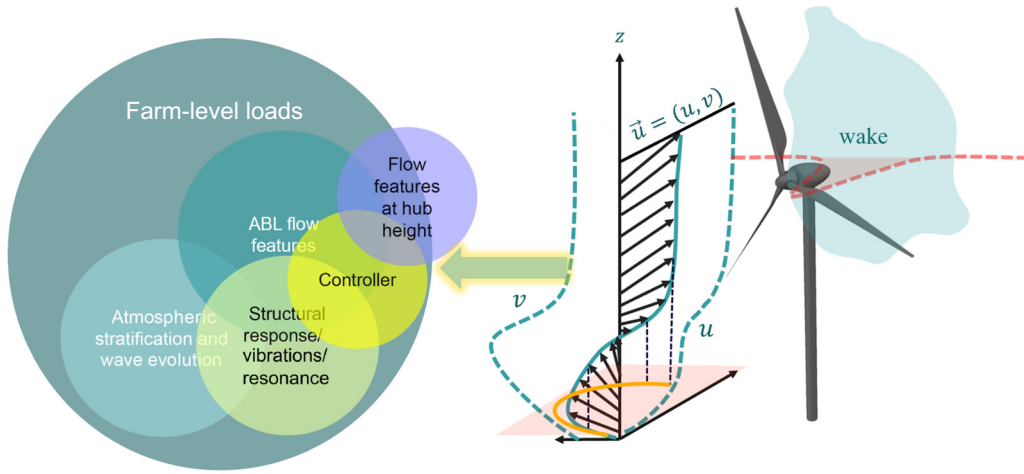


FIG. 21. Venn diagram of what drives wind turbine responses. Higher areas of intersection indicate higher coupling of physics. Sets inside farm-level loads are fully responsible for the load behavior and sets outside farm-level loads: are partially responsible for the load behavior.

approach adopted in engineering models that “*power and loads are driven by hub-height conditions.*” From the spectral signatures of the turbine loads (Fig. 22), we observe two conspicuous regions: (1) a low-frequency region (less than approximately 10^{-1} Hz) driven primarily by turbulence, and (2) a high-frequency region (greater than approximately 10^{-1} Hz) due to the structural response around the system’s natural frequencies. It is important to note

the presence of a prominent band of the $-5/3$ law in the turbulence-driven region. For the blade root moments (B_{Mx} and B_{My}), lower spectral content is clearly observable in the low-frequency region, indicating the influence of lower TI in coastal LLJs contributing to lower standard deviation or DELs. The spectral energy content of the rotor loads for the coastal LLJ are stronger (compared with the MS case) around the natural frequency of the first tower mode, but

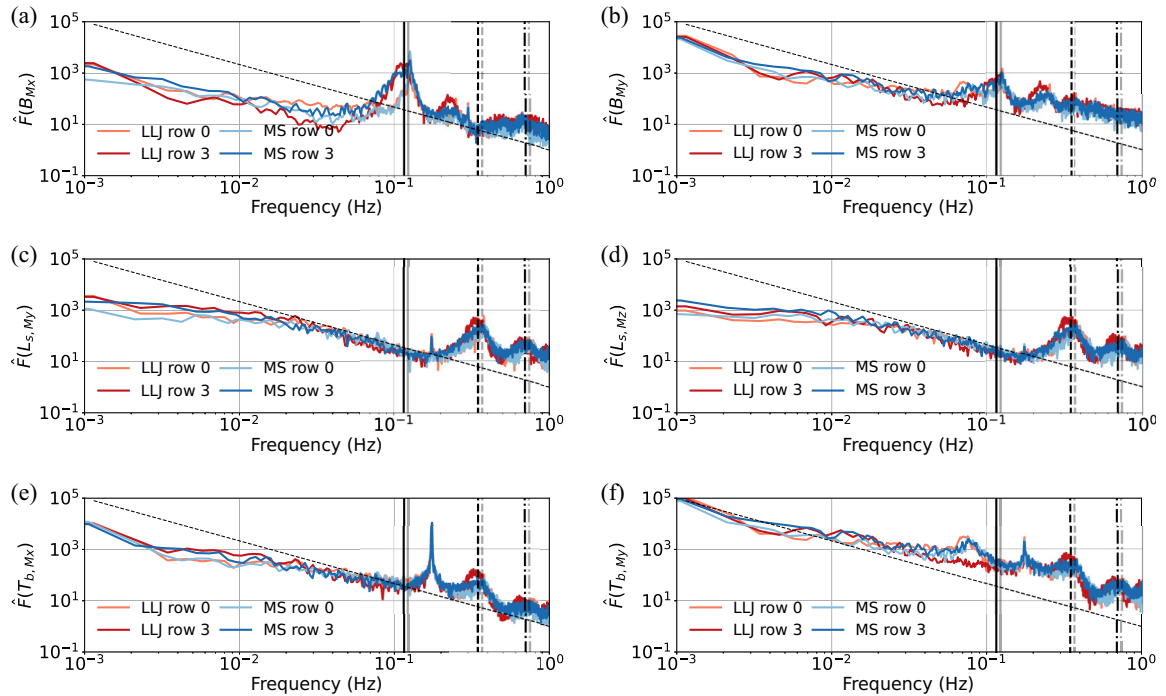


FIG. 22. Comparison of array-averaged load FFT spectra: blade, low-speed shaft and tower between coastal LLJ and baseline MS case for a 20 turbine farm layout for different rows. (a) Blade edgewise moment, (b) blade flapwise moment, (c) rotating low-speed shaft bending moment, (d) rotating low-speed shaft torsional moment, (e) tower side-side moment, and (f) tower twisting moment. Vertical solid lines correspond to 1P ($\Omega_{rotor}/2\pi$), vertical dashed lines correspond to 3P ($3\Omega_{rotor}/2\pi$), and vertical dash-dotted lines correspond to 6P ($6\Omega_{rotor}/2\pi$). Black lines represent the LLJ case and gray lines represent the MS case. Inclined dashed lines correspond to $f^{-5/3}$.

compared with the structural-response-driven spectra, the turbulence-driven spectra has a higher magnitude and has a major contribution to the DEL loads. As we move from the rotor loads to the analysis of shaft and tower loads, we see a clear distinction. The spectral energy content of structural response driven spectra is of a similar or higher order of magnitude compared to the turbulence driven counterpart. For the shaft loads the prominence of 3P (thrice of 1P) frequency is evident (rotation of three-blade system), albeit at smaller magnitudes than in the turbulence-driven region. Additionally, at lower frequencies (turbulence-driven region), we do not observe any noticeable differences in the spectra for the LLJ compared with the MS cases, corroborating that it is not the veer variation but is the *mean veer* that plays a crucial role in the first row of turbines. At downstream locations it is the interplay of mean veer and possibly the standard deviation of du/dy that excites the system frequencies and hence increases the DELs. There exists a sharp energetic peak at the tower modal frequency (approximately 0.18 Hz) for the side-side moment, which indicates the prominence of vibrations in the tower side-side loads for the coastal LLJ and MS case. The peaks are less prominent for the tower fore-aft moment. Additionally, at a frequency of less than approximately 0.07 Hz, a region of low spectral energy content for the coastal LLJ event in the downstream turbines is noted that gives rise to the lower DELs for the tower fore-aft moments (also noted in rotor-averaged velocity spectra). The frequency region is “turbulence-driven,” and the phenomenon is caused possibly by the lack of wake meandering as in the MS case, but further in-depth analysis is needed. Finally, in the system-level framework, owing to kinematic connections or constraints of the turbine components, one load characteristic would have a direct impact on some other loads, e.g., the signature for low-speed shaft bending load ($L_{s,Mz}$) is very similar to the yaw-bearing and tower torsional loads coming from the strong presence of veer dv/dz and lateral gradients du/dy due to wakes and how it excites the turbine natural frequency. These insights serve as cornerstones for mechanical load assessments of wind farms and subsequent controller design to mitigate the effect of harmful loads.

V. CONCLUSION

This study presents a high-fidelity investigation of coastal LLJs and their impact on offshore wind turbine performance and structural loads, using GPU-accelerated LESs coupled with aeroservoelastic turbine models. Simulations were conducted on the now-decommissioned Summit supercomputer at Oak Ridge National Laboratory, modeling a virtual wind farm in the New York Bight under realistic mesoscale forcing.

Coastal LLJs are nonstationary events and are characterized by a triple-shear profile and strong veer—features

that emerge under stable thermal stratification. Our results show that these conditions can lead to 50% power losses in downstream turbine rows and significantly increased loads on key structural components, such as the low-speed shaft and tower. These effects arise from two primary mechanisms: (1) unconventional rotor-scale gradients in wind speed and direction, and (2) the downstream evolution of those gradients under suppressed turbulent mixing due to thermal stratification.

Importantly, the load patterns across the farm are not uniform. First-row turbines are influenced most by the inflow’s veer and shear, while downstream turbines experience compounded effects of these wind flow characterization from persistent wakes and weak vertical mixing. This nonuniformity highlights a critical shortcoming in conventional turbine design and siting practices, which typically rely on hub-height metrics and simplified turbulence assumptions, including nominal shear and veer.

We find that turbine loading is governed not by mean wind speed alone, but by a nonlinear interaction between atmospheric flow structures—shear, veer, turbulence intensity, and lateral gradients—and the turbine’s structural dynamics. These interactions can excite resonance modes, amplifying vibrations and fatigue, particularly in stratified conditions.

This work yields four key implications:

- (1) *System-level load drivers*: Rotor-scale flow features such as strong veer and lateral gradients must be explicitly accounted for in turbine load evaluations—especially in stratified marine environments.
- (2) *Rethinking DLC frameworks*: Current IEC-based design load cases are insufficient to capture the spatial and temporal complexity of LLJs. New, site-aware DLCs are needed to reflect the gradient-rich nature of offshore inflow.
- (3) *Environment-aware control strategies*: Real-time detection of wind gradients offers an opportunity to embed flow physics into control algorithms, enabling predictive load mitigation and extended turbine life.
- (4) *Exascale simulation as an engineering tool*: Coupling mesoscale atmospheric realism with detailed turbine models in a high-performance computing environment enables a physics-driven approach to offshore wind design and reliability analysis.

In summary, we establish a paradigm for modeling offshore wind systems—where high-impact unconventional meteorological events such as coastal LLJs are treated not as edge cases but as central to turbine design, operation, and survivability. These insights are especially timely as the offshore wind industry scales into deeper waters and more dynamically complex atmospheric regimes.

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DATA AVAILABILITY

Data are not publicly available.

APPENDIX A: WRF-LES SOLVER

The wall-modeled large eddy simulation framework is based on the AMR-Wind solver [25], which uses a framework of variable density, constant viscosity, and incompressible flow using a second-order projection method with an adaptive mesh [65]. The equations solved are

$$\begin{aligned} \partial_t \rho + \partial_j \rho \tilde{u}_j &= 0, \\ \partial_t \tilde{u}_i + \tilde{u}_j \partial_j \tilde{u}_i + 2\epsilon_{ijk} \Omega_j \tilde{u}_k \\ &= \frac{1}{\rho} \left(-\partial_i p - \partial_j \tau_{ij}^D + \frac{\tilde{\theta} - \theta_0}{\theta_0} g_i + F_i^u \right), \\ \partial_t \tilde{\theta} + \tilde{u}_j \partial_j \tilde{\theta} &= -\partial_j q_j + F^\theta, \end{aligned} \quad (\text{A1})$$

where ρ is the density, $\tilde{u}_i$ is the three-dimensional resolved velocity field, p is the pressure, and θ is the potential temperature. For the Coriolis forcing term, $u_{k,G} = (u_G, v_G, 0)$ is the geostrophic wind velocity, ϵ_{ijk} is the Levi-Cevita symbol, and $\Omega = (0, \omega \cos \phi_L, \omega \sin \phi_L)$, where ω is the rotation rate of Earth and ϕ_L is the latitude. τ_{ij}^D , the deviatoric part of the subgrid scale (SGS) stress tensor and q_j , the subgrid scale temperature flux vector, are modeled with use of the Moeng model [66]. Additionally, the wall model for the LES is adapted with the use of Monin-Obukov similarity theory in line with the Moeng model. This is because the “bottom wall” sea surface is modeled as a simplified “phase-averaged” wave model [67] that lumps the wind-wave momentum transport through a bulk roughness length-scale parameter z_0 . For the current offshore simulation framework, $z_0 = \alpha u_*^2/g$, as per Charnock's relationship, results in $z_0 = 1.0 \times 10^{-4}$ for $\alpha = 0.11$ [67,68]. $u_* = 0.3$ m/s is the friction velocity and $g = 9.81$ m/s² is the acceleration due to gravity. As we see later in the validation plots, this wall modeling is sufficient to capture the wind-wave coupling as is benchmarked against the New York Bight region buoy data.

Figure 24 illustrates the resolved turbulence and the modeling capacity of the SGS stress and wall model for the precursor ABL simulations with 10 m grid resolution. Here, $\gamma = k_{\text{resol}}/(k_{\text{resol}} + k_{\text{SGS}})$ for turbulent kinetic energy and $\gamma_{\eta\xi} = |\eta\xi_{\text{resol}}|/(|\eta\xi_{\text{resol}}| + |\eta\xi_{\text{SGS}}|)$ for all $\eta\xi = uv$, with vw and uw expressing the resolution for turbulent stresses. Here the subscripts “resol” and “SGS” denote the resolved (unmodeled) and subgrid scale (modeled) quantities. γ and $\gamma_{\eta\xi}$ tend to 1 as $z \rightarrow \infty$ (toward the outer layer). The resolution requirement for a convectively unstable ABL is relaxed compared with that for coastal LLJ environments with stable stratification. Figure 24 further illustrates that more than 90% of turbulent kinetic energy and shear stresses near the rotor/tower region are resolved by the precursor LES grid (more than 95% in wind farm simulations) while the remaining 10% are modeled by the SGS and wall model. $((\tilde{\theta} - \theta_0)/\theta_0)g_i$ denotes the buoyancy force, with $g_i = (0, 0, -9.81)$ the gravitational acceleration vector. The external force fields in the momentum transport F_i^u and potential temperature equation F_θ have different implications depending on whether the simulations are for atmospheric precursor or full-scale wind farms. x and y denote the horizontal directions (northing, easting), while z is the vertical direction. For WRF driven precursor simulations, e.g., in the LLJ, the forcings are designed as a proportional controller assimilating horizontally averaged WRF momentum and potential temperature in microscale LES [69]. The forcing function for the WRF forcing in the coastal LLJ environment is expressed as follows:

$$\begin{aligned} F_i^u &= \rho K_i (\tilde{u}_i(x, y, z, t) - \langle U_{i,\text{WRF}} \rangle_{xy}(z, t)), \\ F_\theta &= K_i (\tilde{\theta}(x, y, z, t) - \langle \Theta_{\text{WRF}} \rangle_{xy}(z, t)), \end{aligned} \quad (\text{A2})$$

where $K_i = 0.2 \text{ s}^{-1}$ for all $i = 1, 2$ is the constant used in the proportional controller. We set $K_i = 0$ for all $i = 3$. $\langle U_{i,\text{WRF}} \rangle_{xy}(z, t)$ and $\langle \Theta_{\text{WRF}} \rangle_{xy}(z, t)$ are horizontally averaged velocity and potential temperature fields from the WRF simulation. The WRF simulations are done with WRF 4.2.1, encompassing a domain size of approximately $600 \times 600 \text{ km}^2$ with two layers of nested horizontal grid resolution of 6 and 2 km, respectively. Sixty-one vertical cells have been used in the current WRF framework, with the near surface levels at 12, 34, 52, 69, 86, 107, 134, 165, and 200 m (range of lidar buoy data). Nudging is performed from the ECMWF Reanalysis v5 dataset on the boundary of the outer 6 km resolution domain every 6 h. The planetary boundary layer scheme used in the model is the Mellor-Yamada-Nakanishi-Niino scheme. Additionally, the Moderate Resolution Imaging Spectroradiometer with 30 arc second at 1 km resolution is used for the land-use data source. The WRF simulation outputs are written out as a 5 min time-averaged flow field. Figure 23 provides a time snapshot of a horizontal plane of WRF simulations at $z = 100 \text{ m}$ (the location of the jet nose) near the New York Bight region, manifesting spatial scales of the jet event being more than 100 m, and was observed for a time scale of approximately 6 h [35]. For more details regarding the validation of WRF data against NYSEDA buoy datasets, see Refs. [35,63,70].

A schematic of the WRF-LES framework is shown in Fig. 25. In the current LLJ simulation, the WRF momentum and temperature forcing terms have been validated against the experimental floating lidar buoy observations deployed by NYSEDA in the New York Bight region. For details regarding the validation of the WRF-LES framework, see Refs. [2,69].

For canonical turbulence, e.g., the convectively unstable MS case, the ABL forcing term is written as

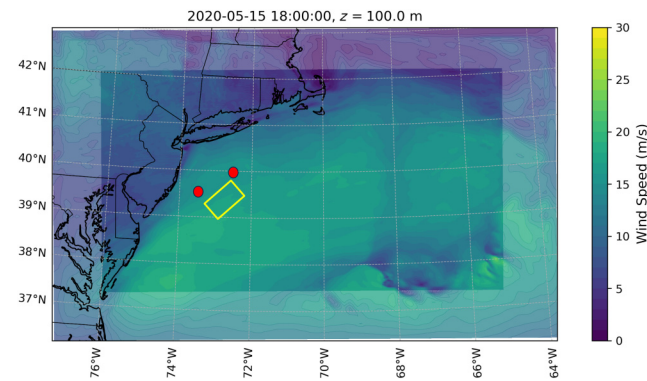


FIG. 23. Horizontal snapshot of nested WRF simulation of the coastal LLJ used to drive the atmospheric boundary layer precursor. The transparent box indicates the nested domain of 2 km resolution. $z = 100 \text{ m}$ corresponds to near the jet-nose location. Red dots indicate the locations of northeasterly and southeasterly floating lidar buoys. The yellow box represents the hypothetical wind farm scale.

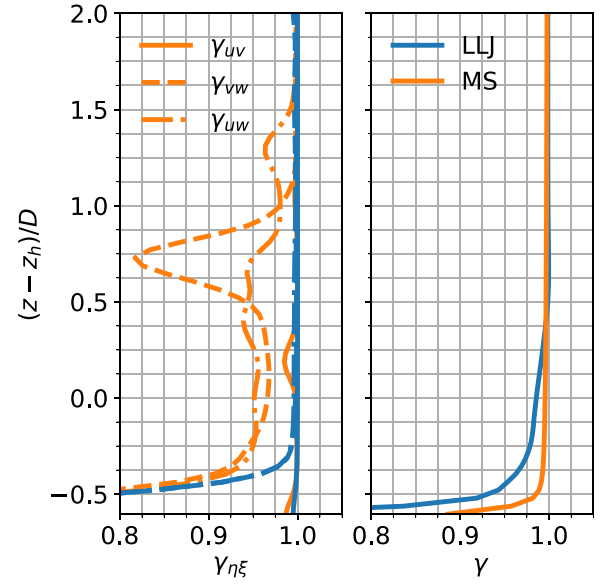


FIG. 24. Metrics for LES grid resolution for the precursor ABL (resolution 10 m). Variation of (a) γ_{uv} , γ_{vw} , γ_{uw} and (b) γ with normalized height $(z - z_h)/D$ from the ground. Blue lines correspond to the convectively unstable MS case and orange lines correspond to the coastal LLJ.

$$F_i^u = \frac{1}{\Delta t} (\bar{u}_{i,\text{target}}(z = z_{\text{target}}, t) - \langle \tilde{u}_i \rangle_{xy}(z = z_{\text{target}}, t)), \quad (\text{A3})$$

where $\bar{u}_{i,\text{target}}$ is the target ABL velocity at prescribed height $z = z_{\text{target}}$ and Δt is the time step for numerical simulation. For the current work, $z_{\text{target}} = z_h = 150 \text{ m}$. $\langle \tilde{u}_i \rangle_{xy}$ is the horizontally averaged canonical ABL data from the LES calculations. For wind farm simulations, $F_i^u = \partial_j p_{\text{precursor}} + F_{\text{ALM}}^i$, where $\partial_j p_{\text{precursor}}$ is the large-scale pressure gradient or body force term derived from the precursor to drive the wind farm simulations and F_{ALM}^i is the actuator line forcing to mimic wind turbine blade motions.

1. Actuator line model

In the ALM the lift and drag forces on the turbine blades are computed on the discretized N radial sections of the blades, computing velocity and forces in the center of the radial section, and interpolating/smearing the forces across the actual computational fluid dynamics mesh points using an isotropic smoothed Gaussian kernel [42,45,71]. In particular, the lift and drag forces can be calculated by $L = \frac{1}{2} \rho C_L(\alpha) \tilde{u}_{\text{rel}}^2 c \Delta r$ and $D = \frac{1}{2} \rho C_D(\alpha) \tilde{u}_{\text{rel}}^2 c \Delta r$, where $C_L(\alpha)$ and $C_D(\alpha)$ are the coefficients of lift and drag as a function of the angle of attack α , c is the chord length, and Δr is thickness of the discretized radial blade span. The relative velocity intercepting the blade airfoil at an angle of attack α is given as

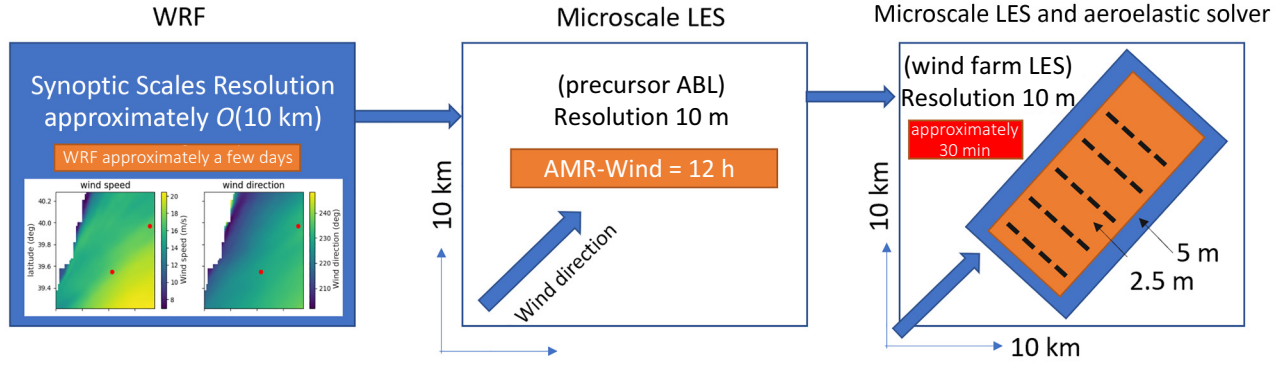


FIG. 25. WRF-driven LES. From left to right, WRF simulations in a mesoscale grid (resolution approximately 10 km). WRF forcing drives the precursor microscale ABL LES (resolution approximately 10 m). The precursor ABL body forcing term drives the nested wind farm LES (maximum resolution 10 m, minimum resolution 2.5 m).

$$\tilde{u}_{\text{rel}} = \sqrt{(\tilde{u}_1 \cos \gamma - \dot{x}_1)^2 + (\omega(t)r - \tilde{u}_\theta - (\tilde{u}_1 \sin \gamma \cos(\psi(t)) - \dot{y}_1))^2}. \quad (\text{A4})$$

For brevity, the functional dependence of $\tilde{u}_1$, $\tilde{u}_\theta$, and $\tilde{u}_{\text{rel}}$ on (x) , y , z , and t is dropped. The flow angle ϕ can be expressed as

$$\phi = \tan^{-1} \left(\frac{\tilde{u}_1 \cos \gamma - \dot{x}_1}{\omega(t)r - \tilde{u}_1 \sin \gamma \cos(\psi(t)) - \tilde{u}_\theta - \dot{y}_1} \right), \quad (\text{A5})$$

where ψ and γ are the azimuthal angle and the turbine yaw misalignment, and the angle of attack $\alpha = \phi(t) - \theta_{\text{twist}}(r) - \beta(t)$, where θ_{twist} is the geometric twist of the

blade (function of blade span r) implemented as part of the blade design that corresponds to the optimal angle of attack for the rated conditions. $\beta(t)$ is the pitch angle set by the turbine controller. $\dot{x}_1(t)$ and $\dot{y}_1(t)$ are the structural velocities of the blade in the x_1 and θ directions in rotating coordinate systems [72,73] computed/interpolated at the center point of the actuator panels. The current LES computations do not consider the potential flow modulation induced by the tower [73] and incorporate a simple aerodynamic drag model. Figure 26 illustrates a schematic of the actuator line model. The lift and drag forces on the

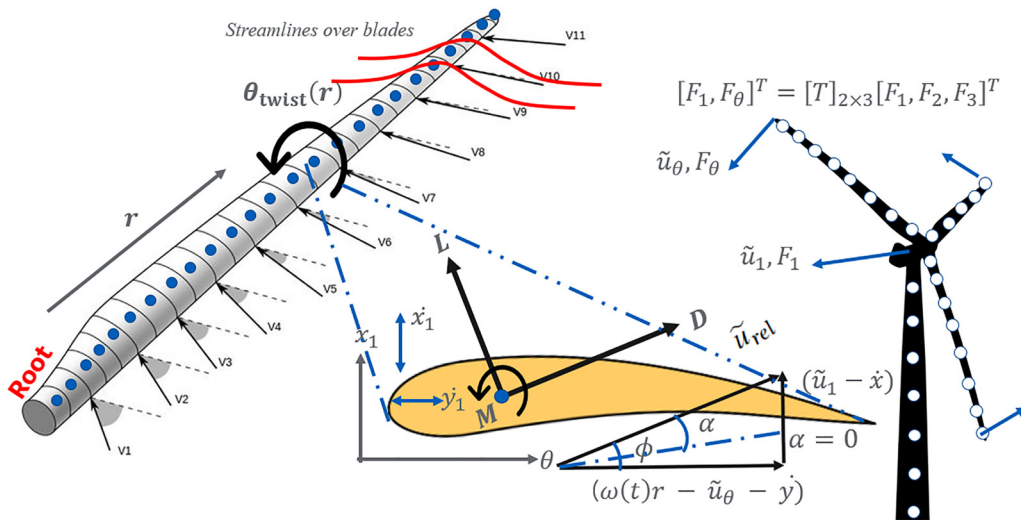


FIG. 26. Actuator line model and velocity triangle used in the aeroelastic coupled AMR-Wind-based LES solver for yaw angle $\gamma = 0$. Lift L , drag D , and pitching moment M are defined at the aerodynamic center. θ_{twist} is the structural twist in the blades. Three blades and a tower are divided into N actuator panels.

blade sections defined on the aerodynamic center of the blade airfoils are given by

$$\vec{F}_{LD} = L\vec{e}_L + D\vec{e}_D,$$

where $\vec{e}_L$ and $\vec{e}_D$ are the unit vectors in lift (perpendicular to $\tilde{u}_{rel}$) and drag (parallel to $\tilde{u}_{rel}$) forces. Additionally, the pitching moment M at the aerodynamic center is defined as $M = \frac{1}{2}C_m(\alpha)\tilde{u}_{rel}^2c^2$, which contributes to the blade aero torsional loads and motion. Currently, in the OpenFAST one-dimensional Beam model-based ElastoDyn solver, the capability of handling the blade torsional loads and blade twist has not been implemented, and resides only in the BeamDyn finite-element solver, which is currently not used owing to computational expense. To accommodate aerodynamic stall-induced vibration in blades, the perturbations in the lift, drag, and pitching moment coefficients during dynamic stall are modeled with the use of unsteady Beddos-Leisman models [74], which modifies the actuator line forces. For production operations with nominal pitch offset in the turbine blades, the Beddos-Leisman model works well for the polar corrections of C_l , C_d , and C_m and the current set of blade mode shapes that are also designed for power production. The blade forces for the N actuator elements as external forces in the momentum budget can be written as

$$\begin{aligned} F_{ALM}^i(x_p, y_p, z_p, t) \\ = \sum_{n=1}^N F_{LD}^i(x_n, y_n, z_n, t) \eta_\epsilon((x_p - x_n), (y_p - y_n), (z_p - z_n)), \end{aligned} \quad (A6)$$

where $\eta_\epsilon(x, y, z) = (1/\epsilon^3\pi^{3/2})\exp[-(d/\epsilon)^2]$, with $d^2 = (x - x_n)^2 + (y - y_n)^2 + (z - z_n)^2$. Note that x_p, y_p , and z_p are locations of cell centers of the mesh, and x_n, y_n , and z_n are the coordinates of the actuator points.

APPENDIX B: AEROELASTIC SOLVER AND CONTROLLER MODULE

The aero-elasto-servo-hydro component of the wind turbine model is tackled by coupling OpenFAST to the LES solver AMR-Wind. The aerodynamic forces in the turbine blades are handled with the use of an actuator line model, while the blade elastic forces are solved with the use of a structural one-dimensional dynamic model (Euler-Bernoulli beam models) induced by the aerodynamic interactions. The aeroelastic solver essentially behaves like a one-way fluid-structure interaction solver with some capability of handling analytical corrections of flow around the tower due to structural response [16]. The controller for the aeroelastic wind turbine solver for the IEA 15 MW turbine [61] is designed with the use of ROSCO, which is linked to OpenFAST [26]. The controller design uses analytical

wind plant models [Eq. (B1)] to develop the linearized state-space matrices, thus avoiding the computation of those state-space matrices through the aero-servo-elasto solver OpenFAST [75]:

$$\dot{\omega}_g = \frac{N_g}{J_r}(\tau_a - N_g\tau_g\eta_{gb}), \quad (B1)$$

where ω_g is the generator shaft speed, N_g is the gearbox ratio, η_{gb} is the gearbox efficiency, τ_g is the generator torque, and the aerodynamic torque $\tau_a = 1/2\rho A_r C_p(\lambda, \beta)\hat{v}^3/\omega_r$, where $\omega_r = \omega_g/N_g$ ($N_g = 1$ for the IEA 15 MW turbine) is the low-speed shaft rotating speed, ρ is the air density, C_p is the power coefficient obtained from the lookup table, $\hat{v}$ is the reference hub-height wind speed seen by the controller, and A_r is the rotor area. The controller module implements a generic reference tracking proportional-integral (PI) controller for both below and above rated operations of the form

$$y = k_p u + k_i \int_0^T u dt. \quad (B2)$$

For below-rated operations, the PI control is essentially optimal tip speed ratio (TSR) (λ_{opt}) tracking (maximizing C_p) with $y = -\Delta\omega_g = \omega_g(t) - \omega_{ref,\tau}$, the perturbation of the generator speed ω_g from the nominal steady state value, while the pitch $\beta = \beta_{min}$ is set to a fine-pitch value. The reference generator speed $\omega_{ref,\tau} = 2N_g\lambda_{opt}\hat{v}/D$ is guided by the optimal TSR and $\hat{v}$. The input disturbance $u = \Delta\tau_g$ is the perturbation of the generator torque. For above rated operations, a blade-pitch PI controller is used with $y = -\Delta\omega_g = \omega_g(t) - \omega_{ref,\beta}$ and disturbance input $u = \Delta\beta$, which is a perturbation pitch to the steady-state reference value at above rated operations. The blade-pitch PI controller pitches out the blade above rated wind conditions as necessary to limit the aerodynamic torque and hence keep the power at the rated value. Additionally, at very low wind speeds close to the cut-in Ref. [61], a PI controller tracking ω_{min} (to avoid resonance with tower vibrations) is used in conjunction with a minimum pitch schedule β to ensure maximization of C_p . Figure 27(a) illustrates the controller trajectory for cut-in to cut-out wind speed at steady-state operation. Additionally, Fig. 27(b) illustrates the C_p surface used to track the C_p maximizing schedule in the (TSR, pitch) space. The peak-shaving strategy was designed to “shave” the peak of the rotor thrust curve and subsequently reduce the tower loads at the cost of a slight reduction of power. The rotor thrust is given by $T(v) = 1/2\rho v^2 A_{rotor} C_t(\lambda, \beta)$. The peak-shaving limits the maximum rotor thrust $T_{max} = a \max T(v)$, $a \leq 1$, and hence the maximum allowable thrust coefficient $C_{t,max}(v) = 2T_{max}/\rho A_{rotor} v^2$. For all operational TSRs λ , a blade pitch angle $\beta_{ps} = \beta(C_{t,max}, \lambda)$ is identified through the C_t surface in a similar spirit to the C_p surface. This generates the minimum pitch angle schedule β_{min} for all wind

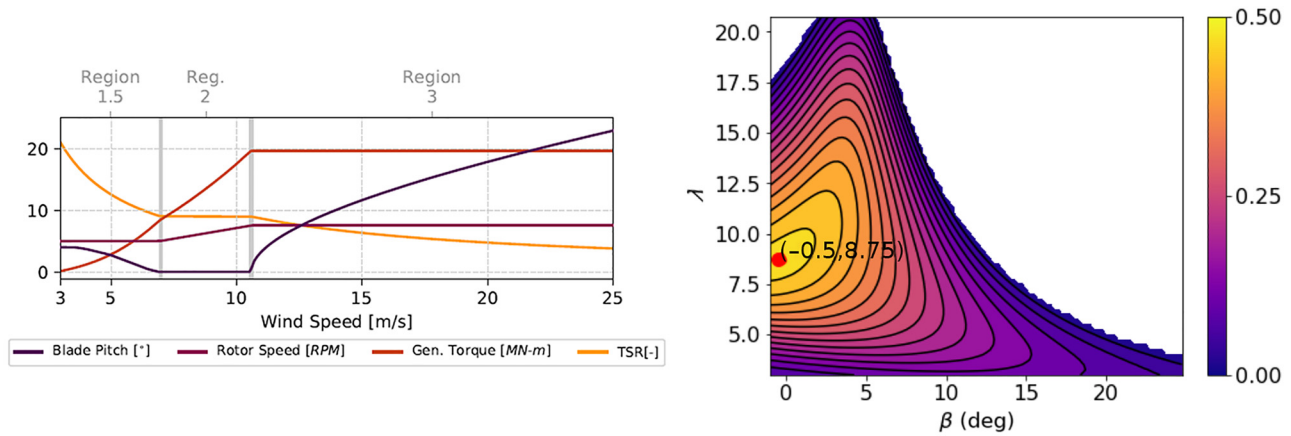


FIG. 27. (a) Controller regulation trajectory of the IEA 15 MW turbine under steady-state wind conditions. Figure is reproduced from Ref. [26] under a Creative Commons Attribution (CC-BY) 4.0 license. (b) Power-coefficient C_p surface-performance plot of the IEA 15 MW turbine in (λ, β) space. The red circle corresponds to $C_{p,\max} = 0.463$. rpm, revolutions per minute.

speeds in the below rated condition as well as in the above rated condition. For the current LESs with the IEA 15 MW turbine, we set $\beta_{\min} = 0$ for all wind speeds. The loads generated in the turbines in LESs thus indicate the fundamental response to turbulent wind conditions actuated by optimal TSR or pitch control.

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