Wind Energ. Sci., 7, 2307–2334, 2022
https://doi.org/10.5194/wes-7-2307-2022

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Scientific challenges to characterizing the wind resource in the marine atmospheric boundary layer

William J. Shaw[1], Larry K. Berg[1], Mithu Debnath[2], Georgios Deskos[2], Caroline Draxl[2,3], Virendra P. Ghate[4], Charlotte B. Hasager[5], Rao Kotamarthi[4], Jeffrey D. Mirocha[6], Paytsar Muradyan[4], William J. Pringle[4], David D. Turner[7], and James M. Wilczak[8]

[1]Pacific Northwest National Laboratory, Richland, WA 99352, USA
[2]National Wind Technology Center, National Renewable Energy Laboratory, Golden, CO 80401, USA
[3]Renewable and Sustainable Energy Institute, Boulder, CO 80309, USA
[4]Argonne National Laboratory, 9700 South Cass Ave., Lemont, IL 60439, USA
[5]DTU Wind Energy, Technical University of Denmark, Risø Campus, Roskilde, Denmark
[6]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[7]Global Systems Laboratory, NOAA, Boulder, CO 80305, USA
[8]Physical Sciences Laboratory, NOAA, Boulder, CO 80305, USA

Correspondence: William J. Shaw (will.shaw@pnnl.gov)

Received: 15 December 2021 – Discussion started: 21 February 2022
Revised: 8 July 2022 – Accepted: 9 October 2022 – Published: 28 November 2022

Abstract. With the increasing level of offshore wind energy investment, it is correspondingly important to be able to accurately characterize the wind resource in terms of energy potential as well as operating conditions affecting wind plant performance, maintenance, and lifespan. Accurate resource assessment at a particular site supports investment decisions. Following construction, accurate wind forecasts are needed to support efficient power markets and integration of wind power with the electrical grid. To optimize the design of wind turbines, it is necessary to accurately describe the environmental characteristics, such as precipitation and waves, that erode turbine surfaces and generate structural loads as a complicated response to the combined impact of shear, atmospheric turbulence, and wave stresses. Despite recent considerable progress both in improvements to numerical weather prediction models and in coupling these models to turbulent flows within wind plants, major challenges remain, especially in the offshore environment. Accurately simulating the interactions among winds, waves, wakes, and their structural interactions with offshore wind turbines requires accounting for spatial (and associated temporal) scales from O(1 m) to O(100 km). Computing capabilities for the foreseeable future will not be able to resolve all of these scales simultaneously, necessitating continuing improvement in subgrid-scale parameterizations within highly nonlinear models. In addition, observations to constrain and validate these models, especially in the rotor-swept area of turbines over the ocean, remains largely absent. Thus, gaining sufficient understanding of the physics of atmospheric flow within and around wind plants remains one of the grand challenges of wind energy, particularly in the offshore environment.

This paper provides a review of prominent scientific challenges to characterizing the offshore wind resource using as examples phenomena that occur in the rapidly developing wind energy areas off the United States. Such phenomena include horizontal temperature gradients that lead to strong vertical stratification; consequent features such as low-level jets and internal boundary layers; highly nonstationary conditions, which occur with both extratropical storms (e.g., nor'easters) and tropical storms; air–sea interaction, including deformation of conventional wind profiles by the wave boundary layer; and precipitation with its contributions to leading-edge erosion of wind turbine blades. The paper also describes the current state of modeling and observations in the marine atmospheric boundary layer and provides specific recommendations for filling key current knowledge gaps.

1 Introduction

For several decades, utility-scale wind energy has experienced accelerating global growth, with most of the initial focus on land-based production owing to simpler development logistics and lower costs. In the past decade, however, costs for offshore wind energy have also begun to fall dramatically, with a corresponding increase in installation of offshore wind power plants. According to WindEurope (Ramirez et al., 2020), for example, the installed capacity for offshore wind energy production in Europe increased from about 3 GW in 2009 to about 22 GW in 2019. The United States has lagged European development but is now also experiencing accelerating deployment. Forecasts reported in Musial et al. (2019) indicated that the United States may go from 30 MW installed capacity in 2020 to as much as 16 GW by 2030, and the target has, as of 2021, been raised by the US government to 30 GW (https://www.whitehouse.gov/briefing-room/statements-releases/2021/03/29, last access: 2 December 2021). This paper builds on the findings of a workshop organized by the US Department of Energy in 2019 (DOE, 2019) that gathered participants from industry, academia, and national laboratories in the United States and Europe to identify the most significant gaps in meteorological and oceanographic knowledge for the development of offshore wind energy.

The context for this paper comprises general research needs as well as distinctive features of the US offshore environment that add complexity beyond that which has already been addressed in the European experience (Fig. 1). These features include the presence of the Gulf Stream off the East Coast of the United States, westerly winds that commonly advect air off the North American continent toward the east, and the deep-water upwelling and severe coastal topography of the West Coast. Since these features bear similarities to other world regions with deep-water upwelling and western boundary currents, we expect that our articulation of scientific challenges for wind resource characterization will find applicability beyond the United States.

With the increasing level of offshore wind energy investment, it is necessary to be able to accurately characterize the resource in terms of energy potential as well as operating conditions affecting performance, maintenance, and lifespan. Wind, of course, is the fuel for wind power plants. It is important to accurately assess the resource at a particular site to support investment decisions (e.g., Brower et al., 2012). Once a wind plant is constructed, accurate wind forecasts are needed to support efficient power markets and integration of wind power with the electrical grid. Further, optimization of the design of wind turbines requires accurate description of the environmental characteristics, such as precipitation and waves, that erode turbine surfaces (e.g., Dashtkar et al., 2019) and generate structural loads as a complicated response to the combined impact of shear, atmospheric turbulence, and wave stresses (e.g., Vorpahl et al., 2013; Kelley, 2011; Kapoor et al., 2020). Recently, considerable progress has been made both in forecast improvement (e.g., Shaw et al., 2019; Wilczak et al., 2019; Olson et al., 2019) and in coupling the real atmosphere to turbulent flows within wind plants (Haupt et al., 2019) over land. Nevertheless, gaining sufficient understanding of the physics of atmospheric flow within and around wind plants remains one of the grand challenges of wind energy, particularly in the offshore environment (Veers et al., 2019).

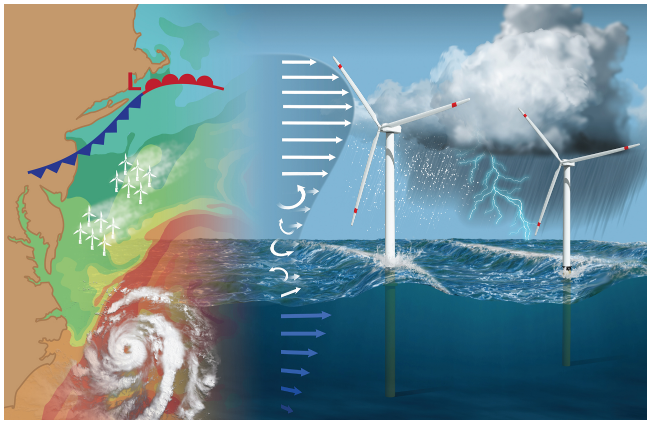

Figure 1. Illustration of phenomena affecting offshore wind plants at varying scales on the US East Coast. Spatial scales range from tropical hurricanes and mid-latitude storm systems such as nor'easters through composite wind plant wakes and low-level jets to breaking waves and small turbulent eddies. The spatial temperature variations arising from the Gulf Stream and the land–sea boundary drive circulations such as sea breezes and modulate thermodynamic stratification. Cloud microphysical processes generate liquid and solid precipitation that can erode leading edges of wind turbine blades.

Modern utility-scale wind turbines typically operate within the atmospheric boundary layer (ABL), the layer of the atmosphere in contact with the surface through which nearly continuous three-dimensional atmospheric turbulence efficiently transports momentum and other scalars (e.g., heat and water vapor; Stull, 1988). Characteristics of the ABL that affect wind turbine operation include turbulence motions at many scales and intensities (Kelley, 2011; Haupt et al., 2019; Bodini et al., 2020), persistent vertical gradients of mean wind speed (shear) and direction (veer), atmospheric wave activity (e.g., Allaerts and Meyers, 2018), and local circulations driven by terrain and by horizontal surface variability such as coastlines (Strobach et al., 2018). From a terrestrial perspective, Banta et al. (2013, 2018) have provided descriptions of these kinds of circulations as they relate to wind energy together with suggested observational strategies for better observing them. Offshore, the ocean forms a dynamic lower boundary to the atmosphere. ABL winds both drive the wave field and are modified by wave roughness of the ocean surface. When winds and waves are not in equilibrium, there can be appreciable deviations from conventional wind profiles (e.g., Patton et al., 2019). Advection of air from western boundary currents, such as the Gulf Stream in North America and the Kuroshio–Oyashio in Asia, can induce strong and persistent thermodynamic stability effects (e.g., Archer et al., 2016), as can upwelling, which occurs off both the Atlantic (e.g., Strobach et al., 2018) and Pacific (e.g., Jacox et al., 2019) coasts of the United States. Stably stratified conditions are associated with significant turbine wake (Lundquist et al., 2019) and upwind blockage effects (Schneemann et al., 2021), with velocity deficits of up to 40 % observed, and wakes remaining detectable for tens of kilometers downstream of the turbines (Christiansen and Hasager 2005; Platis et al., 2018). Finally, the offshore environment of the western North Atlantic, where many US-based offshore wind farms are planned, is susceptible to extreme weather in all seasons of the year. The development of both hurricanes (e.g., Bright et al., 2002) during the warm season and nor'easters (e.g., Businger et al., 2005) during the cool season is supported by the Gulf Stream. Notably, both hurricanes and nor'easters commonly have maximum winds that can interfere with the operation of wind turbines or even cause significant physical damage (Barthelmie et al., 2021). All of these phenomena interact in complex, nonlinear ways over a range of scales that cannot be explicitly resolved in numerical models and that are not fully understood on a theoretical basis.

Accurately simulating the interactions among winds, waves, wakes, and their structural interactions with offshore wind turbines requires accounting for spatial (and associated temporal) scales from O(1 m) to O(100 km). Because processes on these scales interact nonlinearly, it is necessary to account for them simultaneously to fully represent the impact of real atmospheric conditions on turbine structures. Reliable prediction and understanding of turbine power production and structural loading requires high-fidelity numerical simulations of unsteady atmospheric, oceanic, and fluid–structure interaction dynamics, including atmospheric wake interactions within the plant. Such simulations must be coupled to mesoscale models and data in order to relate wind plant performance to regional weather conditions, including extreme events such as nor'easters and tropical cyclones. Accurately simulating this physical complexity is challenging. Doing so in a single simulation framework is especially challenging because it requires understanding both of process physics and of how to transfer key information across interfaces of coupled models. Moreover, the raw computational power needed to solve these multi-scale/multi-physics problems strains current high-performance computing capabilities. Such simulations are at the forefront of current research (e.g., Haupt et al., 2019; Allaerts et al., 2020; Draxl et al., 2021).

An additional, prominent challenge in addressing problems of the offshore environment is a continuing limitation of observations needed to validate the numerical models used to estimate winds and turbulence through the altitudes covered by the rotor plane of the turbines (DOE, 2019). Most long-term observations offshore have been made near the surface from buoys, which are sparsely deployed. Even rarer are permanent offshore platforms such as the Air–Sea Interaction Tower off the northeastern US coast, which supports both in situ measurements near the surface and remote sensing systems for boundary layer profiling (Kirincich, 2020). In Europe, the three offshore FINO (Forschungsplattformen in Nord- und Ostsee) towers (Finger, 2007) and the one at IJmuiden (Kalverla et al., 2017) can make in situ measurements to approximately 80–100 m above the surface. No such towers exist in the United States. More recently, buoy-mounted lidar systems (e.g., Gottschall et al., 2014; Viselli et al., 2019; Shaw et al., 2020) have provided multi-seasonal observations of winds and potentially turbulence information to altitudes exceeding 200 m, but there are limited systems that provide publicly available data. Moreover, there are currently no devices available for unattended operation at sea that can provide critical atmospheric thermodynamic profiles. At the same time, wind turbines, especially offshore, are increasing in height and rotor diameter, with the blade tips of the largest current turbines now reaching heights of 250 m (Gaertner et al., 2020). For a variety of reasons discussed in the sections that follow, surface measurements cannot be used to reliably infer rotor layer wind characteristics.

The following sections provide an overview of the structure of the marine ABL and key challenges in accounting for physical processes within the metocean environment in the context of wind turbine plant design and operation criteria. We address both observational and modeling challenges and provide recommendations for meeting them. While synoptic-scale weather systems are important for driving wind plant inflows in the boundary layer and remain an active area of forecasting challenge and research, the structure and forcing mechanisms of these systems are beyond the scope of this paper.

2 Physical characteristics of the marine ABL

The physical structure and dynamics of the ABL (e.g., Stull, 1988) affect many important flow properties that can strongly modulate wind energy production. A primary characteristic of the marine ABL is its depth, typically marked by a distinct increase in potential temperature (θ) in a thin layer several hundred meters or more above the surface and here denoted by z_i (Fig. 2). This is referred to as an inversion because the temperature commonly increases in this layer. Such inversions can occur for varying reasons throughout the depth of the atmosphere, but the layer at z_i marks the boundary between the largely turbulence-free atmosphere above and the layer below in which generally continuous turbulence efficiently mixes momentum, heat, water vapor, and other quantities. As in terrestrial environments, marine ABL depth is highly variable, sometimes ambiguous, and varies strongly as a function of thermodynamic stability and meteorological forcing. In addition to the potential temperature inversion at z_i, the top of the marine ABL frequently features a distinct reduction in moisture content (e.g., Zeng et al., 2004).

ABL depth z_i is an important parameter used in many scaling relationships and computational approaches to simulating boundary layer flow. It can be estimated from observed profiles of thermodynamic or turbulence variables (e.g., Bianco and Wilczak, 2002), but offshore there is a general lack of such observations. Other remote sensing products, such as lidar backscatter intensity (e.g., Luo et al., 2014), lidar-derived variances of water vapor (e.g., Turner et al., 2014), and vertical velocity variances (e.g., Berg et al., 2017), as well as aerosol layers identified using ceilometer data in combination with thermodynamic profiles (e.g., Di Giuseppe et al., 2012) have all been shown to provide credible estimates of z_i. Each of these approaches has strengths and limitations based on meteorological conditions, including the degree to which aerosol particles, clouds, and fog are present. The greatest limitation at present, however, is the overall lack of these measurement systems in the marine environment. Increased deployment of a variety of remote sensing observation platforms, along with development of improved algorithms to infer marine ABL depth, ideally spanning diverse locations and seasons, would be highly valuable to a broad range of offshore wind energy applications. In addition, spaceborne lidars are beginning to show potential for global mapping of boundary layer depth (Palm et al., 2021).

While the marine ABL shares many characteristics with the terrestrial ABL, important differences apply (Kalvig et al., 2014). Due to the higher thermal inertia of water relative to other surface types, the marine ABL is less sensitive to diurnal forcing than the terrestrial ABL, with generally shallower depths and weaker turbulent mixing during sunlit hours and weaker static stability overnight (Emeis, 2018). However, the slow response of sea surface temperature (SST) to the influence of the temperature of the air above can also lead to very strong convection in the case of cold air flowing over warmer water (e.g., Archer et al., 2016) or strongly stable stratification when warmer air moves over colder water. Non-zero velocities of ocean currents modulate friction between the atmosphere and the ocean, and horizontal SST gradients resulting from these currents and associated eddies occur over a broad range of spatial scales. This has been identified as an important component of ocean–atmosphere coupling (Small et al., 2008; Edson et al., 2013), and the impact of this variability can affect not only marine ABL structure and evolution but also the free troposphere above (e.g., Lambaerts et al., 2013; Wenegrat and Arthur, 2018). Despite several previous observational (e.g., Friehe et al., 1991; Chelton, 2001; Edson et al., 2007; Spall, 2007; O'Neill, 2012) and modeling (e.g., Piazza et al., 2016; Skyllingstad et al., 2007; Seroka et al., 2018) studies, the lack of observations beyond localized case studies has left considerable uncertainty in our understanding of modulation of the marine ABL by variations in SST.

Another distinguishing feature of the marine ABL is that it is frequently capped by a layer of stratocumulus clouds, especially in favored locations such as the US West Coast (e.g., Wood, 2012). Turbulence driven by cloud-top radiative cooling, governed predominantly by cloud liquid water content, can be a significant source and modulator of turbulence within the marine ABL (Wood, 2012). Moreover, enhanced entrainment from cloud-top cooling can strengthen the inversion at z_i, and shear across the inversion can lead to the generation of atmospheric waves. Even in the absence of terrain or other obstructions, these can also strongly modulate flow and turbulence characteristics in the boundary layer (Allaerts and Meyers, 2018).

To facilitate understanding of the various processes occurring within its complicated vertical structure, the marine ABL can be conceptually divided into three layers beneath z_i, as pictured in Fig. 2. The first layer is the wave boundary layer, the layer of the marine ABL in which winds are directly modulated by ocean waves. Immediately above is the surface layer, generally defined as the lowest 10 % of the ABL, within which the wind speed profile is approximately logarithmic, turbulence fluxes are approximately constant with height, and turbulence structure can be scaled with distance from the surface. The remainder of the marine ABL, up to z_i, is characterized by turbulence structure that scales more with the value of z_i than with distance from the surface. The remainder of this section will describe each of these layers in greater detail.

2.1 Wave boundary layer

In the lowest part of the marine ABL, wave-induced surface motion disturbs the marine surface layer, creating an internal layer known as the wave boundary layer (Fig. 2). This layer is in direct contact with the ocean surface, which modulates winds within it through direct dynamic forcing, form drag, dissipation of energy through wave breaking, and other processes (Chalikov, 1995; Edson et al., 1999; Sjöblom and Smedman, 2003). Many of these processes are not accounted for within the assumptions of Monin–Obukhov similarity theory (M–O theory; Obukhov, 1946; Monin and Obukhov, 1954) as it is commonly applied to the surface layer (Hare et al., 1997; discussed further below). For example, under the influence of swell propagating faster than the mean wind, wind speed profiles frequently exhibit maxima near the surface in violation of the logarithmic expectation of M–O theory (e.g., Miller et al., 1999; Smedman et al., 2009). Although the depth of the wave boundary layer is commonly considered to be on the order of 1–3 m, impacts of waves may extend to much greater heights, depending on flow conditions (Janssen, 2004; Kalvig et al., 2014; Cifuentes-Lorenzen et al., 2018). This extended range of impact has been demon-

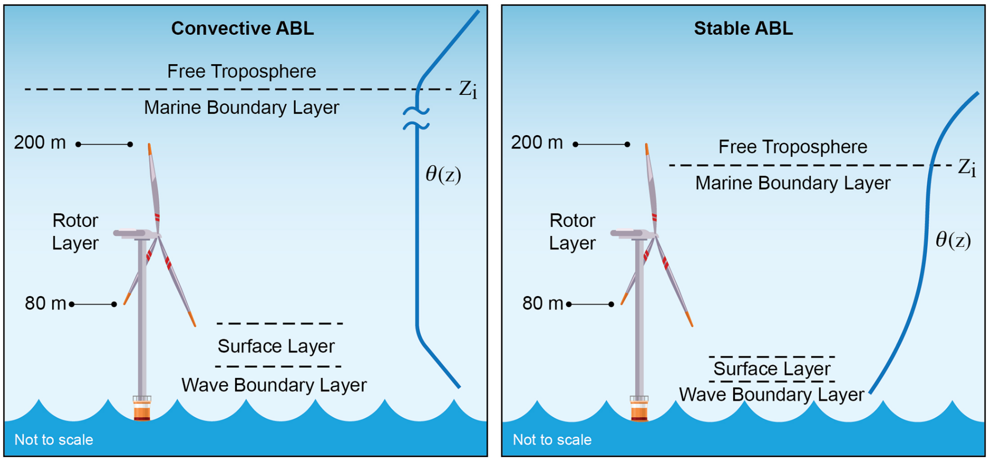

Figure 2. Depiction of the different components of the marine ABL and how those components and overall structure vary with changes of atmospheric stability. θ in the figure is potential temperature and z_i is the inversion at the top of the boundary layer. The break in the θ profile indicates that the depth of the convective boundary layer can be much greater than the height of the surface layer. The figure is exaggerated in the vertical for illustration.

strated by numerous wave-resolving large-eddy simulation (LES) studies that examined the impacts of waves on wind energy relevant quantities of interest extending well into the rotor layer (described more fully in Sect. 4; e.g., Husain et al., 2019; Patton et al., 2019; Sullivan et al., 2008, 2014, 2018a, b; Yang et al., 2014). Cifuentes-Lorenzen et al. (2018) noted that the height above the surface to which impacts of air–sea coupling in the wave boundary layer extend remains an active area of research.

2.2 Surface layer

The surface layer, generally taken to extend from the wave boundary layer top up to 0.1 z_i, spans the depth over which energy fluxes may be treated as constant in height and, thus, for which M–O theory may be considered valid (e.g., Garratt, 1994; Stull, 1988; Arya, 2001). Fluxes in well-mixed boundary layers have been observed to vary approximately linearly with height from their surface values to near-zero at the temperature inversion at the top of the marine ABL. This provides the practical basis for treating the surface layer as 10 % of the depth of the well-mixed layer because statistical errors in flux observations are comparable to or larger than 10 % (Schaller, 1977; Edson and Fairall, 1998; Sjöblom and Smedman, 2003). Thus, if the marine ABL is 1 km deep, the lowest 100 m can be treated as the surface layer where M–O theory is applicable and consequent quasi-logarithmic wind speed profiles would apply. The height of the marine ABL is often quite shallow over upwelling regions of eastern oceans (e.g., Wood and Bretherton, 2004), perhaps only a few hundred meters deep. Under these conditions, state-of-the-art wind turbine hub heights may be well above the surface layer, where M–O theory is no longer valid.

M–O theory holds that under conditions for which turbulence is stationary and horizontally homogenous, variables of interest, such as wind shear, can be scaled with surface turbulence fluxes of momentum and buoyancy and with height above the surface. An assumption of this scaling is that the fluxes are invariant with height in the surface layer. While this theory is routinely used to represent marine ABL characteristics (e.g., Kalvig et al., 2014) and to specify surface boundary conditions in its simulations (e.g., Skamarock et al., 2008), conditions under which M–O theory is considered valid are routinely violated in the surface layer of the marine ABL. Non-logarithmic wind speed profiles as well as significant changes in the momentum flux with height have been documented in both observational (Smedman et al., 2009; Archer et al., 2016) and modeling studies (Sullivan et al., 2008). Other assumptions of M–O theory, including steady-flow conditions and horizontal homogeneity, are likewise not satisfied over coastal zones or over ocean surfaces when significant swell or wave activity is present or active mesoscale or synoptic-scale weather is affecting an area. For example, the roughness of the sea surface varies dramatically in time, often because of distant storms or local conditions (Hanley et al., 2010; Semedo et al., 2011). Weather fronts and tropical disturbances create strong time variations in the local sea state as well as wind and turbulence fields. The strong diurnal cycle over coastal land drives local circulations such as low-level jets (e.g., Pichugina et al., 2012, 2017; DOC/NOAA, 2014; Djalalova et al., 2016) and the sea breeze (Seroka et al., 2018). Simulations show that the sea breeze circulation can extend tens of kilometers offshore (e.g., Igel et al., 2017), which would affect many potential wind plant locations. Nevertheless, M–O theory remains a widely used conceptual framework for understanding and simulating the surface layer, even over the ocean (Gualtieri, 2019).

Considerable research has been devoted to developing and validating mixing layer theories as alternatives to M–O theory that would improve the representation of the modeled wind field. For example, Gryning et al. (2007) proposed a theory for the entire ABL, with emphasis on the lowest 200–300 m, that formulates a simple model for the combined length scale controlling the wind profile and its stability dependence by inverse summation of three component length scales. Gryning et al. (2007) and subsequent studies (Peña et al., 2008, 2010) demonstrated the ability of this model to provide more accurate wind speed profiles within the ABL and under all stability conditions compared to that of the standard M–O theory approach; however, the method is only valid over homogeneous terrain. Sathe et al. (2011) extended its validation to offshore conditions; however, meteorological observations used for this validation reached only to a height of 116 m, which is too limited compared to the size of the state-of-the-art offshore wind turbines (blades may extend up to a height of 270 m as shown in Fig. 2; Gaertner et al., 2020). Holtslag et al. (2017) used meteorological mast observations 85 km offshore and up to 315 m above the surface in the Dutch North Sea to validate the extended diabatic surface layer wind shear model based on the work of Gryning et al. (2007). The extended wind shear profiles are found to outperform the traditional surface layer shear profiles for neutral and strongly stable conditions. However, improvements are needed for strongly unstable conditions. Further, the current formulation underestimates wind speeds above 60 m, which is a critical height for wind energy applications. Additional long-term data sets remain a key need for validating and improving models of surface layer winds and turbulence offshore, especially in areas subject to extremes of stability such as regions of strong upwelling or western boundary currents.

2.3 Mixed layer

For the remainder of the marine ABL between the surface layer and z_i, the vertical transport of momentum, turbulence kinetic energy (TKE), and other constituents tends to be dominated by large turbulent eddies that scale with z_i rather than height above the surface as is the case in the surface layer. Atmospheric stability directly affects the depth of the ABL (and therefore the surface layer). Stable conditions are generally associated with much shallower ABL depths than neutral or convective conditions (illustrated in Fig. 2). Wind speed profiles during stable stratification also frequently exhibit significantly greater vertical changes of wind speed and direction, often including low-level jets (see further details on stable conditions in Sect. 3). Such stably stratified vertical distributions of temperature, coupled with strongly sheared winds, can also support a spectrum of atmospheric wave modes that influence wind plant and turbine performance, including breaking Kelvin–Helmholtz and other gravity waves. Breaking gravity waves can sometimes lead to intermittent turbulence bursting events as well as strong wave-turbulence loading on turbines (Kelley et al., 2006). Simulations suggest that gravity waves generated by wind plants in a stable boundary layer on the other can strongly modulate kinetic energy distributions within the plant, thereby influencing the power that can be generated (Allaerts and Meyers, 2017, 2018; Wu and Porté-Agel, 2017). These studies await validation with observations.

Upstream obstructions can influence downstream flow in the marine ABL, particularly in the presence of strong static stability. These disturbances to the flow, caused by coastal terrain and cities and even the wind plants themselves, generate internal boundary layers (IBLs; Garratt, 1990; Savelyev and Taylor, 2005; Gadde and Stevens, 2021). IBLs form in the presence of discontinuities in surface characteristics, including roughness and temperature. These layers gradually deepen with increasing downwind distance within the existing ABL before eventually merging with it through entrainment. Over the distances within which IBL characteristics remain distinct from those of the background boundary layer, impacts on vertical profiles of wind speed, direction, temperature, and turbulence characteristics can be considerable and can affect the performance of affected wind plants (e.g., Chamorro and Porté-Agel, 2011). For IBLs generated by wind plants themselves, wake effects (Frandsen et al., 2007; Nygaard, 2014; Pryor et al., 2020) become concerns when new plants influence the resources available to previously constructed plants. Evidence of an offshore wind farm influencing the mixed layer can be seen from photos and has been additionally confirmed in numerical modeling (Hasager et al., 2017; Siedersleben et al., 2018, 2020). Current abilities to simulate IBL characteristics and impacts on operating wind plants need to be further investigated to assess the adequacy of resource characterization and wind plant operation guidelines in areas influenced by IBLs (Borvarán et al., 2021). Observations are needed to characterize how often IBLs form, the significance of their effect on wind and turbulence in the rotor plane, and what model improvements are needed to confidently account for their impact on wind power production.

We previously discussed the impact of the ocean surface on the wave boundary layer and the surface layer. Under some conditions, the impact of the wind–wave conditions may affect the wind profile throughout the mixed layer. Studies to date (e.g., Rutgersson et al., 2001; Semedo et al., 2009; Smedman et al., 2009; Sullivan et al., 2008, 2014, 2018a, b; Husain et al., 2019) have been rather idealized, however, and supporting observations remain sparse. As an example, Fig. 3 shows the impact of wind–wave alignment on vertical profiles of wind components from an atmospheric LES model with resolved propagating surface waves characterized by a significant wave height of 6.4 m (Patton et al., 2019). Here, the horizontal and time-averaged zonal $< u >$ and meridional $< v >$ velocity components, as well as scalar wind speed, all normalized by the friction velocity at 10 m above the wave surface, are plotted against height ζ scaled by z_i.

The various colors show different orientations of the wave propagation direction (alpha) with respect to the geostrophic wind ($10\,\mathrm{m\,s^{-1}}$ in the zonal direction). Significant impacts on mean winds emerge throughout the depth of the marine ABL due to differences of the viscous stress and pressure drag effects arising from the different wave orientations.

While a suggestive body of literature is emerging from a growing number of such atmospheric large-eddy simulations studies examining the impact of additional surface wave and atmosphere flow characteristics on ABL mean and turbulence quantities, these numerical investigations have not been sufficiently validated against measurements to yet be regarded as definitive. There is currently little observational information regarding the impact of these conditions on wind shear and turbulence at turbine rotor heights and, consequently, on mechanical loading and power production.

3 The role of stratification and surface temperature heterogeneity

Boundary layer stratification is a key characteristic of the atmosphere for wind energy because of the impacts that it has on wind speed, wind shear and veer, and turbulence. Stable stratification results in decreased frictional coupling with the surface, with stronger wind speeds for the same forcing than would occur with neutral or unstable stratification. Stable stratification generally is also accompanied by weaker turbulence than neutral stratification, and these weaker turbulence levels allow for turbine and wind plant wakes to propagate greater distances downwind, potentially having a detrimental impact on the wind resource available for other turbines and wind plants as noted in the previous section. The decoupling from the surface and the weaker turbulence allow for larger wind shear and veer to develop, and strongly stable stratification can support atmospheric wave activity, as noted in Sect. 2. In contrast, unstable stratification is associated with weaker shear and higher turbulence levels. Large shears, intense turbulence, and atmospheric waves can all place increased stress on turbine blades and gears, and it is important to quantify the range of magnitudes that they can reach. Thus, measuring, understanding, and predicting offshore atmospheric stratification is essential for determining both the wind resource and turbine loads.

For regions of the world where the predominant flow brings continental air over offshore wind energy development areas, such as East Asia and eastern North America, the role of atmospheric stability and its impact on offshore atmospheric flow conditions will likely be significantly different from much of the European offshore wind experience. For example, prevailing westerly flow over the North American continent often results in air temperatures that are significantly colder or warmer (depending on the season) than the ocean temperature in the Mid-Atlantic and New England coastal regions, leading to both strongly stable and unstable boundary layer stratification. In contrast, for most European offshore wind energy production, prevailing westerly flow across the Atlantic results in offshore European atmospheric temperatures that usually are closer to being in equilibrium with sea surface temperatures and a greater preponderance of near-neutral stratification (Sathe et al., 2011; Dörenkämper et al., 2015).

The impact of temperature advection on US offshore boundary layer stratification was investigated by Angevine et al. (2006), who found that stable boundary layers were ubiquitous during the summer months in the Gulf of Maine, as warmer continental air advected offshore over the cooler ocean. Mahrt et al. (2001) showed that for flow of warm air from land over cooler water, as well as for fetches of less than 5 km from the coast, the turbulence rapidly weakened due to buoyancy destruction and reduced shear generation over the less rough sea surface, indicating that the stabilization and modification of the boundary layer can be rapid. The presence of warm Gulf Stream waters further offshore, as well as the sharp SST fronts often associated with it, can also result in stable stratification over nearshore waters, even for onshore flow (Small et al., 2008; Wang et al., 2018; Shutt and Seim 2020). In concordance with the expected seasonality of offshore stratification for a site with a complex coastline off Massachusetts, Archer et al. (2016) found that the relative occurrence of unstably stratified boundary layers is greatest during autumn and winter, as cold continental air advects over a warmer ocean. The instability is especially intense during winter cold-air outbreaks when polar continental air overruns a much warmer ocean (Grossman and Betts, 1990; Field et al., 2014).

The effect of stratification on offshore wind profiles is demonstrated in Fig. 4, which shows wind profiles obtained from 12 months of data collected by a buoy-based lidar system 114 km off New Jersey, a region likely to see significant future wind energy development. The description of the location and data are provided in Debnath et al. (2021). The data set is partitioned into separate averaged profiles dependent on the difference between the 2 m air temperature and the SST ($\Delta T = T\,2\,\mathrm{m} - \mathrm{SST}$). For strongly unstable stratification, suggested when $\Delta T < -2\,\mathrm{K}$, the vertical wind shear is small; for nearer-to-neutral stratification, the shear is moderate; and for strongly stable stratification (suggested when $\Delta T > 2\,\mathrm{K}$), the shear is very large, with the mean wind speeds at 200 m reaching nearly $22\,\mathrm{m\,s^{-1}}$. As suggested by Debnath et al. (2021), strong synoptic pressure gradients and associated temperature advection are required to maintain very stable stratification over the ocean. These pressure gradients drive strong winds, which are further enhanced above the surface owing to the reduction of friction by the stratification. The percentage of time that each category was observed was 33 % strongly unstable, 36 % weakly unstable, 28 % weakly stable, and 2.8 % strongly stable.

Another complicating factor for predicting winds in the offshore stable ABL is that these ABLs are often accompa-

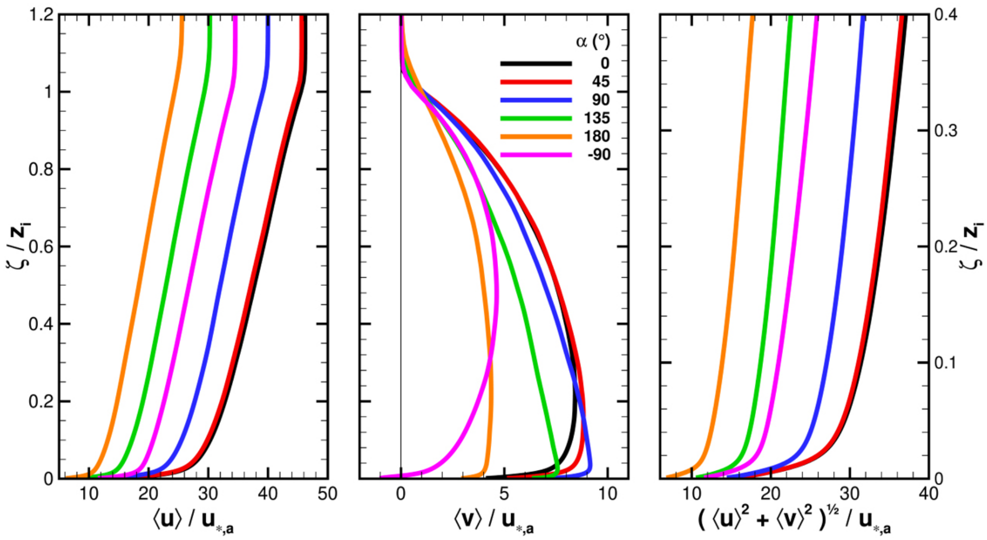

Figure 3. Impacts of various wave propagation directions relative to the mean wind direction on wind components throughout the ABL depth, from wave-resolving atmospheric LES (Patton et al., 2019). Note that 0° denotes that the wind direction is aligned with the wave propagation direction. The difference in the wind profiles for the 90 and −90° is due to Coriolis force.

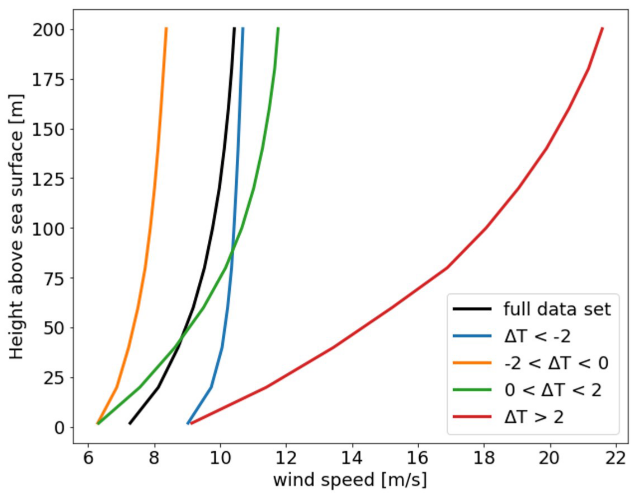

Figure 4. Vertical profiles of mean wind speed calculated from 12 months of buoy-based lidar observations, for four different categories of $\Delta T = T\,2\,\mathrm{m} - \mathrm{SST}$. Temperature differences are in K (DNV-GL, 2020).

nied by low-level jets (Mahrt, 1999; Mahrt et al., 2014; Colle et al., 2016; Pichugina et al., 2012, 2017; Banta et al., 2018). Figure 5 shows an example of a low-level jet (LLJ) derived from the same buoy lidar measurements taken off New Jersey – a high wind shear case presented in Debnath et al. (2021). The top panel of the figure shows a 2 d time series of wind speed at 20 m height intervals up to 200 m a.g.l., while the bottom panel shows the corresponding SST and 2 m air temperatures. The spread of the wind speeds (indicative of wind shear) starts off small at the beginning of the time series when the air–sea temperature difference is small, then increases to a very large spread as stable stratification develops with the air temperature warmer than the SST. At the end of the time series, the shear again decreases as the air–sea temperature difference becomes smaller. The middle panels of the figure show vertical wind speed profiles averaged over two periods with stable stratification, the first when a low-level jet is present with a wind speed maximum at about 100 m a.g.l. The jets can be extremely sharp, with maxima occurring at heights within or even below the rotor plane for offshore wind turbines. The second profile occurs during a period with similar stable stratification but demonstrates a strong monotonic shear.

Although the suppression of turbulence by the vertical temperature gradient in the stable boundary layer allows for LLJs to keep from being mixed out and for strong shears to be maintained, the surface horizontal temperature gradient (baroclinicity) can be important for determining the strength and height of the LLJ (Helmis, 2013; Mahrt et al., 2014). This baroclinicity can result not only from synoptic-scale weather systems but also from land–sea temperature differences and gradients in SSTs, including those caused by coastal upwelling and the presence of the Gulf Stream. These baroclinically driven near-coastal jets can then be influenced by inertial effects and by complex coastlines and associated topography (Burk and Thompson, 1996). The resultant winds can subsequently modify the SSTs, which can then lead to a further adjustment of the winds in a complex feedback process. An example of locally driven coastal winds and their impacts on SSTs is provided by Hong (2009), who found large amplitude, small-spatial-scale SST variability (6 °C over 5–10 km) in the area south of Martha's Vine-

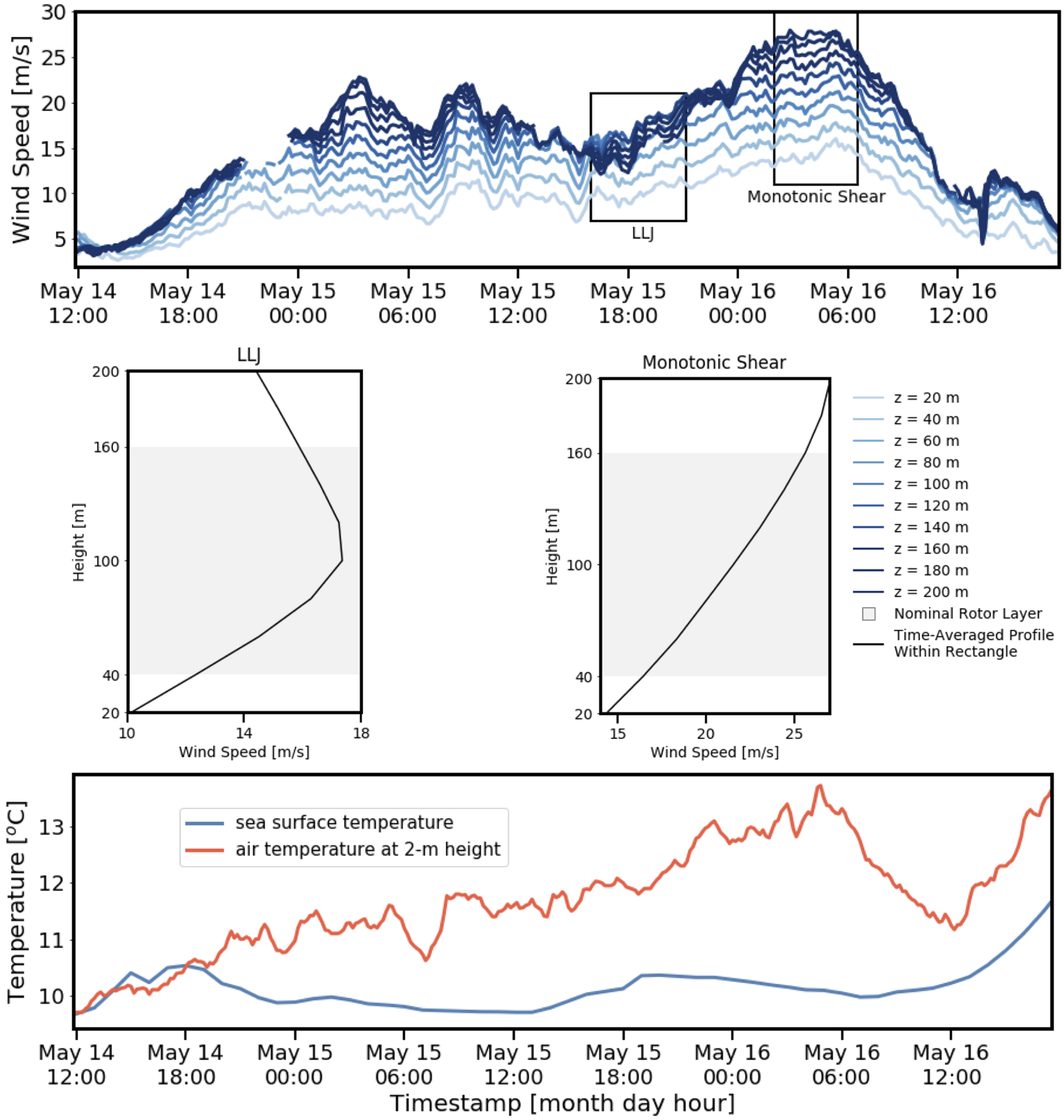

Figure 5. A high-shear wind event measured by a floating lidar deployed within the wind lease areas of the New Jersey coast (top). The middle figure provides the time-averaged wind speed profiles of the black boxes shown in the top figure. The SST and air temperature at 2 m height measured at the same location are provided in the bottom figure (from Debnath et al., 2021).

yard that was linked to highly spatially variable coastal winds associated with the complex coastline. The magnitudes of these SST gradients were observed to change significantly on the timescale of a day.

Physical processes that control ABL stratification include temperature advection and its variation with height, the surface heat flux, subsidence, and entrainment at the top of the boundary layer. In addition, radiative flux divergence can be important, especially in ABLs that contain fog or boundary layer stratus clouds, which often are present in very stably stratified conditions. Coastal fog or stratus can also advect onshore to varying distances and, by doing so, reduce overland heating in the daytime, consequently altering the development of sea breeze flows.

Measuring stratification itself, as well as the controlling physical processes of temperature advection, surface heat flux, subsidence, entrainment, and the radiative flux divergence, both offshore and in the coastal zone, is a daunting challenge; long-term observations of these quantities are largely missing in the difficult offshore environment. Temperature and wind observations through the depth of the boundary layer and the entrainment processes at the top of the ABL will certainly require some type of remote sensing approach, perhaps using a combination of coastal, island, and buoy deployments. For shorter-term intensive observation periods, aircraft, unmanned aerial systems, and ship- or barge-based platforms would be useful.

Given the myriad forcing mechanisms affecting coastal ABL stratification and LLJs, it is not surprising that they are difficult to simulate accurately (Jiang and Edson, 2020). Simulating, including forecasting, these conditions is challenging for multiple reasons. First, forecasting the stable boundary layer is more difficult in general than forecasting the neutral boundary layer, even over land. Small variations in model initial conditions, including spatial gradients, can result in low-level jets with significantly different structure and boundary layer shear. Second, boundary layer parameterizations are less well understood and less constrained by observations for strong stratification, either stable or unstable. As one example of the first issue, Shimada (2015) showed that having accurate, high-resolution SST data sets that resolve near-coastal variability is important for reducing errors in the estimation of annual average wind speeds and for reducing model forecast root mean squared error (RMSE), with a 3 °C difference in SST causing an approximate 6 % difference in the wind energy density at a height of 80 m. Having the ability to run numerical weather prediction models with high-spatial-resolution SSTs is necessary for wind resource estimation, and having the ability to run coupled atmosphere–ocean models that can resolve rapidly evolving coastal SSTs seems a necessity for wind energy forecasting (discussed further in Sect. 5).

4 Wind shear and turbulence in the rotor layer

Unsteady characteristics of wind speed due to various atmospheric phenomena add complexity to wind power generation and reliability (Wagner et al., 2011; Murphy et al., 2020). Ambient turbulence modulates the mixing of the wind inside a wind farm. In this way, the ambient turbulence influences the overall power production from a wind farm and the fatigue loads on the turbines (Wu and Porté-Agel, 2012). For example, low ambient turbulence energy contributes little to no mixing of higher-momentum air aloft into the wind plant. This slows the recovery of flow in individual turbine wakes and can thus reduce the overall power production of a wind farm. Conversely, high ambient turbulence accelerates the mixing of wind and facilitates power production but increases the load on the turbines.

Turbulent wind fluctuations govern the aerodynamic performance of wind turbine blades. The rotating blades add turbulence to the wind as they extract energy, and this turbulence can subsequently propagate throughout the wind farm and substantially increase the wind load on the downstream turbines (Frandsen, 2007). Depending on the ambient turbulence and turbine operating conditions, the blades add different levels of turbulence energy to the downstream wind (Magnusson and Smedman, 1994; Crespo and Hernández, 1996; Chamorro and Porté-Agel, 2009). Understanding ambient wind conditions is therefore necessary to accurately assess the expected lifetime of the turbine blades and the power performance of the wind farms.

The unsteady characteristics and variation of wind with height are conventionally expressed in terms of commonly used variables, such as wind shear, wind veer, turbulence intensity, TKE, and wind coherence. The behavior of these key variables at rotor heights is connected to a wide variety of meteorological phenomena, such as land–sea circulations, wave–atmosphere interactions, synoptic-scale events, and coastal topography, in ways that are not fully understood. These different offshore phenomena create large variations in the wind characteristics and ultimately add uncertainty in the wind plant load and power performance calculations.

Offshore wind turbines are larger in diameter than onshore turbines, with current diameters ranging from 120 to 220 m (IRENA, 2019; GE Renew. Energ., 2019; Gaertner et al., 2020), and the shear and veer within the boundary layer will have significant impact on the offshore turbines and their performance (Murphy et al., 2020). Stable stratification has a notably large impact on such large rotors. The stable ABL generally contains weaker turbulence and lower boundary layer heights together with higher wind shear and veer. Within very shallow boundary layers, the turbine blades can plausibly intersect both the surface layer and top of the ABL. At the lowest point of each rotation, blades may intersect the surface layer. At the top, blade tips may encounter the nose of an LLJ or pass through the boundary layer top, thus covering almost the whole ABL within the rotor-swept area. The resulting variation of turbulence, wind shear, and veer within such a large rotor layer can add significant loads on the turbine blades and gearbox components, thus shortening the life of blades and gearbox components (Lee et al., 2013). Under these conditions, simple power laws or log laws do a poor job of describing the shear and veer conditions encountered by wind turbines. Moreover, there are no other analog functions available for these variables. Validating the ability of numerical models to reproduce the shear, veer, and turbulence in the rotor-swept area for the range of offshore conditions with sufficient accuracy to satisfy turbine engineering and operational needs remains a major challenge for offshore wind energy.

The joint occurrence of shallower boundary layers and low turbulence also results in persistent turbine-induced wakes, which can reduce the power production of downstream turbines within wind plants. Wind turbines extract momentum from wind, producing wakes that propagate downstream and reduce the power production from subsequent turbines. The availability of the wind resource for the downstream turbine is dependent on the recovery of the wake generated by the upstream turbine, and the recovery of the wake is dependent on the mixing and interactions of wake with surrounding ambient wind. If the incoming wind turbulence is low, wakes from the individual turbines persist longer. This in turn reduces the wind resource for the next row of turbines, thus reducing the overall power production from the wind plant (Lundquist et al., 2019; Porté-Agel et al., 2020; Platis et al., 2018). Lundquist et al. (2019) also showed that if the turbulence intensity is low, the aggregate wake from a wind plant can persist up to 40 km downstream. This could substantially influence the planning and design of offshore wind plants.

There are different wind turbine control strategies to manage the wind turbine wake and improve the performance of the wind plant power. The common strategies are wake steering (Fleming et al., 2017, 2019), consensus control (Wang et al., 2018; Gionfra et al., 2017; Annoni et al., 2019), dynamic induction control (Steinbuch et al., 1988; Dilip and Porté-Agel 2017; Munters et al., 2018; Wang et al., 2020), and wake steering with induction control (Bossanyi, 2018). Even the control strategies are dependent on the atmospheric conditions showing significant power gain in stable ABL and minimal power gain in unstable ABL (Fleming et al., 2017, 2019). Thus, an accurate prediction of both height and time variation of the wind (e.g., wind shear, wind veer, turbulence intensity) is important to wind energy applications.

Besides time and height variation of wind, offshore wind faces a significant horizontal variation of wind due to the spatial variation of SST and different marine atmospheric phenomena (Edson et al., 1999, 2007; Wang et al., 2018). Considering the large diameter of offshore wind turbines, the spatial variability of wind and coherent structures could introduce more load on the turbines (Velarde and Bachynski, 2017; Wise and Bachynski, 2020). The wind industry uses hub height turbulence (e.g., turbulence intensity) of the wind flow to estimate the wind loads on turbines. In addition, the class of wind turbines (International Electrotechnical Commission, 2019) for a project is chosen based on the turbulence intensity at the site. The proper selection of turbine classes for a project directly influences the outcome of the project investment. In summary, the cost of offshore wind energy is highly controlled by the wind turbulence (Mora et al., 2019).

Another important aspect of offshore wind turbulence is its interaction with the rotor and thereby its implications for a turbine's power and load fluctuations. A number of recent studies have shown that the rotor acts as a low-pass filter to incoming turbulence (Chamorro et al., 2015; Tobin et al., 2015; Anvari et al., 2016; Deskos et al., 2020). That is, when large, energetic, turbulent structures pass through the rotor, they will yield bending moment and shaft torque fluctuations at a similar frequency and magnitude, while smaller structures will have a smaller effect, apart from the blade-passing frequency and its higher harmonics, in which case the amplitude of the load will resonate with the rotating blade. The spectral distribution of bending moment and torque fluctuations are inherently related to blade and main shaft bearing fatigue and may lead to premature failures of these components. On the other hand, in turbine clusters (arrays), resonant modes are the result of a canonical turbine spacing (equal spacing in each direction) and their spectral signature can be detected in the power and load spectra at much lower frequencies. Recent analysis of the power fluctuations of laboratory-scale and real-scale wind farms has shown that a timescale S/U, where S and U are the spacing and velocity magnitude in the dominant wind direction, is the main parameter that shapes the power spectra (Bossuyt et al., 2017; Lukassen et al., 2018; Seifert et al., 2021). However, the origin of offshore wind plant-aggregate power fluctuations is much more involved, and many environmental factors – such as changes in wind speed or wind direction, influences from neighboring wind farms, or their own state of operation (Seifert et al., 2021) – may play an important role. Nonetheless, such wind plant-wide fluctuations may create challenges for grid stability, particularly in the offshore environment; therefore, additional investigation may be required.

Low-frequency large-scale structures or high-frequency small-scale structures both are important in power production and fluctuation, as well as load on the turbine blades and gearbox components, and, ultimately, add uncertainty to the forecasted power that will be added to the power grid.

Numerical models such as the Weather Research and Forecasting (WRF) model can provide spatial variability of wind and profiles throughout the marine ABL influenced by the synoptic, mesoscale, and microscale processes. However, the WRF model often poorly represents turbulent parameters such as the friction velocity and sensible heat flux and exhibits errors in offshore wind resource assessments due to different mesoscale and microscale forcings as well as sea surface interactions. Numerical weather prediction models provide estimates of TKE rather than turbulence intensity, but these calculations remain largely unvalidated with observations offshore. The numerical models need to have better predictability a priori for offshore wind farms to save the cost of repair in marine environments.

5 Modeling the marine atmospheric boundary layer

5.1 Overview

Many different types of models have been used by the engineering and scientific communities to characterize metocean conditions, as well as conduct offshore wind resource assessments, site selection, and individual turbine and wind farm design and optimization studies (Kalvig et al., 2014; Veers et al., 2019). Yet, there are remaining challenges in modeling the offshore environment that still require significant research efforts to be made. Compared to its land-based counterpart, the marine ABL poses additional challenges from a modeler's point of view thanks to the presence of air–sea interactions that comprise several physical processes spanning multiple orders of magnitude both in temporal and spatial scales (Sullivan and McWilliams, 2010). Traditionally, atmospheric models have been split into two main categories based on their ability to resolve ranges of scales – mesoscale (10–1000 km) models and microscale models (less than 1 km). Mesoscale models are relevant to offshore wind resource assessment, whereas microscale models attempt to better couple wind and waves and more accurately describe the mass, momentum, heat, and humidity exchange at the air–sea interface. From an offshore wind energy point of view, microscale models can potentially be used to obtain structural loads and power output under both operational and extreme weather conditions. Structural load assessment of extreme and non-operational conditions poses an additional challenge, as the modeling approach should account for the coupled influences of the changing wind, wave, and current fields throughout their evolution (Kim et al., 2016). Even under normal operational conditions, technical modeling challenges arise from the presence of combined aero- and hydrodynamic loading effects and the modeler's ability to predict the life cycle fatigue load spectrum. This may require accurately predicting the directional wave spectra in addition to characterizing the available wind resource. Because of the nonlinearities associated with the aerodynamics and hydrodynamics, the simulations are typically run in the time domain. To that end, extrapolation techniques are needed to capture the full range and duration of all the stochastic loading from wind and waves, often in a coupled fashion (Butterfield et al., 2007). An additional complexity in offshore wind energy applications is that the presence of turbine rotors and other supporting structures affects the marine ABL (see Fig. 2), creating atmospheric wakes, potentially triggering gravity waves, as well as impacts via coupling with hydrodynamics in case of floating structures.

5.2 Current state-of-the-art modeling practices

5.2.1 Microscale models

Microscale models can be divided into two main categories – the wave-phase-averaged and the wave-phase-resolving models (Deskos et al., 2021). Wave-phase-averaged models consider empirical bulk formulae to compute interfacial stresses based on quantities such as wave age (Donelan, 1990; Smith et al., 1992; Fairall et al., 2003; Oost et al., 2002), measures of sea spray (Liu et al., 2011), significant wave height and length (Warner et al., 2010; Geernaert et al., 1986, 1987; Geernaert 1990; Smith et al., 1992; DeCosmo et al., 1996; Taylor and Yelland, 2001; Foreman and Emeis, 2010; Jiménez and Dudhia, 2018), or 2-D wave spectra (Wu et al., 2019). On the other hand, wave-phase-resolved simulations (Yang et al., 2013; Sullivan et al., 2008, 2014, 2018a, b; Hao et al., 2018) resolve both the airflow turbulence and the phase of the underlying waves. To this end, phase-resolved models need to combine two models to resolve the flow within the wave boundary layer and thereby accurately capture the momentum and scalar quantities flux transfers (upward or downward) between the wind and waves. The model coupling comprises exchanging velocity, pressure, and free-surface elevation at the air–sea interface. The two models use different assumptions for the flow field; the wave propagation is often described through potential flow theory with nonlinear free-surface dynamic boundary conditions, while the airflow is described via the incompressible Navier–Stokes equations. Wave-phase-resolved simulations represent the highest-fidelity models and exhibit computational limitations due to their increased need for resolution and inherent algorithmic complexity. To this end, they are often used to study the fundamentals of wind–wave interaction or to inform models and correct existing drag law models (e.g., Andreas et al., 2012) about the wave age parameter (Sullivan et al., 2014) or swell direction (e.g., in the WRF model as in Patton et al., 2019). One question arising from the use of wave-phase-resolved simulations is whether two-way coupling between the two models is needed. It can be argued that the timescales characterizing the evolution of wind waves are disparate with waves growing much slower than the evolution of the boundary layer eddies, and therefore two-way coupled simulations may be beneficial for simulations of forecast lengths of > 2 d. In a similar fashion, under swell-dominated seas, the waves are moving much faster than the local winds without dissipating. To this end and for short-term forecasts, a one-way coupling approach (from the waves to the wind) is often preferred (Deskos et al., 2021). It is worth noting, however, that when wind–wave interaction between steep waves with strong wind forcing is considered, which leads to intermittent wave breaking, the above-described loose coupling breaks down, and thus a two-phase flow approach may be needed. Events such as wave plunging may have a substantial impact on the turbulence statistics and flow structures near the wave surface, with timescales comparable to the wind eddy turnover timescale (Yang et al., 2018).

5.2.2 Mesoscale models

Atmospheric and ocean circulation patterns have large scales in both space (10–1000 km horizontally) and time (hours to weeks); therefore, mesoscale models are required to characterize the atmospheric and oceanic "weather" conditions and sea state entering the offshore wind farm region. The charge of modeling ocean wind waves at these scales is particularly challenging because whereas waves are driven by the mesoscale weather, individual waves have periods on the order of seconds and wavelengths on the order of meters. This otherwise computationally prohibitive challenge is removed by using phase-averaged spectral wave models that simulate the integrated wave energy spectrum instead of the time–space evolution of the sea surface elevation (Pringle and Kotamarthi, 2021). Specific phase-averaged spectral wave modes most commonly used for wind–wave coupling are the WAVEWATCH III (WW3; WW3DG, 2019) and the Simulating Waves Nearshore (SWAN; SWAN team, 2020) models. Due to the mesh type and numerical implementations of each model (cf. Pringle and Kotamarthi, 2021), traditionally WW3 is used for global and regional simulations, whereas

SWAN is used for high-resolution simulations in a local region including the nearshore area. Recent developments for handling unstructured meshes and implicit time stepping in WW3 mean that it can now be efficiently applied to simulations across a range of scales, including the nearshore area, in a single model (Abdolali et al., 2020a, b).

To properly characterize the mesoscale weather conditions in the marine ABL for an offshore wind farm requires accounting for the interaction between the atmosphere and the ocean, as represented by separate models for the wind, ocean currents, and waves. A number of so-called coupled atmosphere–wave–ocean modeling systems have been developed in the last one to two decades (e.g., Chen et al., 2007; Liu et al., 2011; Warner et al., 2010; Zhang et al., 2009; Li et al., 2019; Wu et al., 2020). Such coupled models explicitly account for SST evolution from ocean mixing driven by marine ABL winds. They have typically been developed with a primary focus on tropical cyclone research and prediction that can be utilized for such extreme conditions that are encountered offshore of the US Atlantic coastline. However, coupled models such as the Coupled Ocean–Atmosphere–Wave–Sediment Transport modeling system (COAWST; Warner et al., 2010), the Uppsala University Coupled model (UU-CM; Wu et al., 2019), and the Chemical Hydrological Atmospheric Ocean wave System (CHAOS; Varlas et al., 2018) are now being used to characterize the offshore wind energy resource. Results from the North and Baltic seas generally indicate that under low to moderate wind speeds, model coupling will provide lower estimates (order of 10 %) of offshore wind power density than an uncoupled atmospheric model, whereas there is a negligible difference for higher wind speeds (Pringle and Kotamarthi, 2021).

Implementing coupled atmosphere–wave–ocean modeling systems involves linking the individual models through coupling toolkits (e.g., Jacob et al., 2005; Larson et al., 2005; Craig et al., 2017) that interpolate and exchange the pertinent interfacial quantities, such as surface wind velocities, SST, and significant wave heights. Within these coupled modeling systems, the determination of the interfacial air–sea fluxes is one of the most important considerations, which depends on sea surface roughness (waves), SST and velocity, and the effects of sea spray and wave breaking. A number of empirical bulk formulae have been used to parameterize these fluxes with a particular focus on the sea surface roughness aspect, typically based on either wave steepness (Warner et al., 2010; Geernaert et al., 1986, 1987; Geernaert 1990; Smith et al., 1992; DeCosmo et al., 1996; Taylor and Yelland 2001; Foreman and Emeis, 2010; Jiménez and Dudhia, 2018) or wave age (Donelan 1990; Smith et al., 1992; Fairall et al., 2003; Oost et al., 2002; Patton et al., 2019), which indicates whether the waves are being driven by the local winds and growing (a young sea) or whether the waves are mostly old swell waves that are propagating from a far-field location. An additional consideration is accurate resolution of SST variability, which, as described in Sect. 3, can impact both mesoscale and microscale flow parameters of relevance to offshore wind energy.

5.3 Opportunities for improving the modeling of the marine ABL

As we mentioned above, both microscale and mesoscale models provide solutions that can be used to resolve different scales and account for different physical processes. However, there are still pathways and opportunities in the pursuit of improving the current offshore wind energy modeling capability. This includes individually improving existing microscale and mesoscale models; their coupling, also known as meso-microscale coupling (MMC); and the introduction of new algorithms, either physics-based or data-driven, to existing high-fidelity models. Finally, another avenue for improving existing capabilities, although tangential to the modeling efforts, is the optimization of the design and the structure of existing numerical model codebases in order to be adapted to future exascale high-performance computing (HPC) systems.

Starting with the microscale models, and in particular the wave-phase-resolved simulations, a number of challenges remain regarding the representation of the wall-shear stress model atop moving waves (Yang et al., 2013), as well as the incorporation of wave breaking, air entrainment in existing LES models. Wave breaking and slamming during extreme weather conditions, especially in shallow coastal waters, necessitates the use of phase-resolving wave models, while also considering the complex interface with the atmosphere and the effects of sea spray (Richter and Sullivan, 2013). In lieu of physics-based models that can incorporate such complex behavior, ML-based (machine learning) wall-stress models can offer an alternative pathway. Other important topics for future research include modeling of subgrid-scale phenomena, small-wavelength wind-driven waves, and smaller-scale turbulence occurring within the wind turbine wake region. Similarly, mesoscale models can adopt wave-informed drag models that account for different air–sea interaction phenomena, such as wind–wave misalignment (Patton et al., 2019); variable SST boundary conditions; and, potentially, wave breaking.

On improving the MMC modeling aspect of wind–wave interaction, using SWAN or WW3 to generate wave boundary conditions for microscale models may also require an interface between the mesoscale and microscale models. To this end, microscale models will require an accurate prescription of inflow conditions that mimics all relevant characteristics of the atmospheric and oceanic fields, such as the sheared velocity profile, the anisotropy of the turbulence, and the nonstationary nature of the inflow (Sanderse et al., 2011). The effects of highly variable inflow are known to have a nontrivial influence on fundamental aerodynamic characteristics of the airfoil (Veers et al., 2019). Therefore, overly simplified inflow conditions can lead to significant errors. In the metocean environment, the inflow sea state is also critical. This is commonly described by a particular spectrum (e.g., JONSWAP) with a given significant wave height and peak spectral period (Sebastian and Lackner, 2012). However, further research is required to truly understand the effects of different sea states and breaking/non-breaking waves on atmospheric wakes at the rotor layer.

Both microscale and mesoscale models will be greatly benefited by their portability to modern HPC systems, in particular those using GPUs (graphics processing units), which will provide significantly enhanced computation throughput. An additional pathway for improvement is the use of higher-order numerical schemes, which not only afford higher accuracy for the same number of mesh nodes but also provide higher scalability and parallelization of the simulation codes in the upcoming exascale computing systems, such as Summit, Aurora, and Frontier at US Department of Energy laboratories. The systems that will be coming online within this decade (2020–2030) rely heavily on GPUs for performance and require substantial refactoring of the implementation of existing codebases. Existing examples of microscale codes that have been refactored to become GPU-ready to take full advantage of the next HPC frontier include nekRS (Fischer et al., 2021), amr-wind (Sprague et al., 2020), and FastEddy® (Sauer and Munoz-Esparza, 2020).

In addition, there is need to improve data assimilation (DA) methods for offshore wind energy applications. The initial conditions of the model are extremely important, especially for the short-term (hours to days) forecast length. The value of assimilation for wind computations at turbine heights offshore has been demonstrated, for example, for wind profiling radar data (Djalalova et al., 2016). However, because of the interaction between the atmosphere and ocean, a coupled DA approach that initializes both the atmosphere and the ocean states is desirable (e.g., Zhang et al., 2020). It is unclear whether a strongly coupled DA approach, which would produce a balanced set of initial conditions for both the ocean and atmosphere simultaneously (e.g., Frolov et al., 2016), or a weakly coupled DA approach, which initializes the atmosphere and ocean separately (e.g., Browne et al., 2019), would be better. From an abstract point of view, it would seem that the former would provide more optimal initial conditions for the forecast model; however, strongly coupled DA systems are inherently more complex than weakly coupled DA approaches and require colocated observations of the ocean state (including subsurface profiles) and the atmosphere (e.g., Tang et al., 2020). Regardless, any coupled DA method requires observations of the atmosphere and ocean states over and beyond the spatial domain of interest, especially as initial conditions well outside the domain can influence longer forecasts.

6 Impacts of precipitation

The impacts of precipitation to wind turbine blades potentially cause damage at the leading edges, typically at the outer one-third of the blades. Here, the blades travel through the air mass with high speed (Keegan et al., 2013; Slot et al., 2015). The hydrometeor particles hitting the coating material may initiate a progression of changes from initial incubation through to erosion (Dashtkat et al., 2019). The processes are not well known, but it appears evident that higher tip speed worsens the problem. The erosion is initiated near the tip and grows inward along the leading edge, based on observations from turbines in an offshore wind farm (Eisenberg et al., 2018). Similar results are reported from accelerated tests in rain erosion test facilities (ASTM, 2021; Bech et al., 2018).

Knowledge of the drop size and phase of the particles, either liquid or solid, is important for predicting the erosion processes. Liquid precipitation in the form of rain is generally most abundant, but even brief hail events can cause significant damage (Letson et al., 2020a). A hailstone is by definition larger than 6 mm in diameter and therefore larger than most raindrops (although raindrops occasionally can be larger). Rainfall drop size distribution varies with weather type (e.g., stratiform rain is characterized by smaller drops, while convective showers are characterized by larger drops). Interestingly, during high wind speeds, the tendency is that raindrops break up and the size distribution changes (Tilg et al., 2020b). For leading-edge erosion, it is the rain events occurring during high wind speeds that are of particular interest. Wind turbines operate with high rotational speed during high winds; hence, the tip speed is high. The closing velocity between hydrometeors and turbine blades is a combination of the speed of the blade, the drop fall velocity, and the angle of attack. The tip speed is an order of magnitude larger than the drop fall velocity and is therefore the most important variable (Keegan et al., 2013). The impact kinetic energy is a function of speed and mass of the particle.

The main challenge in predicting the leading-edge erosion process at a given site is the sparse knowledge on rain amount and drop size distribution, in particular in offshore locations. It is not (yet) custom to observe drop size and rain rate at wind farm tender areas or at existing wind farms. Observations of rain during high winds suffer from known bias (undercatch), as only a fraction of the falling rain is captured in the rain gauge. Therefore, rain gauges are often located at slightly sheltered sites. Another challenge is to establish a sufficiently long time series to describe the characteristics of the occurrence of wind speed and rain rate jointly. In particular, the high-end tail of the joint distribution of high wind speed and high rain rate is often under-sampled in short-term data sets. Statistics on extreme wind speed as well as extreme rain events call for long consistent time series to provide reliable statistics. A study using over a decade of weather station data in Denmark at 10 min resolution revealed that high rain rates never occurred during high wind speed events at two inland stations, while at all five coastal stations high-wind-speed and high rain rate occur jointly (Hasager et al., 2020). Expanding the study to longer time series and more meteorological stations indicates that 10 years of data are needed to estimate the lifetime (Hasager et al., 2021).

The coastal and marine environments may be more detrimental than onshore conditions to turbine blades. This may, in part, explain why unexpected repairs at several offshore wind farms have been carried out (Herring et al., 2019). In addition, as offshore turbines grow in size, a given rotational speed will generate higher tip speeds, resulting in greater erosion (Keegan et al., 2013).

The mitigation strategies for leading-edge erosion take two routes. The first is to develop coatings that are resistant to rain erosion (Dashtkar et al., 2019; Herring et al., 2019) and to repair blades with degraded coatings more quickly (Mishnaevsky, 2019). While the latter is common practice for offshore sites, repair is costly. It can be difficult to find suitable weather windows, as some coatings require particular temperature and humidity ranges and time for curing. Furthermore, to predict when the next repair is necessary is a challenge without prior knowledge on the leading-edge erosion processes and the wind and rain climate at the site.

The second mitigation strategy is to slow down the turbines during heavy rain events to prolong the lifetime before repair is needed. The turbines should still be in operation but with fewer revolutions per minute (Bech et al., 2018). The method is called erosion-safe mode operation. During hail events, standstill may be safest. Several aspects need to be taken into account before the cost benefit of erosion-safe mode operation for a wind farm owner is clear. First, the loss in energy production during periods slowing down turbines due to heavy rain should be considered. If this happens during times with low electricity market prices, not much earning will be lost. In this case, the spot market price is high, and it might be relevant to operate with only a little slowdown or short interval with over torque. Second, operating the turbines with eroded blades will cause a loss in annual energy production of a few percent (Bak et al., 2020). Third, the cost of repair and the downtime during repair has to be considered. An optimization of the parameters is presented in Skrzypiński et al. (2020) and shows profit for owners. To implement erosion-safe mode operation, rain detection at sufficient temporal and spatial resolution is suggested. One candidate measurement technology for this purpose is to deploy a micro rain radar near the turbines (Tilg et al., 2020a).

In summary, the challenge of predicting leading-edge erosion at sites is to ensure reliable and representative observations. These data could be from disdrometers observing the drop size distribution (Kathiravelu et al., 2016). In the offshore environment, precipitation observation from Earth Observing satellites, such as the Global Precipitation Measurement mission (Huffman et al., 2014; Rios Gaona et al., 2016), may be an option to prepare wind and rain statistics relevant for leading-edge erosion. More specifically, the drop size distribution from the Global Precipitation Measurement mission (Le and Chandrasekar, 2014) may be relevant for leading-edge erosion. Validation of the satellite-based rain products would be useful, and characterization of drop size distribution with high temporal resolution based on in situ observation concurrent with wind measurements would be ideal. A ground-based radar network is an alternative source of information to provide offshore coverage (Fairman et al., 2017). These observations will be affected by scattering off the turbine blades, however (e.g., Norin, 2015). Again, local observations in the offshore environment are necessary to provide reliable rain statistics.

Modeling the wind and rain using numerical weather prediction models is an option for characterizing the precipitation erosion environment. Global-scale and limited-area models using horizontal grid spacings of greater than a few kilometers generally lack the ability to represent precipitation characteristics of relevance to leading-edge erosion, either relying on simplified microphysical treatments or in some cases using superparameterizations (e.g., Khairoutdinov et al., 2005) or other approaches to provide higher-fidelity microphysical information that is then aggregated back to the coarse model mesh. However, models employing grid spacings of a few kilometers or less can employ much more sophisticated bulk or spectral (bin) microphysical parameterizations, or combinations of those approaches, each of which can predict relevant microphysical processes and precipitation characteristics at the scale of the individual cloud or smaller. Many such schemes are available within community atmospheric models, such as WRF, and have been evaluated in storm events featuring heavy precipitation, including supercell thunderstorms, squall lines (which comprise the dominant mesoscale convective storm morphology in offshore environments), or tropical storms and hurricanes (Khain et al., 2015).

Prediction of the raindrop size distribution requires at least the complexity of a two-moment bulk scheme, which independently evolves the mass mixing ratio and mean drop size (whereas single-moment schemes predict only mass mixing ratio) but makes assumptions about the shape of the size distribution. While bulk schemes only predict the number and mass-weighted mean drop fall speeds, the fall speed can be calculated offline using the scheme's fall speed–size relation. Bin schemes, which predict cloud parameters in discrete size intervals, evolve the drop size distribution shape explicitly, as well as calculating the fall speed in each size (or mass) bin (Morrison et al., 2020). Comparisons among single-moment, higher-moment, and bin schemes (Khain et al., 2015) generally conclude that higher-moment bulk schemes and spectral bin schemes provide superior performance to one-moment schemes in WRF and other models in heavy precipitation events and specifically squall lines (e.g., Khain and Lynn 2009; Li et al., 2009a, b; Morrison et al., 2009; Baldauf et al., 2011). Treatment of hail is also possible with higher-moment bulk and bin schemes, with several studies indicating that a three-moment representation of the hail particle size distribution is required to accurately predict hail larger than a couple of centimeters in diameter (Loftus and Cotton, 2014; Milbrandt and Yau, 2006).

Letson et al. (2020b) have investigated output from the WRF model on hailstorms for leading-edge erosion for a short period of less than 1 month. Further investigation of the efficacy of more sophisticated microphysical schemes in WRF and other community models over multiple events and for longer periods is recommended to assess their value relative to their increased computational expense, which can be marginally greater for higher-moment bulk schemes and significantly greater (1 to 2 orders of magnitude) for bin schemes.

7 Applications of machine learning

In recent years, a large institutional and scientific interest in the topic of machine learning (ML) has been emerging in the climate and renewable energy disciplines (e.g., Stevens et al., 2020), and rapid advances have been made, as discussed below. The promise of ML lies in the ability to make full use of big data, including those provided by networks of remote sensing systems and computationally expensive model results. ML can use these data to detect patterns of complex nonlinear phenomena that are typically not feasible using traditional theoretical and empirical analysis. The hope is that this will help further our scientific understanding of the relationship between wind, waves, and turbine wakes within the marine ABL, and provide low-cost surrogate models for a wide range of applications in the offshore wind energy industry.

ML methods, such as neural networks, are well suited to developing functional relationships between inputs and outputs of interest, having been successfully applied to numerous atmospheric physical processes (Wang et al., 2019) to generate new parameterizations, to emulate existing ones (e.g., Lagerquist et al., 2021; Gettelman et al., 2021), or even to emulate the physics and dynamics of a simple general circulation model (Scher, 2018). Recent advances have been made in ML-based surface layer parameterization to replace the M–O theory-based parameterization by developing ML parameterizations directly from observations and thus avoid the assumptions imposed by the M–O similarity theory (McCandless et al., 2022). Initial results from this study indicate that ML models trained on several years of observations from the Cabauw mast in the Netherlands and from the NOAA's Field Research Division tower in Idaho outperform the M–O theory-based surface layer parameterizations.

In addition to these advances in the onshore environment, the difficulty of obtaining a universal, physics-based understanding and representation of how the air–sea interface impacts flow quantities of interest in the offshore environment may also be mitigated by ML methods (e.g., Dettling et al., 2021). Jiang et al. (2018) achieved a reduction of the error associated with the predicted maximum wind intensity of 60 %–70 % by using a neural-network-based algorithm to represent typhoon-induced sea surface cooling. In a similar fashion, Bessac et al. (2019) highlighted that subgrid-scale sea surface fluxes are better represented using stochastic Gaussian process models than deterministic bulk flux parameterizations. Other than model parameterizations, ML devices have also been used to directly forecast offshore wind power by training neural network models on metocean reanalysis data (Balluff et al., 2015) or on in situ supervisory control and data acquisition (SCADA) measurements (Lin et al., 2020).

Finally, it must be stressed that ML methods require extensive data sets upon which to train and therefore will require novel and extensive measurements of key input and output variables spanning a range of atmospheric conditions. Long-term observations, under all stability conditions and representative of various offshore regions, will be critical for advancing this field and evaluating how the emerging ML models perform in the representation of complex physical processes in offshore environments. Furthermore, computational models with sufficiently high fidelity (e.g., LES) can also be used to generate data for training of ML approaches. Recently, Fytanidis et al. (2021) showed that flow wakes behind tall buildings could be accurately predicted with a reduced order model trained on LES simulations, and a similar approach could be applied to offshore wind turbine wakes.

8 Summary and recommendations

8.1 Summary

Early in this review, we noted that atmospheric processes affecting winds and turbulence, which in turn modulate the production of energy from wind, span at least 5 orders of magnitude. In addition, smaller scales become important if processes of fluid–structure interaction are included. Even with modern advances in computing, it is not feasible to resolve all of these scales simultaneously in a single model. A standard approach is to nest models of increasing fine resolution. This requires that unresolved processes be parameterized, however, and current parameterizations are generally scale-dependent and often embody assumptions that are routinely violated, as in classical M–O theory, or are simply not tested over the range of atmospheric conditions to which they are applied. The range of scales and the uncertainty of the some of the physics supporting the subgrid-scale parameterizations make the accurate representation of wind flow into and through wind plants one of the grand challenges of wind energy science.

The atmospheric sciences grand challenge is enhanced offshore for the following reasons:

- The marine ABL is poorly observed for wind energy, which has severely limited the validation of existing models and the associated identification of specific physics issues in the models.

- Air–sea interaction is a complex process involving nonlinear feedbacks between winds and waves that both modify the wind profile and generate complex physical loads on wind turbine structures.

- Current-driven spatial SST variations often generate stable thermodynamic stratification, which generates complicated layering, wind profiles, and turbulence impacts in the rotor layer.

- The coastal boundary between land and sea generates phenomena such as low-level jets, which are difficult to simulate accurately but are low enough in altitude to significantly affect both power generation and mechanical loads on turbine structures.

- Optimal modeling approaches offshore are currently unclear with respect to the way the ocean and the atmosphere should be coupled for the various time and space scale of interest. Does the ocean mixed layer need to be fully coupled to the marine ABL? Should there be two-way coupling between the waves and the atmosphere, or is one-way coupling sufficient? Can artificial intelligence and ML assist with some of the more troublesome parameterizations?

- Precipitation is a significant contributor to leading-edge erosion on wind turbine blades, but our ability to simulate associated drop size distributions offshore is severely limited by the lack of observations of what those distributions actually are.

8.2 Specific challenges and recommendations

8.2.1 Model validation

There is no substitute for observations in the real atmosphere for validation of atmospheric models, and validating observations need to span a large subset of the conditions to which models will be applied. The marine ABL, however, is a notably hostile environment for making measurements, and there are few stable platforms at sea on which to mount sophisticated profiling instrumentation. Except for satellite observations of clouds and the surface and for surface measurements from buoys, long-term observations of the marine ABL, especially in the rotor-swept area, remain rare. Recommendations are the following:

- *Large-scale, multi-seasonal field studies.*

  Validating models that span many scales is most efficiently done with observation sets that also span the simulated scales. The second Wind Forecast Improvement Project (WFIP2; Shaw et al., 2019) was a successful realization of this concept on land, and similar studies are needed in the offshore environment. Such studies are costly and require national-scale investment, but as WFIP2 demonstrated, the payoff can be significant.

- *Adaptation of land-based measurement systems for long-term deployment at sea.*

  Many important observations, such as surface winds, sea surface temperatures, current profiles, wind profiles, and wave spectra, are already routinely available from buoys or other platforms at sea. However, for understanding and advancing model performance offshore, the following additional observations are needed.

  - *Remote sensing methods.*
    These methods are currently the most promising path for obtaining key observations above the surface in a cost-effective manner. Motion-correcting Doppler lidar systems are now routinely mounted on buoys and deployed for many months, and these excel at providing wind profiles through the rotor-swept area of wind turbines. However, this only provides wind information to a maximum altitude of about 300 m above the surface. To understand resource characterization model performance, the following information is also needed:

    - wind vector profiles through the entire depth of the marine ABL and above, as are currently provided on land by Doppler radars and Doppler lidars
    - profiles of temperature and humidity at least through the depth of the marine ABL, as are provided on land by multichannel infrared and microwave radiometer profiling systems
    - the depth z_i of the boundary layer, an important metric for model performance and potentially available from automated measurements with laser-based systems and temperature profiles retrieved from multichannel radiometers
    - turbulence profiles, derived from lidar- or radar-based systems, adapted for moving platforms at sea.

  - *Additional observations.*

    - Eddy correlation measurements of near-surface turbulence, including temperature and water vapor, are needed to evaluate conditions of validity for classical theories of the atmosphere.
    - Drop/particle size distribution observations, such as are made on land via disdrometers, are needed to develop data sets to realistically address turbine blade leading edge erosion.

- Measurements of areal coverage and physical characteristics of breaking waves are needed to relate them to other concurrent observations of air–sea interaction processes and provide input for structural loading models.

8.2.2 Model improvement

In conjunction with the fundamental challenge of understanding the physics of key metocean phenomena and processes offshore, the process of modeling itself has specific challenges. One is properly representing the dynamic atmosphere–ocean interface. Non-equilibrium interactions between the two fluids introduces complications, and some preliminary work indicates that direct momentum transfer from the ocean to the atmosphere may modify wind profiles at hub height under some conditions. How to determine when two-way coupling between the atmosphere and the ocean surface may be required and when one-way coupling is sufficient is not clear. A second challenge lies in how to numerically couple fully compressible but lower-resolution models of the atmosphere to higher-resolution, incompressible microscale models that allow computation of wakes and other fine-scale phenomena in such way that the microscale models retain essential fidelity to key atmospheric structure. Related questions include how fine the compressible model's resolution needs to be at the boundary, how best to spin up resolved turbulence in the microscale model, and whether two-way coupling between the atmospheric and microscale models is necessary to properly account for intra-plant and inter-plant wakes offshore. Recommendations are the following:

– Research into methods to couple atmospheric and microscale models is receiving increasing attention. This work should be continued, including the investigation of two-way coupling, and expanded in the offshore environment, perhaps using coupled models as "hypotheses" to develop validating field studies.

– Systematic investigation of model sensitivities using tools such as uncertainty quantification should be used to focus costly offshore studies. Emerging tools such as ML should also be explored for this purpose.

– New subgrid-scale parameterizations, especially in the atmospheric models, should be developed to address known inconsistencies in currently used parameterizations and to provide important variables, such as drop size distributions, that are currently not available.

– Where the path to improved physics remains unclear, or as an adjunct to improved physical understanding, ML should be used improve the practical value of wind resource characterization modeling.

– New data assimilation methods, especially those that are able to initialize coupled ocean–atmosphere models, need to be developed to better use the available observations to initialize both short-range and medium-range weather prediction models.

– Improvements need to be made to both experimental models, such as those used by the community (e.g., WRF), and operational models (e.g., the High-Resolution Rapid Refresh (HRRR); Dowell et al., 2022; James et al., 2022). The latter are especially important, as the operational weather prediction models run by the National Weather Service often serve as foundational forecasts used by the energy community to both integrate wind power into the electric grid efficiently and to make the energy grid more resilient.

Code availability. The code used in this paper is not publicly available but can be obtained from the author upon request.

Data availability. The data are publicly available. The data can be obtained at the following link: https://oswbuoysny.resourcepanorama.dnvgl.com/download/f67d14ad-07ab-4652-16d2-08d71f257da1 (last access: 16 November 2022, DNV-GL, 2020). Neither NYSERDA nor OceanTech Services/DNV-GL has reviewed the information contained herein, and the opinions in this report do not necessarily reflect those of any of these parties.

Author contributions. WJS drafted Sects. 1 and 8. JDM, PM, JMW, and DDT drafted Sect. 2. DDT, VPG, and JMW drafted Sect. 3. JMW, MD, GD, DDT, VPG, and RK drafted Sect. 4. CD, WP, GD, and LKB drafted Sect. 5. CBH drafted Sect. 6. WP, JDM, DDT, PM, and GD drafted Sect. 7. All authors contributed actively to the editing and review of all sections.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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Acknowledgements. The genesis of this article lies in the 2019 Workshop on Research Needs for Offshore Wind Resource Characterization supported by the Wind Energy Technologies Office of the DOE and in the cited Veers et al. (2019) paper on grand challenges in the science of wind energy. We are grateful to the participants in the DOE workshop and in the meetings supporting the grand-challenges paper for their stimulating and valuable exchange of ideas. We are also grateful to Sue Haupt, Julie Lundquist, Shannon Davis, Colleen Kaul, Raghu Krishnamurthy, and Chris Fairall for their very helpful comments on early versions of the paper. Any remaining flaws, of course, are entirely the responsibility of the authors. Charlotte B. Hasager was supported by IFD grant 6154-00018B. Pacific Northwest National Laboratory is operated by Battelle Memorial Institute for the DOE under contract DE-AC05-76RL01830. Argonne National Laboratory is a US Department of Energy laboratory managed by UChicago Argonne, LLC, under contract DE-AC02-06CH11357. This work was authored (in part) by NREL, operated by the Alliance for Sustainable Energy, LLC, for the DOE, under contract DE-AC36-08GO28308, with funding provided by the DOE Office of Energy Efficiency and Renewable Energy Wind Energy Technologies. Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security, LLC, for the US Department of Energy National Nuclear Security Administration under contract DE-AC52-07NA27344. NOAA authors were supported by NOAA's Atmospheric Science for Renewable Energy program. The views expressed in the article do not necessarily represent the views of the DOE or the US government. The US government retains, and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for US government purposes.

Financial support. This research has been supported by the US Department of Energy (contract nos. DE-AC02-06CH11357, DE-AC52-07NA27344, DE-AC36-08GO28308, and DE-AC05-76RL01830), the National Oceanic and Atmospheric Administration, and the Innovationsfonden (grant no. 6154-00018B).

Review statement. This paper was edited by Jakob Mann and reviewed by Stefan Emeis and one anonymous referee.

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