



# Meteorological Impacts of Offshore Wind Turbines as Simulated in the Weather Research and Forecasting Model

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**Abstract.** Offshore wind energy projects are currently in development off the east coast of the United States and will likely influence the local meteorology of the region. Wind power production and other commercial uses in this area are related to atmospheric conditions, and so it is important to understand how future wind plants will change the local meteorology. We compared one year of simulations from the Weather Research and Forecasting model with and without wind farms incorporated, focusing on the lease area south of Massachusetts and Rhode Island. We assessed changes in wind speeds, 2 m temperature, surface heat flux, turbulent kinetic energy, and boundary layer height during different stability classifications and ambient wind speeds over the entire year. Because the wake behavior may be a function of boundary-layer stability, in this paper, we also present a machine learning algorithm to quantify the area and distance of the wake generated by the wind plant. This analysis enables us to identify the relationship between wake extent and boundary-layer height. Hub-height wind speed is reduced within and downwind of the wind plant, with the strongest impacts occurring during stable conditions and faster wind speeds. Wind speeds at 10 m increase within the wind plant area during stable conditions. Differences in 2 m temperatures and surface heat fluxes are small, but are largest during stable conditions and strong wind speeds. Turbulence kinetic energy (TKE) increases within the lease area with increasing wind speeds at both the surface and at hub height. At hub height, TKE increases do not depend on stability, but at the surface, TKE increases most during unstable conditions as the turbulence injected at hub height is mixed down to the surface. Boundary-layer heights increase within the wind plant, and decrease slightly downwind during stable conditions. Deeper boundary-layer heights, exceeding 100 m, tend to correlate with smaller wake areas and distances, though other factors likely also play a role in determining the extent of the wind farm wake.

*Copyright statement.* This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under contract no. DE-AC36-08GO28308. Funding was provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by



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## 1 Introduction

25 Wind plants along the northeastern U.S. coast are projected to undergo rapid expansion in the coming years, aiming to achieve a capacity of 30 GW by 2030 and 110 GW by 2050 (U.S. Department of Energy, 2023). Currently, 27 areas are leased along the mid-Atlantic Outer Continental Shelf for future offshore wind development (Bureau of Ocean Energy Management, 2023).

Wind plants produce wakes that can influence local environments. The aggregation of individual wind turbine wakes into a wind farm wake results in a wind speed deficit downwind of the wind plant (Christiansen and Hasager, 2005; Platis et al., 2018, 2020), with the strongest deficit generally occurring in the top half of the turbine rotor disk (Bodini et al., 2021). Stronger and larger wakes are also associated with stable conditions, moderate wind speeds, low boundary-layer heights, and low ambient turbulence kinetic energy (TKE) (Christiansen and Hasager, 2005; Dörenkämper et al., 2015; Platis et al., 2018; Lundquist et al., 2019; Fischereit et al., 2022; Pryor et al., 2021; Bodini et al., 2021; Rosencrans et al., 2024). TKE is enhanced near wind plants, but this increase diminishes rapidly downwind (Bodini et al., 2021). The most pronounced enhancement in TKE typically occurs in the upper half of the turbine rotor disk. The degree of TKE increase is influenced by atmospheric stability: in unstable conditions, ambient TKE levels are high, resulting in only a slight increase in TKE in the presence of wind plants; in contrast, during stable conditions, wind plants significantly increase TKE levels (Bodini et al., 2021).

Wind farms can also cause changes in surface temperatures. Wind plants tend to cause a warming at the surface during stable conditions (Baidya Roy and Traiteur, 2010; Fitch et al., 2013; Rajewski et al., 2014; Siedersleben et al., 2018; Golbazi et al., 2022). The hypothesis proposed by Baidya Roy and Traiteur (2010) suggests that enhanced vertical mixing induced by wind turbine wakes causes this warming. During stable conditions, temperature increases with height, so enhanced mixing at the surface would result in warmer air from aloft mixing with cooler air at the surface. Similarly, during unstable conditions, cooler air from aloft is mixed with surface air, resulting in a cooling effect. This warming effect in stable conditions has been observed in wind farms near peat bogs in Scotland (Armstrong et al., 2016), wind farms in cropland in Iowa (Rajewski et al., 2014), China (Luo et al., 2021), and other locations. Satellite observations also suggest apparent surface warming due to the mixing of warm air down to the surface in stably stratified conditions Zhou et al. (2012b, a); Walsh-Thomas et al. (2012); Harris et al. (2014); Slawsky et al. (2015); Xia et al. (2016); Chang et al. (2016). In contrast, the VERTEX field campaign, in coastal marshland, did not find increased TKE or momentum fluxes in comparison to non-waked areas, suggesting that vertical mixing is not responsible for the observed temperature changes (Archer et al., 2019). The exact nature of the wind farm warming effect is likely due to complex interactions between the ambient atmosphere, the wind turbine wake, and surface characteristics.

The height of the wind turbine can also influence temperature changes in the wind plant. Golbazi et al. (2022) compared surface temperature changes for turbines with a hub height of 81 m to "extreme-scale" turbines with hub heights of 119 m and 250 m. Warming was observed below the turbine for both cases; however, for the extreme-scale turbines, warming did not extend all the way to the surface. Instead, slight cooling was found at the surface.



55 Changes in surface temperatures are coupled with heat flux changes at the surface. When conditions are unstable, heat fluxes are typically positive (upward). Similarly, during stable conditions when warmer air lies over cooler air, heat fluxes are negative (downward) (Stull, 1988). According to Golbazi et al. (2022), the magnitude of the heat flux decreases in areas experiencing cooling. This weakening is indicated by a positive change when the atmosphere is stable and a negative change when the atmosphere is unstable. As part of the Crop Wind-Energy Experiment campaign, Rajewski et al. (2014) found that turbines  
 60 have the largest influence on surface heat flux at night, in which a larger transport of heat was observed as warm air from aloft was brought to the surface by turbine-induced mixing. In contrast, during the day, the turbine-induced mixing was weaker than the ambient boundary-layer-scale mixing, resulting in inconsistent signals of warming and cooling differences between times with and without turbines. The large-eddy simulations of Lu and Porté-Agel (2011) also find that turbines induce strong changes on heat and momentum fluxes in a stable boundary layer.

65 The planetary boundary layer height (PBLH) is the height of the layer of the atmosphere that is influenced by the surface. Wind plants increase the boundary-layer height in stable (Lu and Porté-Agel, 2011) and neutral (Wu and Porté-Agel, 2017) conditions. As wind turbines extract energy from incoming flow, kinetic energy is entrained from the flow above, resulting in an increased boundary layer depth. An internal boundary layer (IBL) develops above the wind plant as relatively slower flow at rotor height moves upwards, interacting with slightly faster air. The IBL grows; it may eventually interact with the free  
 70 atmosphere and modify the planetary boundary layer (PBL) height (Wu and Porté-Agel, 2017; Gadde and Stevens, 2021). The growth of the IBL is dependent on the stratification of the boundary layer with which it interacts. During situations with weak stratification in the free atmosphere above the PBL, the IBL can nudge the PBL to deeper heights. However, when the layer above the PBL is strongly stratified, the IBL cannot necessarily push the PBL higher (Wu and Porté-Agel, 2017). Because the vertical growth of the boundary layer is limited for these strongly stratified conditions, flow instead goes around the wind plant  
 75 in the horizontal direction (Gadde and Stevens, 2021).

The relationship of the boundary-layer height with wake length is also an area of active research. Weather Research and Forecasting (WRF) model simulations of Pryor et al. (2021) in this region found that lower PBL heights favor longer and more intense wakes, though stable conditions and low ambient TKE also increase wake strength and extent. In the German bight, the large-eddy simulations of Maas and Raasch (2022) find longer wakes for shallower boundary layers, with some wakes  
 80 exceeding 100 km.

In this paper, we aim to determine how offshore wind plants influence the local environment by comparing WRF model (Skamarock et al., 2021) simulations with and without wind plants included over a one-year period. We quantify the difference in hub-height and 10 m wind speed, boundary-layer height, 2 m temperature, surface heat flux, and TKE at the surface and at hub height in the Massachusetts-Rhode Island offshore wind lease area. We compare differences between simulations for  
 85 different stability classifications and ambient wind speeds. Finally, we assess the relationship between the boundary-layer height and the extension of the wind plant wakes. In Sect. 2, we describe the dataset used for our analysis, and in Sect. 3 we introduce our method to determine the extension of the wakes using machine learning. We present our results in Sect. 4 and provide conclusions and suggested future work in Sect. 5.



## 2 Dataset

90 In this study, we use the NOW-WAKES dataset introduced in Rosencrans et al. (2024) as part of the 2023 National Offshore  
 Wind dataset (Bodini et al., 2023). Full details on the dataset can be found in Rosencrans et al. (2024), but a brief summary  
 is provided here. The dataset was created using WRF version 4.2.1, and the wind plant parameterization of Fitch et al. (2012)  
 updated with the bug fix of Archer et al. (2020) but with 100 % added TKE rather than 25 % added TKE. We use the innermost  
 domain (domain 2) of the two nested domains, bounded by 76.208W - 64.977W and 37.389N - 42.137N (Figure 1). Domain  
 95 2 has a 2 km horizontal resolution and a 10m vertical resolution near the surface with stretching aloft. There were 34 vertical  
 levels in the lowest 2,000 m, and 29 in the lowest 750 m. The period from 1 September 2019 00:00 UTC - 31 August 2020  
 23:50 UTC provides a temporal resolution of 10 minutes; we used hourly time steps for our analysis.

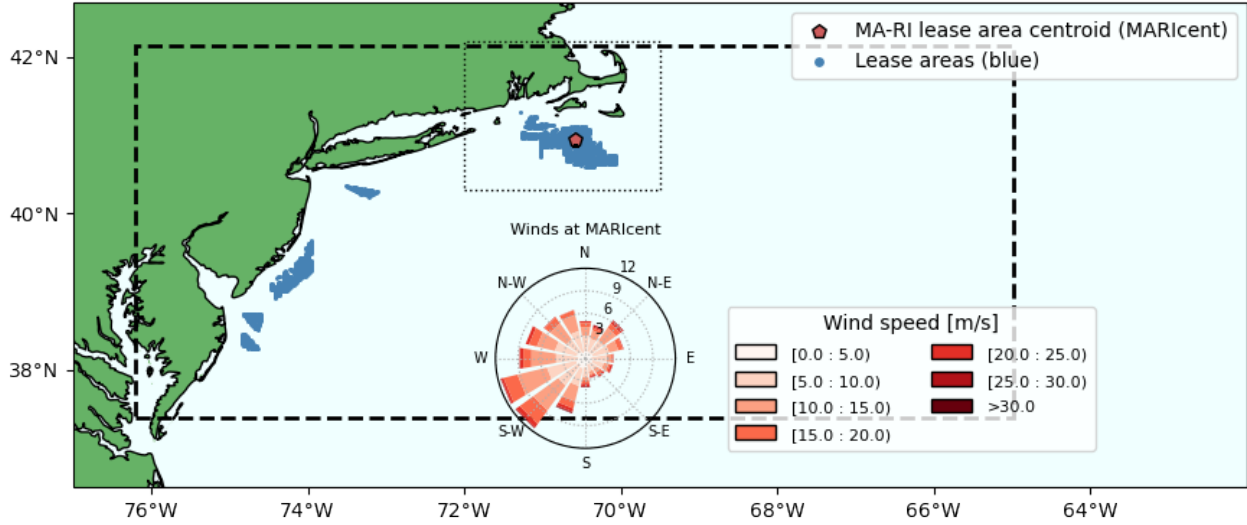
We consider two sets of NOW-WAKES simulations (Table 1). The first simulation ("no wind farm", NWF) does not include  
 any wind turbines, and has been validated in comparison to floating lidar observations at two locations in the domain (Rosen-  
 crans et al., 2024). The other simulation considers a wind turbine layout with turbines from all lease areas (LA100). For this  
 100 analysis, we compare the NWF simulation to the LA100 simulation, as this layout is most relevant for the region of interest  
 marked in Figure 1. (The "100" refers to the 100 % added TKE factor.) Figure 1 shows the locations of the wind turbines  
 for each of these simulations. The turbines introduced in these simulations are 12 MW with a rotor disk extending from 30  
 m to 245 m and a hub-height of 138 m. The power curve for these turbines is described by Figure 2. To assess the effect of  
 including turbine-generated TKE, separate simulations with 0 % and 100 % added TKE are available, but we consider only  
 105 the 100 % TKE simulation as comparisons to large-eddy simulations. (Vanderwende et al., 2016) suggest that added TKE is  
 critical. When TKE generation within the wind farm parameterization is disabled, the model produced unrealistic wind speeds,  
 wind directions, and turbulence.

**Table 1.** Summary of the two NOW-WAKES simulations considered in our analysis.

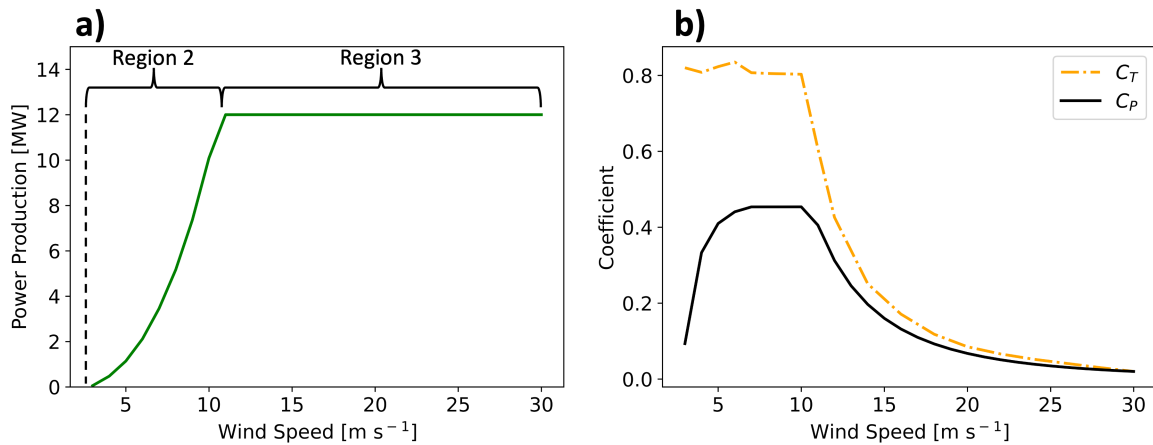
Simulation Type	Acronym	Turbine Type	Time Period	Added TKE	# Turbines
No wind plants	NWF	N/A	09/01/2019 - 08/31/2020	N/A	0
All lease areas	LA100	12 MW	09/01/2019 - 08/31/2020	100%	1418

### 2.1 Quantities of interest

110 We focus on assessing the impact of offshore wind turbines on wind speed, 2 m temperature, surface heat flux, TKE (modeled  
 in WRF as QKE), and planetary boundary layer height. Figures of average hub-height wind speed, 10 m wind speed, 2 m  
 temperature, surface QKE, and sea-surface temperature in each season are available in the appendix (Figs. A1, A2, A3, A4 and  
 A5). All other quantities are discussed in further detail here.

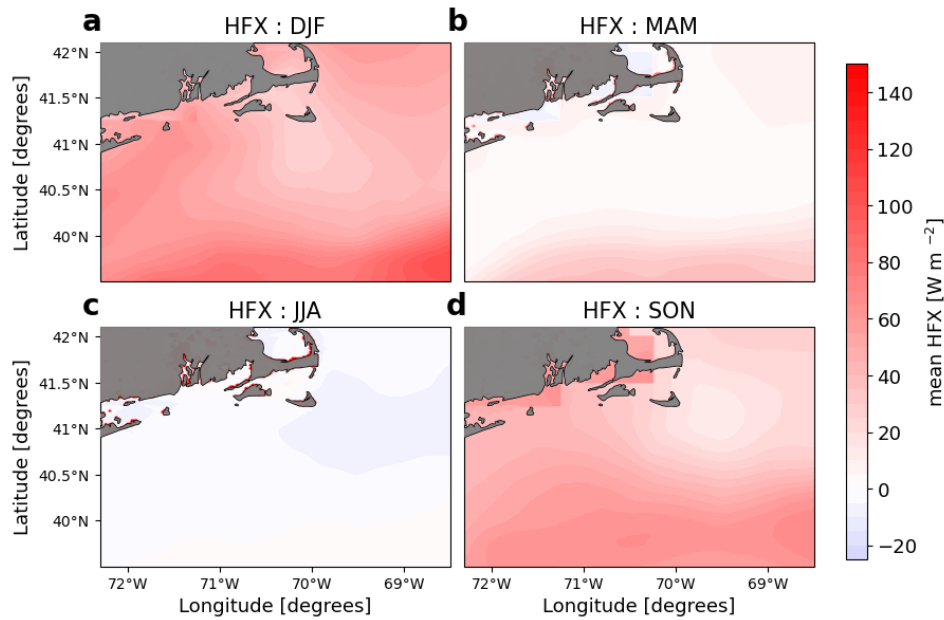


**Figure 1.** Simulation domain, including turbine locations and a wind rose near the centroid of the Massachusetts-Rhode Island lease area (MARICent). The MARICent location is marked in red. The turbine locations are shaded, and all wind plants included in the lease area simulations are in blue. The boundary of the NOW-WAKES innermost domain is outlined in the dashed black line. The dotted gray line indicates the region of interest for this study. The wind rose shows the wind speed (shading) and direction (angle) at 130 m over the 1 year modeled in NOW-WAKES. The distance from the center of the rose indicates the percentage of values in each bin.



**Figure 2.** Characteristics of the 12-MW turbine used in the NOW-WAKES simulations. (a) The power curve and (b) curves showing the thrust coefficient ( $C_T$ ) in dashed orange and power coefficient ( $C_P$ ) in solid black. Figure courtesy of Rosencrans et al. (2024).

We assess the impact of wind plants on surface heat flux. Positive surface heat flux values refer to the transfer of heat  
 115 upwards, which is common during unstable conditions when warmer air underlies cooler air. Negative surface heat flux values

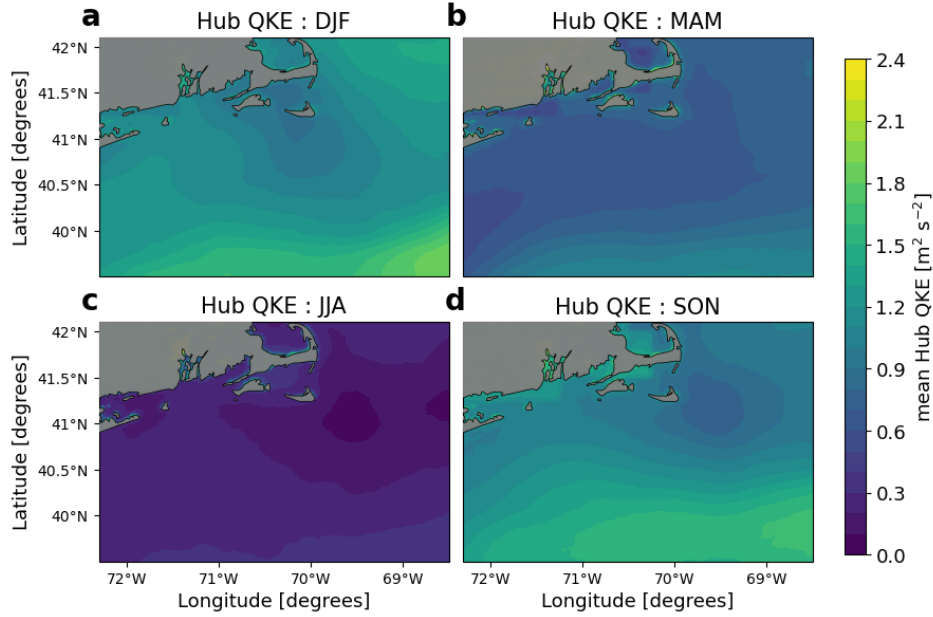


**Figure 3.** Same as in Fig. 5, but for surface heat flux.

are common in stable conditions, and refer to the transfer of heat downwards. Heat flux varies seasonally and by location (Fig. 3). In spring and summer over water, heat fluxes are often negative due to the more frequent occurrences of stable conditions. Heat fluxes are also relatively consistent across the region. In fall and winter, heat fluxes are positive due to more frequent unstable stratification. Heat fluxes during these months vary with distance from the coast, becoming more strongly positive further from the coast.

We also consider how wind plants influence turbulence at hub height and at the surface. WRF outputs QKE, which is defined as 2 times the TKE, and is the relevant variable from the Mellor–Yamada–Nakanishi–Niino (MYNN) PBL scheme used here. In the MYNN PBL scheme, TKE created by sub-grid processes such as wind plants is not always advected horizontally, but TKE advection (Archer et al., 2020) is turned on in these simulations (Rosencrans et al., 2024). TKE estimates the intensity of turbulence and is produced mechanically by wind shear or by buoyant thermals. The change in TKE over time depends on advection, shear generation, buoyant production, self transport, wind turbine production, and the viscous dissipation rate (Nakanishi and Niino, 2009). Hub-height QKE varies seasonally and by location (Fig. 4). In the spring and summer, QKE at hub height is small due to the prevalence of stable conditions. In the fall and winter, QKE is larger due to more frequent unstable conditions. QKE increases with distance from the coast, especially during the fall and winter.

Wind turbines generally operate within the boundary layer, and thus may influence the PBLH. Deeper planetary boundary layer (PBL) heights are associated with faster wake recovery due to the larger volume of air that can be drawn into the wake (Maas and Raasch, 2022; Pryor and Barthelmie, 2024). In the MYNN PBL scheme used in the NOW-WAKES WRF simulations, the PBLH is derived from a blend of a potential temperature and TKE-based definitions, depending on the stability



**Figure 4.** Same as in Fig. 5, but for hub-height QKE.

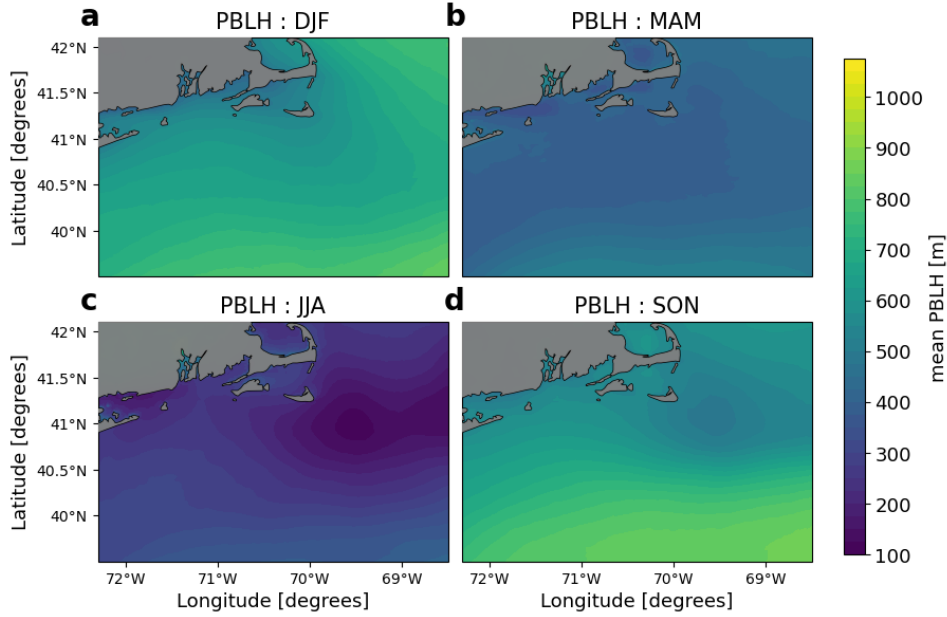
of the atmosphere (Olson et al., 2019). For stable conditions, most relevant for significant wakes, the TKE definition dominates,  
 and the boundary layer height is the height at which turbulent motions drop to 5% of the surface TKE value (Olson et al., 2019).  
 During neutral and unstable conditions, the potential temperature definition dominates, and the boundary-layer height is the  
 height at which the surface inversion ends. The algorithm of Nielsen-Gammon et al. (2008) determines the minimum virtual  
 liquid water and ice potential temperature in the lowest 200 m of the atmosphere ( $\theta_{vli\_min}$ ). Then, the boundary layer height is  
 the height at which  $\theta_{vli} = \theta_{vli\_min} + \Delta\theta_{vli}$ , where  $\Delta\theta_{vli}$  is set to be 0.5 K over water and 1.25 K over land. In this region, the  
 average PBLH varies spatially and seasonally (Fig. 5). Mean PBL heights range from 112 m to 1,086 m. During the summer,  
 when stable conditions are more common, the shallowest PBL heights occur, with a mean PBL height of 453 m. Unstable  
 conditions in the fall and winter lead to the deepest PBL heights, with mean values of 715 m in the fall and 698 m in the winter.  
 PBL heights generally increase with distance from the coast. In the summer and fall, a minimum in PBLH is observed to the  
 east of Nantucket.

## 2.2 Partitioning of the dataset

In this study, we quantify how hub-height wind speed, boundary-layer height, 2-m temperature, surface heat flux, and turbulence kinetic energy (QKE) at the surface and hub height vary between the NWF and LA100 simulations.

While presenting our results, we highlight the variability of such changes as a function of atmospheric stability and wind speed at hub height (Table 2), both evaluated at the centroid of the MARICent (Figure 1).





**Figure 5.** Average PBLH in the region is shown for each season from September 2019 – August 2020. (a) December, January and February (DJF) (b) March, April, and May (MAM) (c) June, July, and August (JJA) (d) September, October, and November (SON)

**Table 2.** The dataset is partitioned in six different ways, using labels in Column 1. The stability classification, wind speed range, wind direction range, and total number of hours in each partition are listed in Columns 2, 3, 4, and 5, respectively.

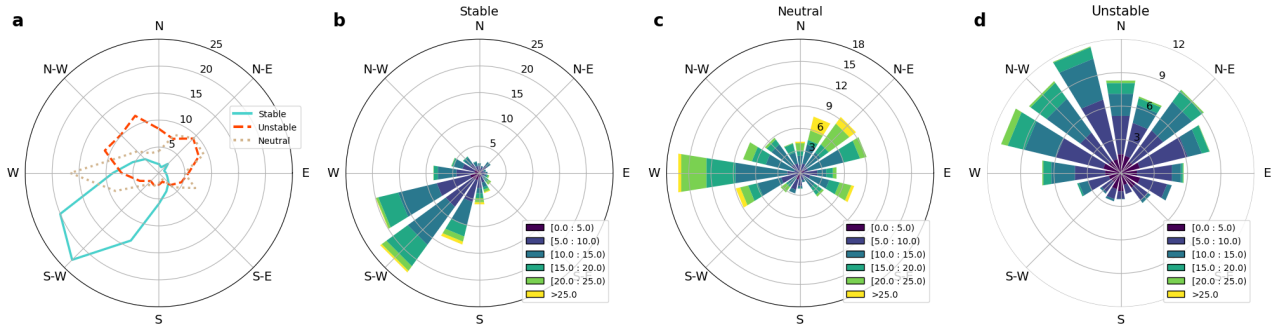
Label	Stability	Wind speeds [ $\text{m s}^{-1}$ ]	Wind directions [degrees]	Total # of hours
a	stable	all	all	3898
b	unstable	all	all	3899
c	neutral	all	all	987
d	stable	0-3	180-270	61
e	stable	3-11	180-270	1157
f	stable	11+	180-270	1334

150 Wakes tend to be stronger and last longer in stably stratified conditions (Lundquist et al., 2019; Pryor et al., 2021; Rosencrans et al., 2024). We classify atmospheric stability by calculating the Obukhov length ( $L$ ):

$$L = -\frac{u_*^3 \overline{\theta_v}}{\kappa g (\overline{w' \theta_v'})} \quad (1)$$

where  $u_*$  is the friction velocity,  $\theta_v$  is the virtual potential temperature,  $\kappa$  is the von Kármán constant of 0.4,  $g$  is gravitational acceleration, and  $\overline{w' \theta_v'}$  is the vertical turbulent surface heat flux. Values between 0 m and 500 m are considered stably stratified





**Figure 6.** (a) The frequency of each 22.5-degree wind direction bin for each stability classification. Wind roses for stable, neutral, and unstable conditions are shown in Panels b, c, and d, respectively. In all panels, radial distance from the center refers to the percentage of values in each 22.5 degree bin.

conditions, and values from -500 m to 0 m are considered unstable. Values outside of this range are considered neutral (Gryning et al., 2007; Sathe et al., 2011).

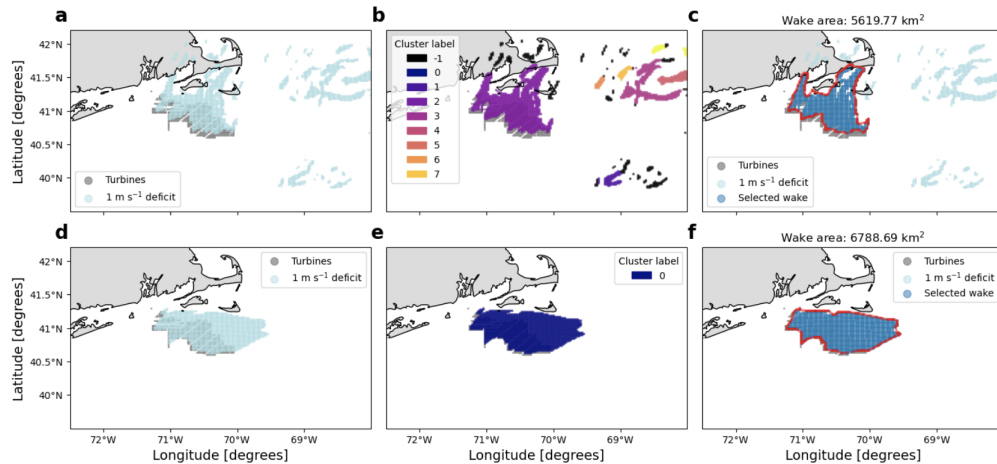
We note that the variability of atmospheric stability often reflects changes in wind direction in the region (Fig. 6). Winds in this region are often southwesterly and parallel to the coastline, but other wind directions do occur in the region (Fig. 1). Stable conditions almost always occur when winds are southwesterly. Wind directions vary more for unstable and neutral conditions: in unstable conditions, winds tend to be northerly, with a preference for northwesterly flow; in neutral conditions, winds are typically westerly or northeasterly. Because of this tight coupling of stability and wind direction, further exploration of results as a function of wind direction is not presented, as they are redundant with the results as a function of atmospheric stability.

We also partition the dataset by considering three wind speed ranges based on the power curve of the turbines used in the NOW-WAKES simulation (Figure 2): 0-3 m s<sup>-1</sup>, 3-11 m s<sup>-1</sup>, and 11+ m s<sup>-1</sup>. These modeled turbines do not produce any power when winds are 0-3 m s<sup>-1</sup>. Then, power production steadily rises as wind speeds increase from 3-11 m s<sup>-1</sup> (Region 2 on the power curve). At 11 m s<sup>-1</sup>, turbine blades begin to pitch, resulting in a leveling of the power production of the turbine (Region 3). To isolate the effect of the variability in hub-height wind speed on wake impacts from those caused by differences in stability and wind direction, when showing the variability of the wake impacts with hub-height wind speed, we only consider periods with stable conditions and southwesterly (180 - 270 °) winds.

### 3 Characterizing wind plant wake area and length with machine learning

We characterize the wind plant wake area and wake length for each of the 3,898 hours of the year with a stably stratified atmosphere.

We first determine the difference in wind speed between the LA100 and NWF simulations. The wind speed  $U$  is calculated at the model level closest to the turbine hub height ( $\sim 138$  m). Waked locations are identified as points with a wind speed deficit of at least 1 m s<sup>-1</sup>.



**Figure 7.** Example of the three steps taken to identify the wind plant wake on 14 December 2019 at 22:00 UTC (a, b, and c) and on 04 February 2020 at 07:00 UTC (d, e, and f). Turbines are marked in gray. (a and d) All points identified with a  $1 \text{ m s}^{-1}$  deficit are marked in light blue. (b and e) The points with a wind speed deficit are clustered, and a label is assigned to each cluster by the DBSCAN algorithm. The -1 label indicates points classified as noise. (c and f) The selected wind plant wake is in darker blue, with its wake boundary in red.

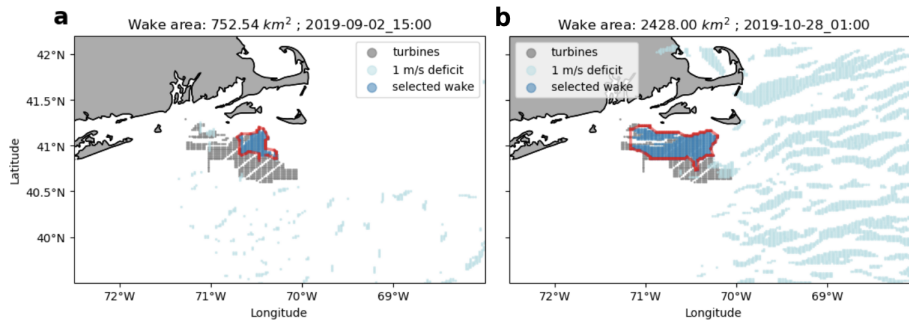
Next, the points that show a wind speed deficit that should be attributed to the wind plant wake need to be identified. As an example, in Fig. 7a, the wind plant wake should be contained in the cluster of points around the wind plants, but some other remote locations, not contiguous with the wind plant wake, also show a wind speed deficit of at least  $1 \text{ m s}^{-1}$ . To handle these situations, we employ the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) method (Ester et al., 1996) to accurately identify the wind plant wake. The algorithm groups points together based on their distance to dense regions. DBSCAN requires two main parameters. The first is the maximum distance between two points for one to be considered in the neighborhood of another. The second parameter is the minimum number of points in a neighborhood for a point to be considered as a core point. Here, we use a maximum distance value of 0.1 degrees and a minimum points value of 30. Using these parameters, points are grouped into clusters that are assigned a label, as in Figure 7b and 7e.

The next step is to select the cluster that is likely to be the wind plant wake. For each cluster identified by the DBSCAN algorithm, we determine the percentage of points in the cluster that are within the wind plant. All clusters with fewer than 15% of points in the wind plant are excluded from consideration. Then, the cluster with the most points overall is selected.

Once the wind plant wake cluster is selected, we create a concave hull shape around its points (Fig. 7c and 7f). We define the area of the wind plant wake as the area of this concave hull polygon. The wake length is the maximum distance from MARICent to any bounding point of the identified wind plant wake polygon (red outline in Fig. 7c and 7e).

Many cases have a clearly defined wake and a straightforward wake detection process, as shown in Fig. 7d, 7e and 7f).

However, 15.2% of hours have ill-defined wakes, so that they are flagged by our algorithm and not included in the final results of our analysis. An hour can be flagged if either of the following two situations occurs:



**Figure 8.** Example of two cases that are flagged by the wake detection algorithm and therefore not considered for further analysis. These plots follow the same convention as the right panel in Fig. 7.

1. Less than 40% of the coordinates located in the wind plant are classified as part of the wind plant wake. This ensures that the identified wind speed deficit is connected to the wind plant, which is the source of the wake.
2. The ratio of the number of points in the wind plant wake cluster to the total number of points with a wind speed deficit of at least  $1 \text{ m s}^{-1}$  is less than 0.2. This flags exceptionally noisy times when the selected wake represents a small number of the locations with a significant wind speed deficit.

In addition, no wake is identified at all if there are less than 4 points with a wind speed deficit greater than  $1 \text{ m s}^{-1}$ , or if less than 5% of points identified by DBSCAN are located within the wind plant. An additional 5.5% of hours are excluded from our analysis due to these criterion.

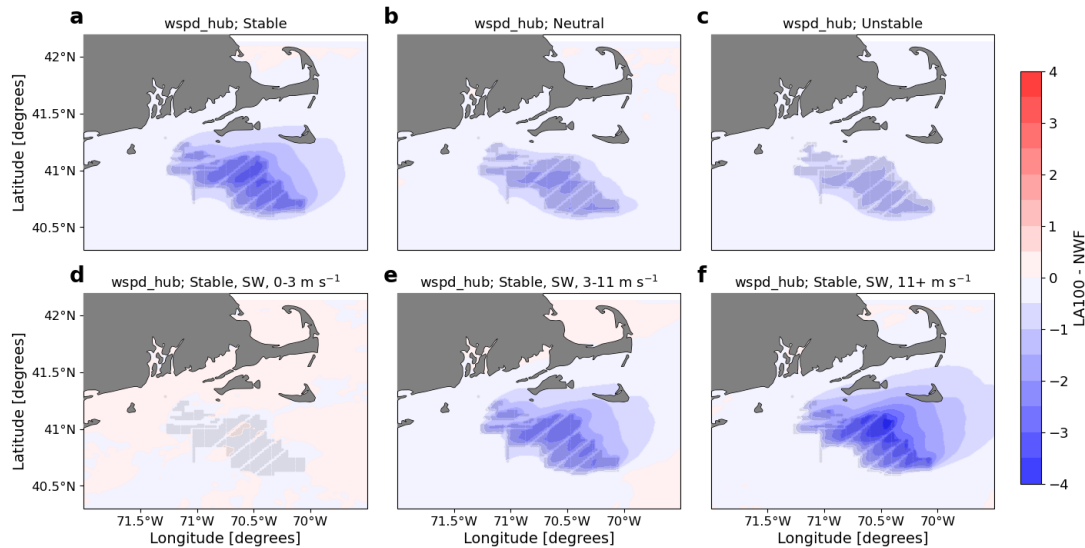
The cases in Figure 7 would not be flagged. While the case in the top row of Figure 7 has some noise, the identified wake clearly originates from the wind plant and covers most of the wind plant area. In addition, the points not selected for the wake represent a small fraction of all points with a wind speed deficit greater than  $1 \text{ m s}^{-1}$ . On the other hand, Figure 8 shows two examples of cases that are flagged by our algorithm: in (a), fewer than 40% of the wind plant is covered by the wake; in (b), the identified wake includes less than 20% of all the locations with a wind speed deficit greater than the  $1 \text{ m s}^{-1}$  threshold.

## 4 Results

### 4.1 Wind plant wake impacts on wind speed

#### 4.1.1 Hub-height wind speed

Hub-height wind speeds in wakes are reduced most in stable conditions and least in unstable conditions (Fig. 9a and 9c). Within the wind plant, wind speeds are reduced by up to  $2.7 \text{ m s}^{-1}$  in stable conditions, and up to  $1.5 \text{ m s}^{-1}$  in unstable conditions. In stable conditions, there is also a significant decrease in wind speed downwind of the wind plant (to the northeast, given the dominant southwesterly wind direction during stable condition; see Fig. 6), while in neutral and unstable conditions the extent



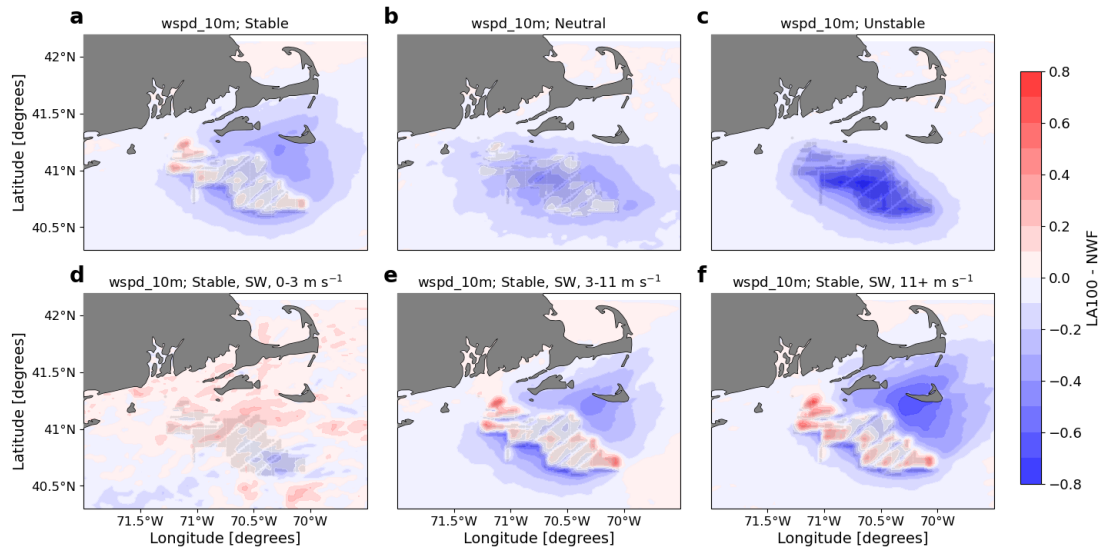
**Figure 9.** Mean hub-height wind speed difference between the LA100 and NWF simulations in (a) stable conditions, (b) neutral conditions, (c) unstable conditions, (d)  $0-3 \text{ m s}^{-1}$ , (e)  $3-11 \text{ m s}^{-1}$ , and (f)  $11+ \text{ m s}^{-1}$ . Panels d, e, and f are only during times with stable conditions and southwest winds. Turbines are marked in gray.

of the wake is much smaller. During unstable conditions, wind speeds are replenished faster due to increased mixing from aloft, which reduces the extent of the wake. These results confirm the results reported in Figure 12 of Rosencrans et al. (2024).

In stable conditions and when the wind is from the southwest, hub-height wind speeds are reduced more with increasing ambient wind speeds (Fig. 9d, 9e, and 9f). There is almost no difference between the simulations for quiescent winds, when wind turbines are not operational, as expected. Hub-height wind speeds are reduced by up to  $2.5 \text{ m s}^{-1}$  for wind speeds in Region 2 of the turbine power curve, and up to  $3.6 \text{ m s}^{-1}$  for wind speeds above  $11 \text{ m s}^{-1}$ . The wake also extends further for faster wind speeds: a wind speed deficit of at least  $0.5 \text{ m s}^{-1}$  extends out to the northern edge of Nantucket Island for moderate wind speeds, and several kilometers further than this for faster wind speeds.

Hub-height wind speeds decrease within and downwind of the wind plant, with the largest impacts occurring during stable conditions and for faster ambient wind speeds. Wind speed deficits in the wake of wind plants are well documented for cases both onshore and offshore (Christiansen and Hasager, 2005; Fitch et al., 2013; Dörenkämper et al., 2015; Platis et al., 2018; Fischereit et al., 2022). Our results on the impact of atmospheric stability on wakes confirm the results of Rosencrans et al. (2024), who uses the same dataset. In the central United States, Fitch et al. (2013); Rajewski et al. (2013); Smith et al. (2013) also find that the largest wind speed deficits occur for faster wind speeds, stable conditions, and when turbulent mixing is inhibited.

For individual turbines, the magnitude of the wake varies with wind speed differently than observed here. For individual turbines (Rhodes and Lundquist, 2013), maximum wake wind speed deficits occur near rated power when the turbine thrust



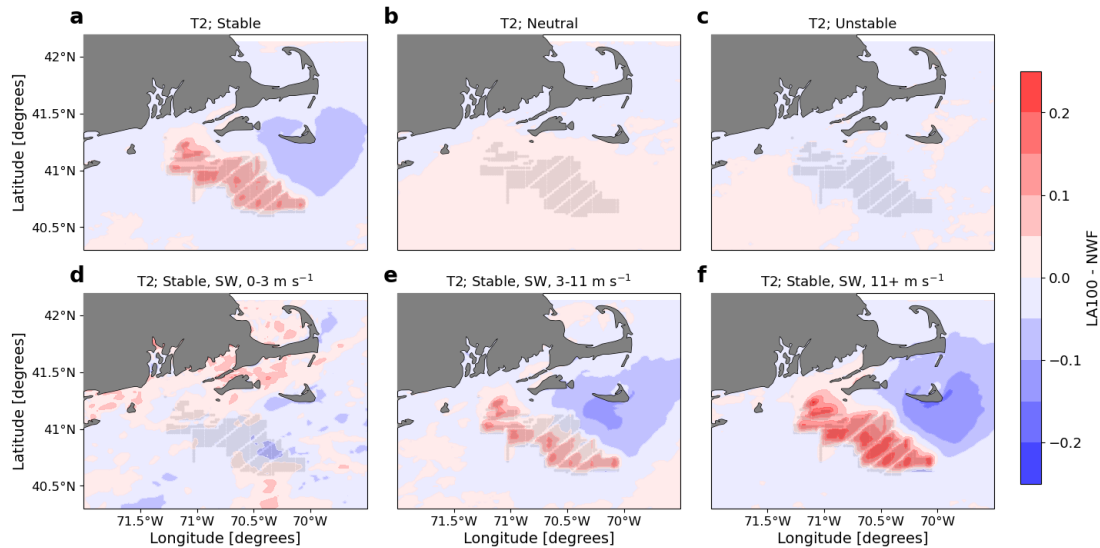
**Figure 10.** Mean 10 m wind speed difference between the LA100 and NWF simulations in (a) stable conditions, (b) neutral conditions, (c) unstable conditions, (d) 0-3  $\text{m s}^{-1}$ , (e) 3-11  $\text{m s}^{-1}$ , and (f) 11+  $\text{m s}^{-1}$ . Panels d, e, and f are only during times with stable conditions and southwest winds. Turbines are marked in gray.

coefficient is near its maximum value, with decreasing wake wind speed deficits as wind speeds increase and thrust coefficient decreases. Here, the wake wind speed deficits continue to amplify as wind speeds increase.

#### 4.1.2 Wind plant wake impacts on 10 m wind speed

Wind plant wake impacts on 10 m wind speed depends on the stability of the atmosphere (Fig. 10a, 10b, and 10c). In stable conditions, wind speeds increase by up to 0.32  $\text{m s}^{-1}$  within the wind plant, while in neutral and unstable conditions, wind speeds decrease by up to 0.45 and 0.82  $\text{m s}^{-1}$ , respectively. Outside of the wind plant, 10 m wind speeds are reduced in all stability classifications. The spatial extent of the wake is smaller for unstable conditions than for neutral and stable conditions. During unstable conditions, wind speeds are replenished faster due to increased mixing from turbines above, which reduces the extent of the wake.

Under stable conditions and southwesterly winds, 10 m wind speeds are reduced more with increasing ambient wind speeds (Fig. 10d, 10e, and 10f). There are minimal differences between the simulations for quiescent winds, when wind turbines are not operational, as expected. Downwind of the wind plant, 10 m wind speeds are reduced by up to 0.60  $\text{m s}^{-1}$  for wind speeds in Region 2 of the turbine power curve, and up to 0.70  $\text{m s}^{-1}$  for wind speeds above 11  $\text{m s}^{-1}$ . The wake also extends further for faster wind speeds: a wind speed deficit of at least 0.1  $\text{m s}^{-1}$  extends out to the northern edge of Nantucket Island for moderate wind speeds, and several kilometers further than this for faster wind speeds. For moderate and fast wind speeds, there is also a reduction in wind speeds upwind of the wind plant. The extent of this effect is slightly larger for moderate wind speeds than for stronger wind speeds. Within the wind plant, surface accelerations also differ slightly between moderate and fast wind



**Figure 11.** Mean 2 m temperature difference between the LA100 and NWF simulations in (a) stable conditions, (b) neutral conditions, (c) unstable conditions, (d)  $0-3 \text{ m s}^{-1}$ , (e)  $3-11 \text{ m s}^{-1}$ , and (f)  $11+ \text{ m s}^{-1}$ . Panels d, e, and f are only during times with stable conditions and southwest winds. Turbines are marked in gray.

speeds: wind speeds increase by up to  $0.50 \text{ m s}^{-1}$  for moderate ambient wind speeds and by up to  $0.57 \text{ m s}^{-1}$  for fast wind speeds.

250 Changes in wind speed at 10 m are much smaller than at hub-height: wind speed reductions in the wake at the surface are about 4.5 times weaker than at hub-height. At 10 m, wind speeds accelerate slightly within the wind plant during stable conditions only, a phenomenon that was also observed in the simulations and lidar observations of Bodini et al. (2021) and the large-eddy simulations of Vanderwende et al. (2016). Upwind of the wind plant, wind speeds are reduced slightly, especially when winds are in Region 2 of the power curve and the thrust coefficient is near its maximum value. Wu and Porté-Agel (2017)  
 255 identifies this effect in large-eddy simulations of neutral boundary layers.

#### 4.2 Wind plant wake impacts on 2-m temperature

Differences in 2-m temperature are small, less than 0.3 K, when wind plants are present. Any differences are the most significant during stable conditions (Figure 11a). During stable conditions, temperatures increase by around 0.1 degrees Celsius within the wind plant and decrease by a similar amount downwind of the wind plant. In neutral conditions, temperatures increase  
 260 by around 0.05 degrees both within and around the wind plants (Figure 11b). In unstable conditions, temperature differences are very small, but a slight decrease in temperature is observed within the wind plant (Figure 11c). During stable conditions, turbines mix warmer air from aloft down to the surface, resulting in a temperature increase. In unstable conditions, the boundary layer is well mixed, which likely dominates any temperature changes caused by wind turbines.





In stable conditions for southwesterly winds, changes in 2-m temperature become more significant with increasing hub-height wind speed (Figure 11d, 11e, and 11f). Temperature differences at the surface are negligible for quiescent winds when turbines are not operational. Temperature increases by up to 0.14 K for moderate wind speeds, and up to 0.2 K for wind speeds greater than  $11 \text{ m s}^{-1}$ . The largest temperature increases occur near the front of the wind plant, which is the southwestern side of the lease area here. During moderate wind speeds, there is no difference between the NWF and LA100 simulations on the northeastern side of the lease area. Temperatures are reduced downwind of the wind plant for moderate and fast wind speeds; however, the strongest reduction occurs for fast wind speeds. The extent of this moderate temperature reduction is large, extending to Massachusetts.

Differences in 2-m temperature are small, but we find increased temperatures within the wind plant and decreased temperatures downwind. The strongest temperature differences occur during stably stratified conditions and hub-height wind speeds faster than  $11 \text{ m s}^{-1}$ . Few differences occur between the NWF and LA100 simulation when conditions are unstable or during quiescent winds. Several other studies have identified warming below the turbine hub, with the strongest impacts occurring during stable conditions Baidya Roy and Traiteur (2010); Lu and Porté-Agel (2011); Fitch et al. (2013); Siedersleben et al. (2018); Golbazi et al. (2022). The simulations used here use wind turbines with a hub-height of 138 m, which resembles the "extreme-scale" turbine of Golbazi et al. (2022). While they find cooling at the surface for extreme-scale turbines, we still find warming at the surface during stable conditions.

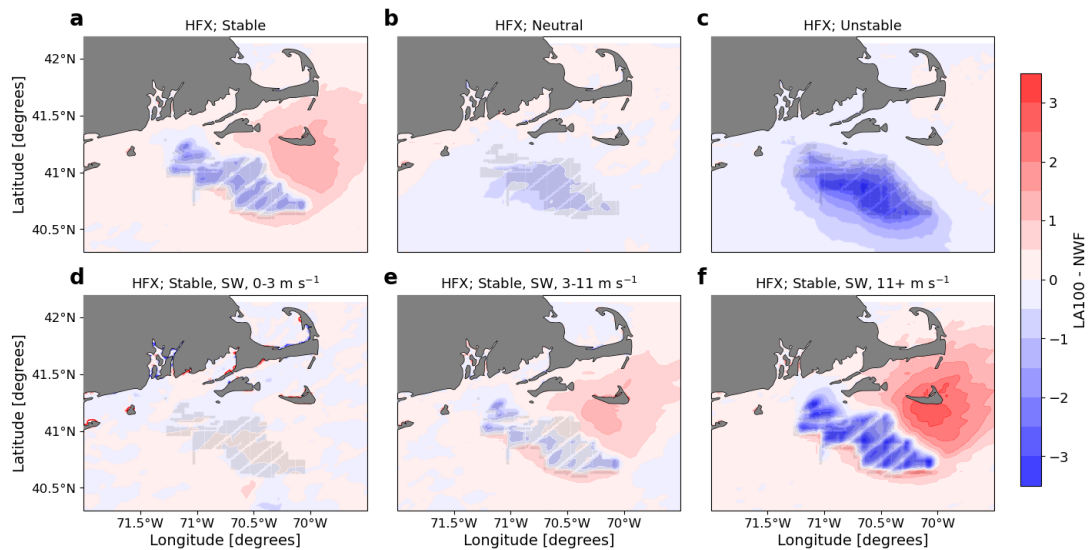
The amount of added TKE may also have an impact on observed temperature changes. Baidya Roy and Traiteur (2010) found larger differences in temperature for small amounts of ambient TKE than for large amounts of TKE. Our simulations use the 100% added TKE option, which promotes more mixing and could explain the small differences observed here. We also observe slightly smaller temperature changes than in Fitch et al. (2013), which identified warming below the rotor of up to 0.8K.

For stably stratified mesoscale simulations onshore (Texas), Xia et al. (2019) find that the turbine-added turbulence drives the surface warming signal by enhancing vertical mixing. In contrast, the turbine drag component causes the remote downwind surface cooling by reducing shear and promoting near-surface thermal stratification. A similar process occurs here, most visible in the stably stratified conditions (Fig. 11a).

### 4.3 Wind plant wake impacts on heat flux

Within the wind plant, heat fluxes are reduced for all stability classifications (Fig. 12a, 12b, and 12c). Heat fluxes are least affected during neutral conditions, with a reduction less than  $1 \text{ W m}^{-2}$  throughout the region. The heat flux reduction within the wind plant is largest during unstable conditions, with differences up to around  $3 \text{ W m}^{-2}$ . Heat fluxes are typically positive during unstable conditions, so a reduction in heat flux corresponds to less heat being transferred upwards. During stable conditions, heat flux is moderately reduced within the wind plant, implying that more heat is transferred to the surface. We also observe an increase in heat flux downwind of the wind plant of around  $1.5 \text{ W m}^{-2}$  during stable conditions, implying that less heat is transferred to the surface. No downwind effect on heat flux occurs during neutral and unstable conditions.

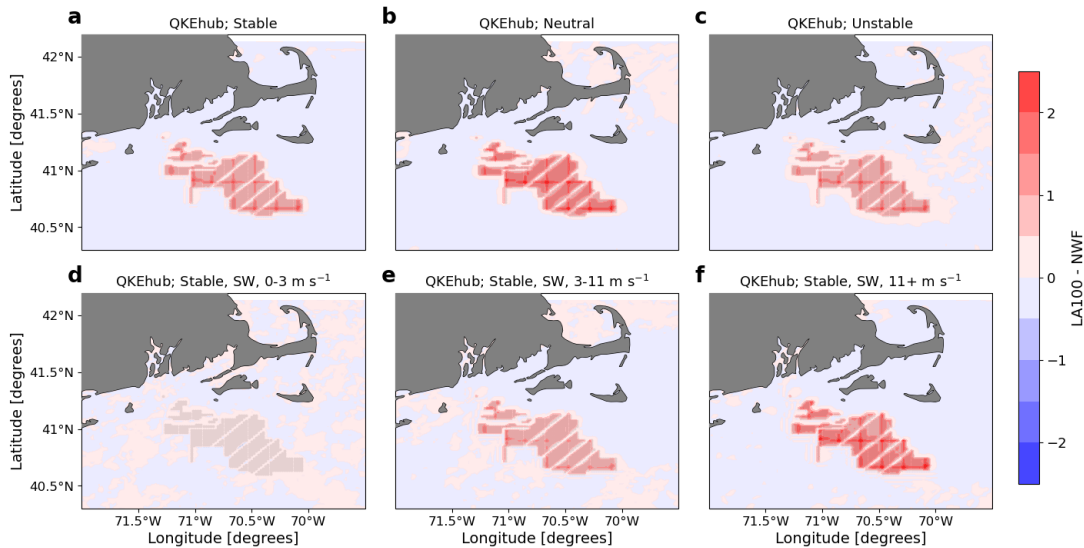




**Figure 12.** Mean heat flux difference between the LA100 and NWF simulations in (a) stable conditions, (b) neutral conditions, (c) unstable conditions, (d) 0-3  $\text{m s}^{-1}$ , (e) 3-11  $\text{m s}^{-1}$ , and (f) 11+  $\text{m s}^{-1}$ . Panels d, e, and f are only during times with stable conditions and southwest winds. Turbines are marked in gray.

Impacts of the wind plant on heat flux increases with increasing wind speeds (Fig. 12d, 12e, and 12f), during stable conditions and for southwesterly winds. Weak winds correspond to negligible differences in heat flux due to nonoperational turbines. Heat flux decreases within the wind plant for moderate and fast wind speeds, with largest changes for wind speeds in Region 3 of the power curve. Similar to the results seen for 2-m temperature, the strongest changes in heat flux occur near the front of the wind plant, on the southwestern side. Downwind of the wind plant, heat flux increases by up to  $1.5 \text{ W m}^{-2}$  for moderate wind speeds, and up to  $2.75 \text{ W m}^{-2}$  for fast wind speeds. The spatial extent of this downwind effect is similar to that observed for 2-m temperatures, as changes in surface heat flux are related to changes in surface temperature. We find that the heat flux is weakened where cooling is found (northeast of the wind plant for stable conditions, southwest winds, and strong winds), which is in agreement with findings in Golbazi et al. (2022).

The surface heat flux decreases within the wind plant. The strongest reduction in heat flux occurs during unstable conditions and fast wind speeds. Golbazi et al. (2022) suggests that cooling is associated with a weakening of the heat flux. Our findings support this observation: during stable conditions, we observe cooling and an increase in surface heat flux to the northeast of the wind plant; in the wake of the wind plant in stable and neutral conditions, we find an increase in the surface heat flux, which is consistent with Rajewski et al. (2014). Xia et al. (2019) also suggests that temperature changes within the wind plant are driven by changes in heat flux, with a decrease in sensible heat flux near turbines and an increase downwind, which aligns with our stable stratification results in Fig. 12a.



**Figure 13.** Mean hub-height QKE difference between the LA100 and NWF simulations in (a) stable conditions, (b) neutral conditions, (c) unstable conditions, (d) 0-3 m s<sup>-1</sup>, (e) 3-11 m s<sup>-1</sup>, and (f) 11+ m s<sup>-1</sup>. Panels d, e, and f are only during times with stable conditions and southwest winds. Turbines are marked in gray.

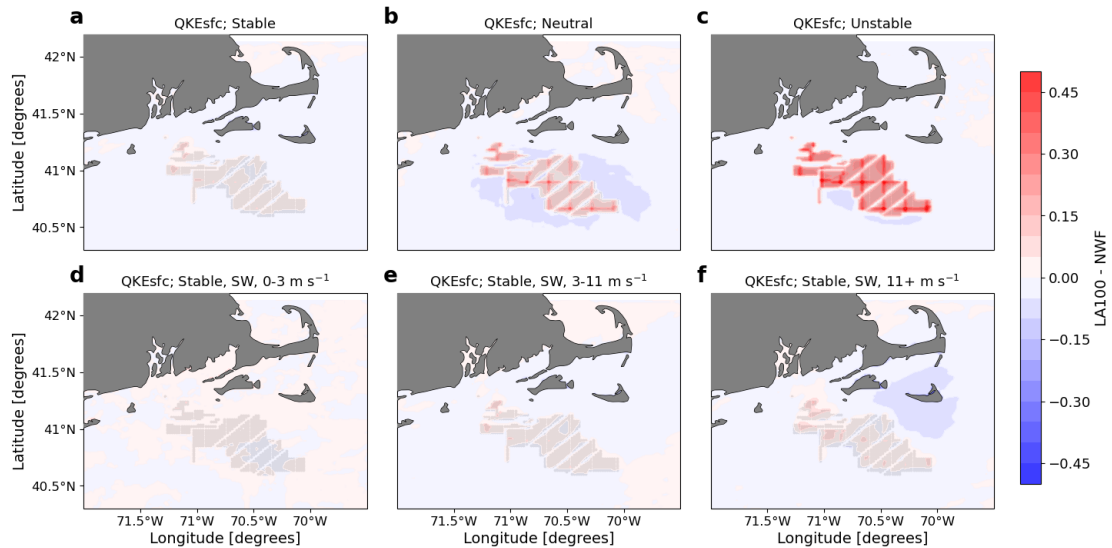
#### 4.4 Wind plant wake impacts on QKE

Wind turbines impact QKE at both hub height and at the surface. The wind turbine parameterization injects turbulence into the simulations at the altitudes of the turbine rotor disks, with more turbulence injected into cells with more turbines.

##### 4.4.1 Hub-height QKE

In the vicinity of the wind plants, QKE increases at hub height. A similar magnitude in this increase occurs for all stability classes, suggesting that stability does not immediately modify the QKE generated by turbines (Fig. 13a, 13b, and 13c). The largest increases in QKE occur in the grid cells populated by turbines, where the turbulence is introduced. This hub-height QKE increase rapidly erodes downwind of the wind plants. The amount of added turbulence directly relates to the number of turbines in each grid cell, resulting in a grid pattern of larger QKE values corresponding to cells with more turbines.

When focusing on stable conditions with southwesterly winds, the magnitude of the increase in hub-height QKE within the wind plant increases with increasing ambient wind speed (Fig. 13d, 13e, and 13f). Negligible QKE is generated for quiescent winds, when turbines are not operational and the parameterization does not add any turbulence. The most added turbulence at hub height is evident in the fastest wind case (Fig. 13c). The fastest wind speeds may also result in more mixing on their own. Increases in QKE are localized to the cells with turbines, with the strongest values occurring where turbine density is the greatest.



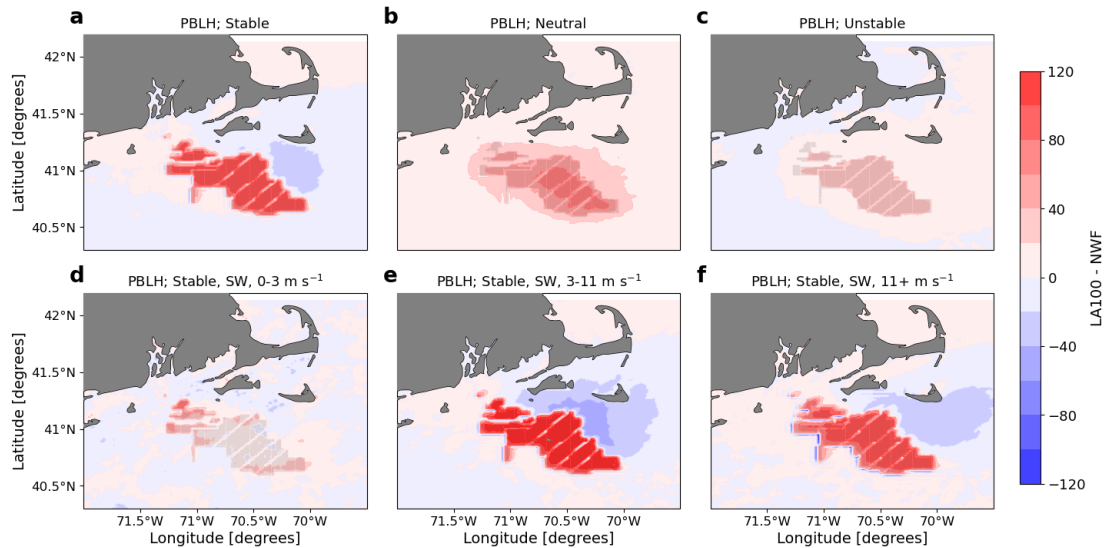
**Figure 14.** Mean surface QKE difference between the LA100 and NWF simulations in (a) stable conditions, (b) neutral conditions, (c) unstable conditions, (d) 0-3 m s<sup>-1</sup>, (e) 3-11 m s<sup>-1</sup>, and (f) 11+ m s<sup>-1</sup>. Panels d, e, and f are only during times with stable conditions and southwest winds. Turbines are marked in gray.

#### 4.4.2 Surface QKE

Differences in surface QKE are subtler than differences at hub height but show more variability with stability (Fig. 14a, 14b, and 14c). During stable conditions, QKE at the surface is largely unaffected by the presence of wind turbines. Vertical mixing is suppressed during stable conditions, making it unlikely that turbulence from the turbines, injected at the rotor disk altitudes, can reach the surface. Surface QKE increases within the wind plant during neutral conditions, although changes are limited to areas close to turbines. During unstable conditions, QKE increases throughout the entire lease area, albeit by a factor of four less than at hub height. Surface QKE slightly decreases in areas outside of the wind plant for all stability classifications, although the largest reductions occur during neutral and unstable conditions.

Ambient hub-height wind speed also influences the change in QKE at the surface (Fig. 14d, 14e, and 14f) in stable conditions and for southwesterly winds. As we found at hub height, quiescent winds are not associated with any noticeable change in surface QKE, due to turbines being nonoperational. Moderate wind speeds also have very small differences, but there is a slight increase in surface QKE on the upwind side of the lease area. During strong wind speeds, differences between the LA100 and NWF simulations are most apparent. Surface QKE increases on the upwind side of the lease area and decreases downwind. Downwind of the wind plant, wind speeds are reduced in the wake, which results in less QKE producing wind shear.

QKE increases within the wind lease area both at hub height, where the turbulence is injected, and at the surface. Not surprisingly, impacts at the surface are much smaller than at hub height, where the increase in QKE is about 10 times greater



**Figure 15.** Mean PBLH difference between the LA100 and NWF simulations in (a) stable conditions, (b) neutral conditions, (c) unstable conditions, (d)  $0-3 \text{ m s}^{-1}$ , (e)  $3-11 \text{ m s}^{-1}$ , and (f)  $11+ \text{ m s}^{-1}$ . Panels d, e, and f are only during times with stable conditions and southwest winds. Turbines are marked in gray.

than at the surface. At hub height, differences between both simulations diminish quickly with distance from the wind plant, as we observe minimal changes outside of the lease area. This simulated behavior concurs with the simulations in Bodini et al. (2021). Atmospheric stability does not seem to impact the magnitude of QKE increase at hub height (as the amount of added TKE is not a function of stability but rather of wind speed and the number of turbines), but it does at the surface. Differences in QKE increases with increasing wind speed at both levels.

#### 4.5 Wind plant wake impacts on boundary layer height

In the vicinity of wind plants, the PBL height increases for all stability classifications (Figure 15a, 15b, and 15c). The atmospheric stability modulates the strength of this effect. The PBL height increases by up to 99 m during stable conditions from a mean value of 268 m, and up to 67 m and 39 m for neutral and unstable conditions, respectively, from means of 556 and 644 m, respectively. During stable conditions, PBL heights are generally lower and often within the rotor region, which results in a larger overall change in PBL height. During neutral and unstable conditions, PBL heights are generally deeper; thus, turbines are less likely to interact with air in the free atmosphere.

Downwind of the wind plant, PBL heights also change. Distant from the wind plant, PBL heights are reduced by up to 45 m during stable conditions as compared to the no-wind-farm, likely due to the decreased shear in the wake of the wind plant. During neutral and unstable conditions, PBL heights increase throughout the region during neutral conditions, while the impact of wind plants is limited to the lease areas during unstable conditions.



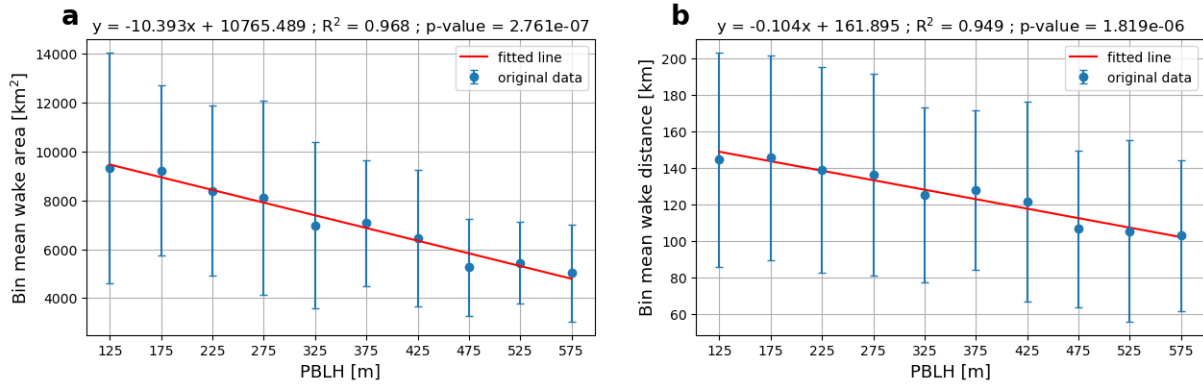
In stable conditions and for southwesterly winds, in the vicinity of wind plants, the PBL height is raised for all wind speeds, but this effect is strongest for wind speeds of  $3\text{--}11\text{ m s}^{-1}$ , and negligible for quiescent winds (Figure 15d, 15e, and 15f). Wind turbines are not operational when wind speeds are below  $3\text{ m s}^{-1}$ , and thus we do not expect wind plants to have a large effect on PBL height. The magnitude of the increase in PBLH within the wind plant is larger for hub-height wind speeds of  $3\text{--}11\text{ m s}^{-1}$  than for wind speeds of  $11\text{+ m s}^{-1}$ . Turbines have a smaller effect on winds once they reach Region 3 on the power curve, which likely explains this difference. Both moderate and fast wind speeds show a reduction in PBL height downwind of the wind plant, with the largest reduction associated with wind speeds in Region 2 of the power curve.

The PBLH increases within the wind plant and generally decreases downwind of the wind plant as compared to simulations with no wind plants. The largest differences occur during stable conditions and when winds are in Region 2 of the turbine power curve. This variability concurs with the large-eddy simulations of Wu and Porté-Agel (2017), which found increased PBL heights in the wind plant and depressed PBL heights in the exit region of the wind plant. Fitch et al. (2013) also finds, in mesoscale simulations, that wind plants elevate the height of the PBL height by up to 145 m. PBLH values were also slightly depressed downwind of the wind plant during stably stratified conditions.

#### 4.6 Relationship between PBLH and wake extent

The wind plant wake extent in stable conditions depends on the PBLH in the Massachusetts-Rhode Island lease area in a statistically significant way (Fig. 16). Wake area and length are determined using the methodology described in Section 3. Wake area and length generally decrease with increasing PBLH for PBLH values between 100 m and 600 m. As PBLH increases, the volume of air available to recover the wake increases, so wakes in deeper PBLs tend to have a smaller area and length. When the PBLH is shallow, lower than 100 m, the wind plant wake area increases with increasing PBLH (not shown). These lower PBLH values are below hub height and are associated with smaller wakes because the wake mostly propagates in the free atmosphere, where a large volume of air is available to quickly recover the wake. In Figure 16, a linear relationship appears between mean lease area PBLH and the mean wake area or length for each bin. For every 1 meter increase in PBLH, the wake area decreases by approximately  $10.4\text{ km}^2$ , and the wake distance decreases by about 0.1 km. The significance of these results is supported by the p-values, which are significantly below the 0.05 threshold. Still, the standard deviation is quite large, indicating considerable variability, likely associated to the fact that other factors such as ambient TKE and wind speed may also influence the wake extent in conjunction with the PBLH.

The analysis of stable wake areas and lengths demonstrates that deeper PBLs support faster wake recovery in a statistically significant way. The PBLH is inversely proportional to wake area and length, but other variables likely contribute to influencing the variability of wake extent. In a 55-day set of mesoscale simulations, Pryor et al. (2021) also suggest a negative relationship between PBLH and a normalized wake extent parameter. The large-eddy simulations of Maas and Raasch (2022) also find that wakes, at least for very large wind farms, tend to be longer with shallower boundary layers.



**Figure 16.** The mean (a) wake area and (b) length as a function of the mean lease area PBLH during stable conditions, where the PBLH values are binned every 50 m from 125 m to 575 m. The mean PBLH values are calculated as the average PBLH across the wind lease area. For each bin, the blue dots show the mean value, and the blue vertical lines represent the  $\pm 1$  standard deviation error bar. The best-fit line for the bin means is in red. Each panel displays the line of best fit equation,  $R^2$  value, and p-value on the top.

## 5 Conclusions

Here, we assess the meteorological impact of offshore wind farms using one year of WRF simulations with and without wind plants incorporated into the model. We assess the difference in hub-height wind speed, 10 m wind speed, 2 m temperature, surface heat flux, hub-height turbulence, surface turbulence, and boundary-layer height during different stability classifications and ambient wind speeds in the Massachusetts-Rhode Island lease area. We also demonstrate the relationship between boundary layer height and the area and length of the wind plant wake.

Hub-height wind speeds are reduced within and downwind of the lease area, especially during stable conditions and wind speeds above  $11 \text{ m s}^{-1}$ . A subtle (less than 0.2 K) increase in 2-m temperature within the wind plant can occur; this increase is strongest during stable conditions and faster wind speeds. Also during stable conditions, temperature decreases slightly downwind of the wind plant, as has been observed in mesoscale simulations in other regions. Changes in heat fluxes are also small. Heat flux is reduced within the wind plant and increased downwind. The largest reduction occurs during unstable conditions, while the largest downwind increase occurs for stable conditions and faster wind speeds. We find that turbulence, as simulated by QKE, increases at hub height in the immediate vicinity of turbines. Only in unstable conditions does this increase in QKE manifest at the surface as well. Wind turbines nudge the boundary layer up in the immediate vicinity of the wind turbines, especially during stable conditions and when winds are in Region 2 of the power curve. During stable conditions, the boundary-layer height is slightly reduced downwind. Finally, we find that shallower boundary-layer heights promote larger wakes.

These simulations use one type of turbine and the planned 1 nm spacing for these wind farms. Further investigations could assess how these impacts change with varying turbine layouts and sizes, as in Golbazi et al. (2022); Pryor et al. (2021).



While Golbazi et al. (2022) considers larger turbines similar to turbines used here, more research into their impacts on local meteorology is needed.

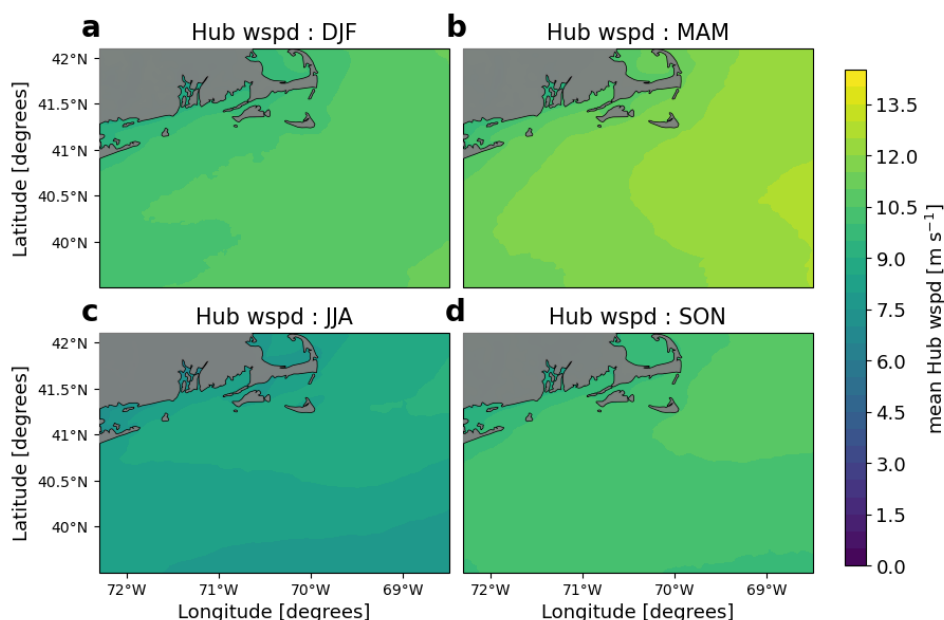
Over water, wind plant wakes may influence ocean dynamics (Raghukumar et al., 2022, 2023), including upwelling. Therefore, coupling with wave and ocean models could provide insight into potential wake impacts on the ocean. Daewel et al. (2022) considers the impact of offshore wakes on primary production, but additional analysis on surface currents would provide a more complete picture of wake impacts.

Our analysis is based on one complete year of simulations, rather than one season or selected multiday studies, but a multi-year study could provide more insights into interannual variability.

Finally, while we focused on one lease area, it is important to conduct further analysis on other lease areas in the region and worldwide.

*Code and data availability.* The NOW-WAKES simulation data is available at <https://dx.doi.org/10.25984/1821404> and code is available at <https://zenodo.org/doi/10.5281/zenodo.10993297>.





**Figure A1.** Same as in Fig. 5, but for hub-height wind speed

## Appendix A: Additional variable climatologies

### A1 Hub-height wind speed climatology

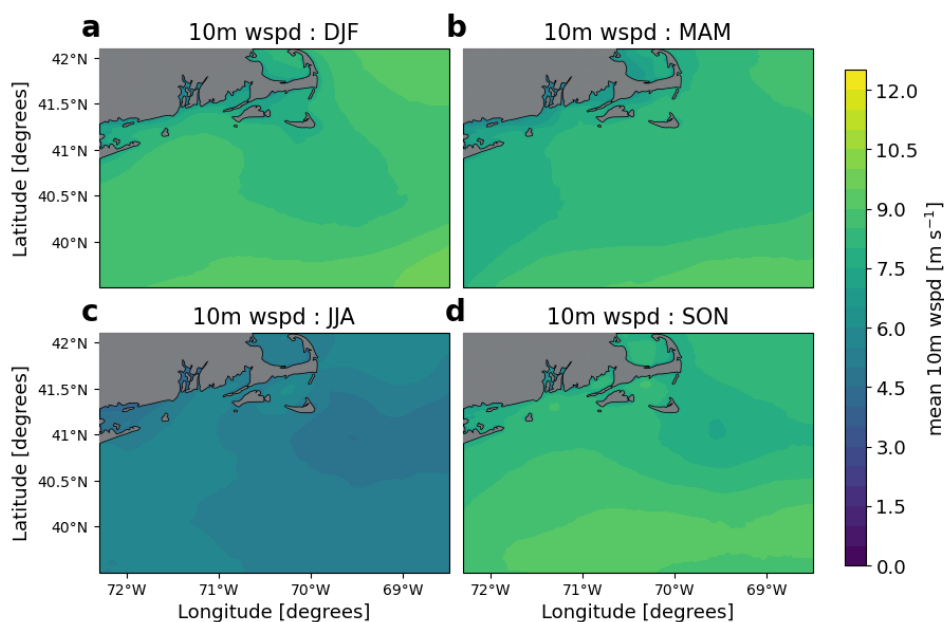
Hub-height wind speeds are fastest during the winter and spring, with means of 10.5 and 11.3 m s<sup>-1</sup>, respectively (Fig. A1). In the summer and fall, hub-height wind speeds are slightly slower, with means of 7.6 and 9.5 m s<sup>-1</sup>, respectively. During all seasons, hub-height wind speeds generally increase towards the east.

### A2 10 m wind speed climatology

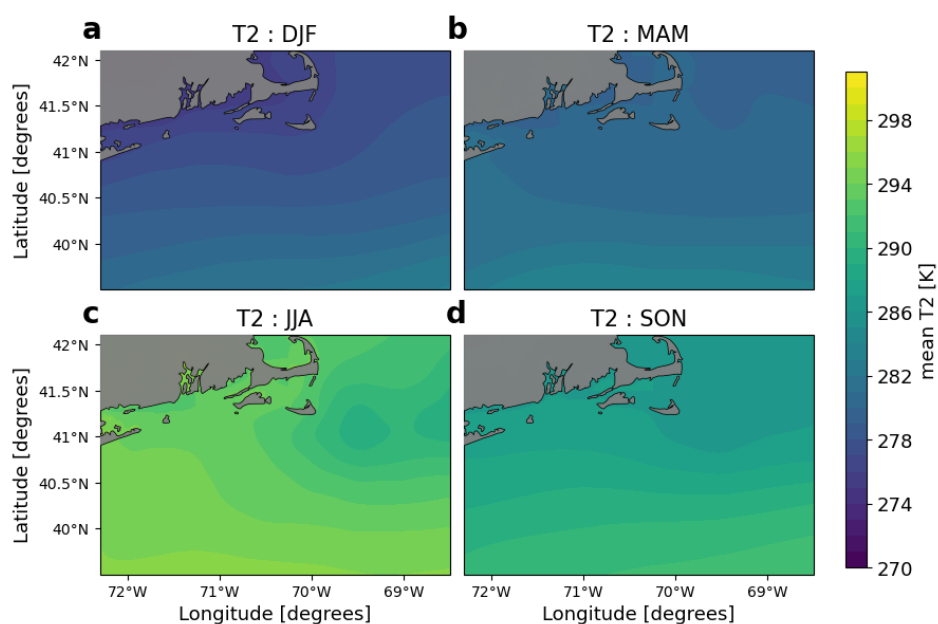
Ten meter wind speeds are fastest during the fall, winter, and spring, with means between 7 and 8 m s<sup>-1</sup> (Fig. A1). Wind speeds generally increase with distance from the coast during these seasons. In the summer, 10 m wind speeds are slower, with a mean of 5.2 m s<sup>-1</sup>. A minimum in mean 10 m wind speeds exists to the east of Nantucket in the summer.

### A3 2 m temperature climatology

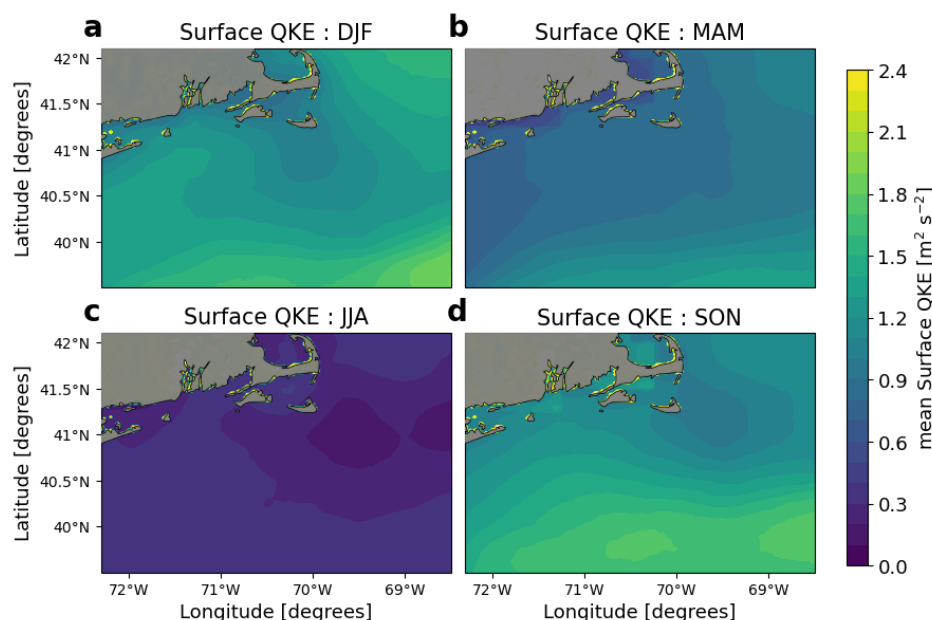
Mean 2 m temperature (T2) is warmest in the summer with a mean of 300 K, and coldest in the winter with a mean of 298 K. T2 is generally warmer to the south of the considered area for all seasons. In the summer, a T2 minimum occurs east of Nantucket. In the winter, minimum temperature occurs close to land. (Fig. A3).



**Figure A2.** Same as in Fig. 5, but for 10 m wind speed



**Figure A3.** Same as in Fig. 5, but for 2 m temperature.



**Figure A4.** Same as in Fig. 5, but for surface QKE.

#### A4 Surface QKE climatology

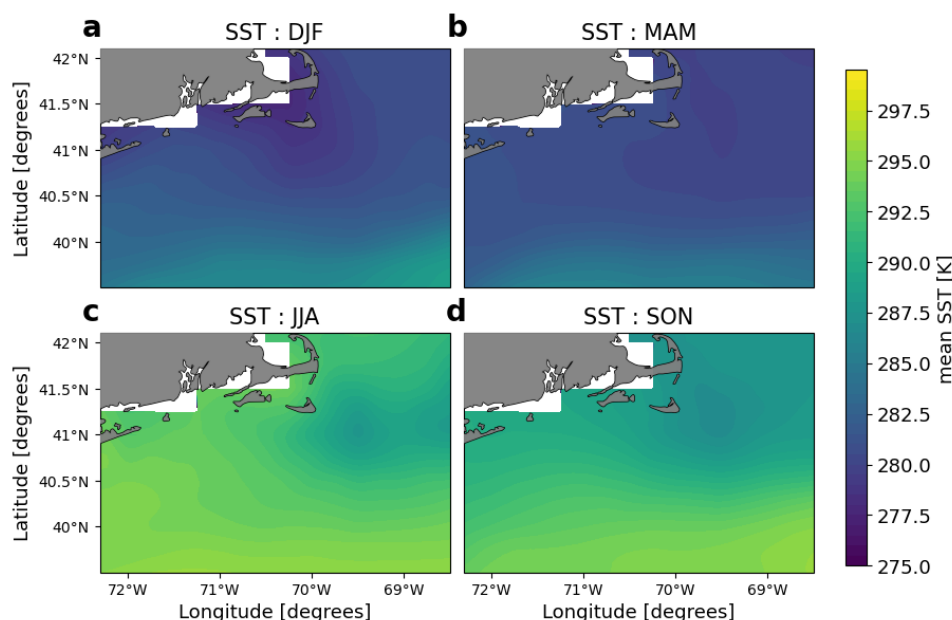
Surface QKE is highest in the fall and winter and smallest in the summer, with mean values of 1.5, 1.6, and 0.7  $\text{m}^2 \text{s}^{-2}$  (Fig. A4). In all seasons, surface QKE is larger to the south, away from the coast. Mean surface QKE is similar to values at hub-height that have mean values close to 1  $\text{m}^2 \text{s}^{-2}$ .

#### 440 A5 Sea surface temperature climatology

Sea surface temperature (SST) is warmest in the summer and coldest in the winter. SST is generally warmer to the south of the considered area for all seasons. In the spring and summer, an SST minimum occurs east of Nantucket. In the winter, minimum SST occurs close to land. (Fig. A5).

#### Appendix B: Meteorological impacts of wind plant wakes as a function of wind direction

445 Meteorological impacts of offshore wind farms also vary with wind direction. These results are likely driven by effects of atmospheric stability, as each stability class is associated with a dominant range of wind directions (Fig. 6). In particular, southwesterly winds almost always occur during stable conditions.



**Figure A5.** Same as in Fig. 5, but for SST.

### B1 Wind plant wake impacts on hub-height wind speed

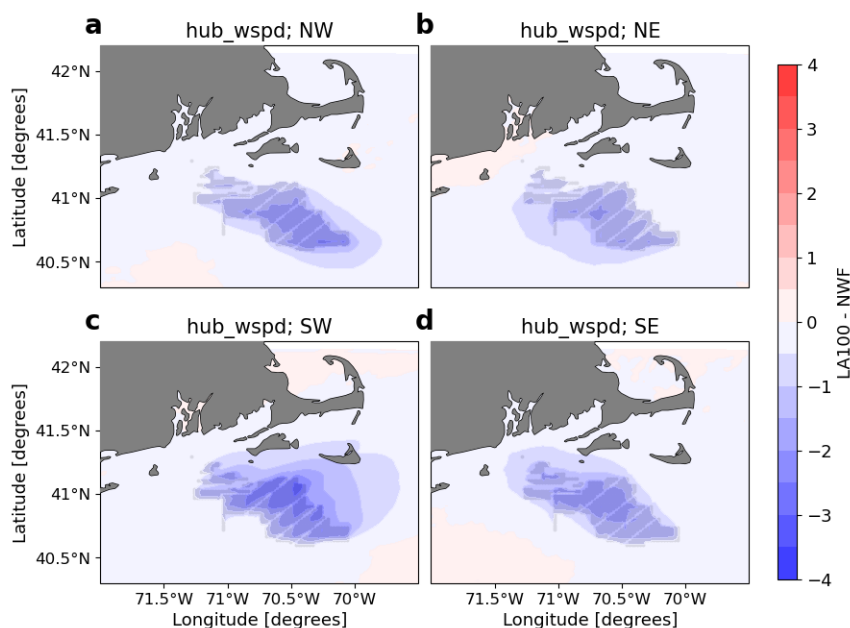
All wind directions observe a wind speed deficit both within and downwind of the wind plant (Fig. B1). Southwesterly winds have the strongest wind speed deficit within the wind plant and a larger wake than the other wind directions. In fact, southwesterly winds are typically associated with stable conditions, which are associated with larger wakes.

### B2 Wind plant wake impacts on boundary layer height

In the vicinity of wind plants, the PBLH increases for all wind directions (Figure B2). This effect is the strongest when there is southwesterly flow (i.e., stable conditions) and weaker for the other three quadrants. Southwesterly and northeasterly wind both exhibit a downwind reduction in PBL, while this effect is minimal for southeasterly winds and nonexistent for northwesterly winds. The downwind reduction in PBLH is strongest for southwesterly winds.

### B3 Wind plant wake impacts on 2-m temperature

The largest temperature differences occur during southwesterly flow (Figure B3). Temperatures increase by around 0.1 degrees Celsius in the lease area, and decrease by a similar amount downwind of the wind plant. Temperature differences are much smaller for other wind directions. In general, southerly winds are associated with an increase in temperature within the wind plant and a reduction in temperature outside of the wind plant. Temperature differences are very small for northerly winds. When winds are from the northeast, a slight warming is observed downwind of the wind plant.



**Figure B1.** Mean hub-height wind speed difference between the LA100 and NWF simulations for (a) NE, (b) NW, (c) SE, and (d) SW wind directions. Turbines are marked in gray.

#### B4 Wind plant wake impacts on heat flux

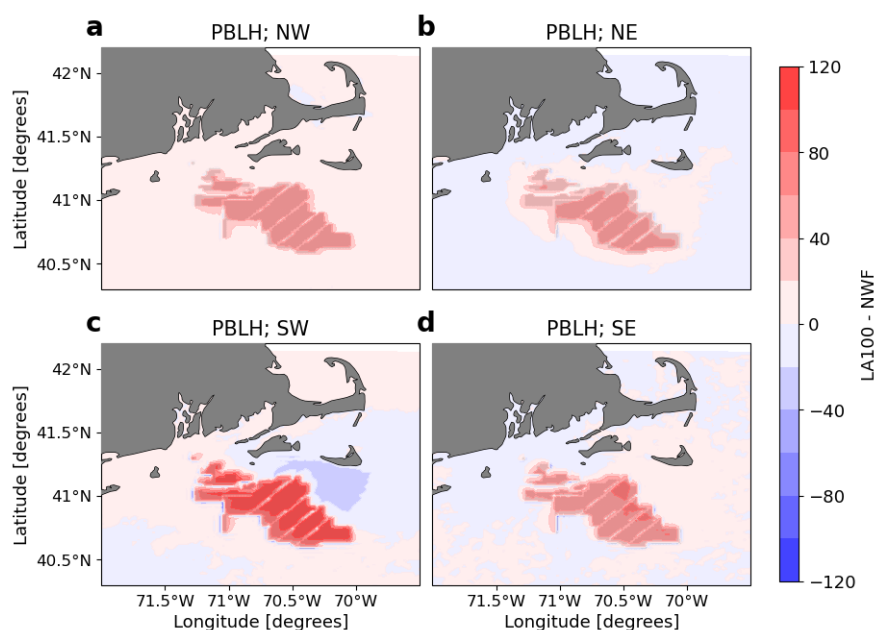
Heat fluxes are reduced within the wind plant for all wind directions (Fig. B4). The strongest reduction in heat flux occurs  
 465 for northwesterly winds, with reductions of up to  $3 \text{ W m}^{-2}$ . The other 3 quadrants see differences of around  $2 \text{ W m}^{-2}$   
 within the wind plant. When winds are northerly, heat flux is also reduced downwind of the wind plant, with the magnitude  
 decreasing with distance from the wind plant. In contrast, heat flux increases downwind of the wind plant when winds are from  
 the southwest. In addition, heat flux is slightly elevated in the immediate upwind direction.

#### B5 Wind plant wake impacts on hub-height QKE

470 Hub-height QKE increases similarly for all wind directions (Fig. B5).

#### B6 Wind plant wake impacts on surface QKE

Surface QKE increases within the wind lease area for all wind directions (Fig. B6). Surface QKE increases more when winds  
 are from the northwest or the northeast, with values over  $0.3 \text{ J kg}^{-1}$ . Southerly winds are associated with an increase in QKE  
 closer to  $0.2 \text{ J kg}^{-1}$ . We also notice a downwind reduction in surface QKE for all wind directions, although the magnitude of  
 475 the reduction is larger for northerly winds.

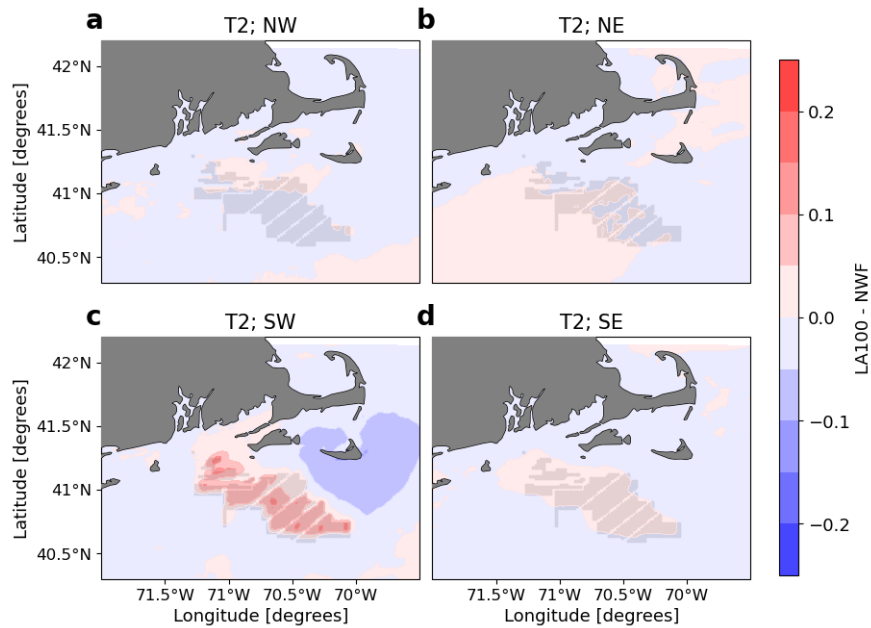


**Figure B2.** Mean PBLH difference between the LA100 and NWF simulations for (a) NE, (b) NW, (c) SE, and (d) SW wind directions. Turbines are marked in gray.

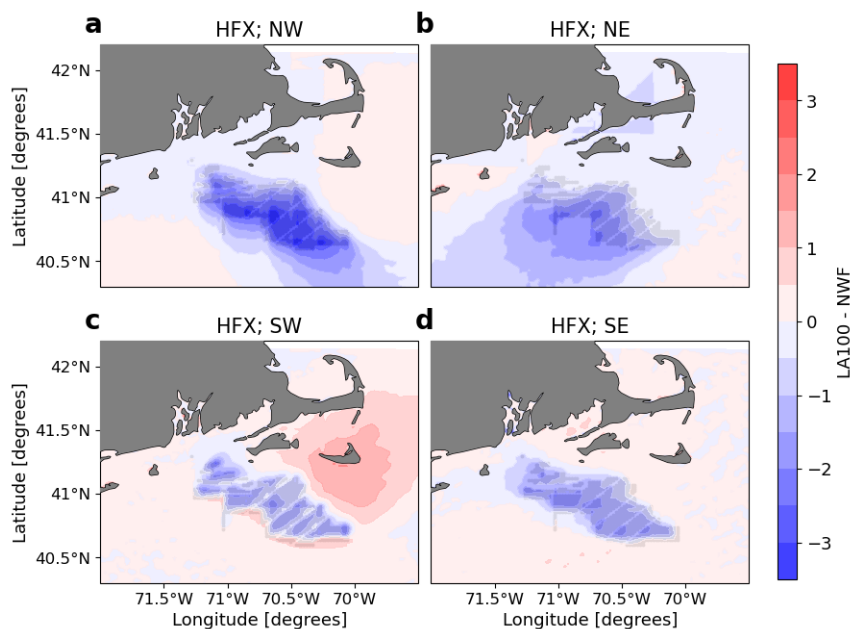
*Author contributions.* JKL and NB conceptualized the project and acquired funding and resources for the project. DR completed the WRF simulations and provided the dataset. DQ carried out the formal analysis and investigation, including developing software and carrying out the visualization, with supervision from JKL and NB. DQ prepared the initial draft. All authors reviewed and edited the publication.

*Competing interests.* At least one of the (co-)authors is a member of the editorial board of Wind Energy Science.

480 *Acknowledgements.* This research was performed using computational resources sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy and located at the National Renewable Energy Laboratory. This work was supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists under the Science Undergraduate Laboratory Internship program.

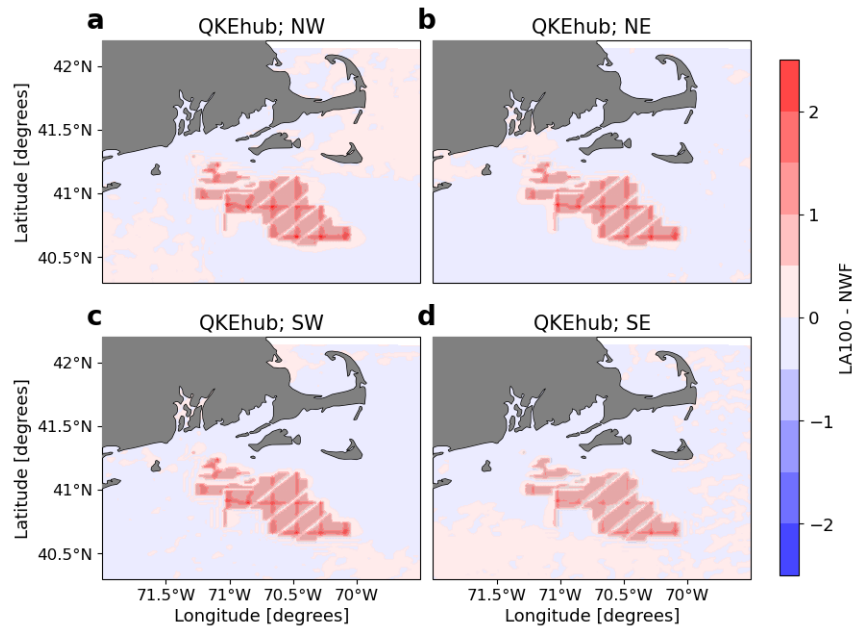


**Figure B3.** Mean 2-m temperature difference between the LA100 and NWF simulations for (a) NE, (b) NW, (c) SE, and (d) SW wind directions. Turbines are marked in gray.

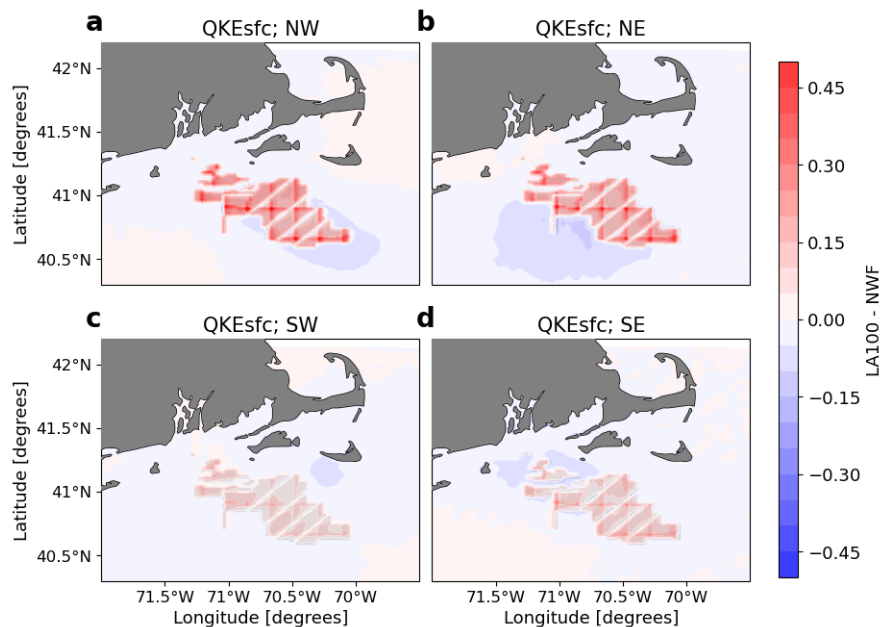


**Figure B4.** Mean heat flux difference between the LA100 and NWF simulations for (a) NE, (b) NW, (c) SE, and (d) SW wind directions. Turbines are marked in gray.





**Figure B5.** Mean hub-height QKE difference between the LA100 and NWF simulations for (a) NE, (b) NW, (c) SE, and (d) SW wind directions. Turbines are marked in gray.



**Figure B6.** Mean surface QKE difference between the LA100 and NWF simulations for (a) NE, (b) NW, (c) SE, and (d) SW wind directions. Turbines are marked in gray.



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