A Study on Modeled Wind Speed Errors Using the U.S. Department of Energy Buoys

July 2020

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Pacific Northwest National Laboratory
Richland, Washington 99354
Abstract

The Pacific Northwest National Laboratory operates two AXYS WindSentinel lidar buoys for the U.S. Department of Energy's Wind Energy Technologies Office. The purpose of these buoys is to collect hub-height winds and supporting meteorological and oceanographic information to facilitate the development of wind energy in the U.S. waters. The first deployment for one buoy was off the coast of Virginia from December 2014 to May 2016, and the first deployment for the other buoy was off the coast of New Jersey from November 2015 until February 2017. This report describes recent analysis of data collected during these first two deployments. Specifically, we compare hub-height wind speed estimates using Monin-Obukhov Similarity Theory to the lidar measurements and examine how those errors are affected by wind direction, atmospheric stability, wind-wave direction differences, and various measures of the wave state. The comparisons are done using standard similarity functions based on Monin-Obukhov Similarity Theory; including the Businger-Dyer, the Beljaars and Holtslag, and the Vickers and Mahrt similarity functions. All models produced large errors over the range of atmospheric stabilities that were observed, with the largest errors occurring for stable flows. The Vickers and Mahrt function resulted in the largest overall bias and standard deviation, while Beljaars and Holtslag function gave the smallest bias and standard deviation due to its better performance under stable conditions. The models performed best under unstable conditions, but even in this regime there was a consistent overestimation of the wind speed of between roughly 0 to 1 ms⁻¹ compared to the lidar measurements. We identified specific metocean conditions (i.e., stability and wind and wave directions) at each of the deployment locations that led to large errors in Monin-Obukhov Similarity Theory predictions. Finally, a coupled ocean–atmosphere model framework was investigated to simulate large errors in weather research forecasting.
Acknowledgments

Thank you to Mikhail Pekour of Pacific Northwest National Laboratory (PNNL) for his constructive technical suggestions as well as his technical review of the final document. This work was funded by the Wind Energy Technologies Office of the U.S. Department of Energy’s Office of Energy Efficiency and Renewable Energy. PNNL is operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE AC05 76RL01830.
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<table>
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<tr>
<th>Acronym</th>
<th>Definition</th>
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<tr>
<td>BD</td>
<td>Businger-Dyer</td>
</tr>
<tr>
<td>BH</td>
<td>Beljaars and Holtslag</td>
</tr>
<tr>
<td>CF</td>
<td>compact flash</td>
</tr>
<tr>
<td>CTD</td>
<td>Conductivity (C), Temperature (T), and Pressure (P, but commonly written as D for depth)</td>
</tr>
<tr>
<td>DOE</td>
<td>U.S. Department of Energy</td>
</tr>
<tr>
<td>HYCOM</td>
<td>HYbrid Coordinate Ocean Model</td>
</tr>
<tr>
<td>Metocean</td>
<td>Meteorological and Oceanographic</td>
</tr>
<tr>
<td>MOST</td>
<td>Monin-Obukhov Similarity Theory</td>
</tr>
<tr>
<td>MSL</td>
<td>mean sea level</td>
</tr>
<tr>
<td>PNNL</td>
<td>Pacific Northwest National Laboratory</td>
</tr>
<tr>
<td>RAP</td>
<td>Rapid Refresh model</td>
</tr>
<tr>
<td>ROMS</td>
<td>Regional Ocean Modeling System</td>
</tr>
<tr>
<td>TOGA-COARE</td>
<td>Tropical Ocean-Global Atmosphere-Coupled Ocean Atmosphere Response Experiment</td>
</tr>
<tr>
<td>UTC</td>
<td>coordinated universal time</td>
</tr>
<tr>
<td>VM</td>
<td>Vickers and Mahrt</td>
</tr>
<tr>
<td>WRF</td>
<td>Weather Research and Forecasting</td>
</tr>
<tr>
<td>WW3</td>
<td>WAVEWATCH III</td>
</tr>
<tr>
<td>SWAN</td>
<td>Simulating WAves Nearshore</td>
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<tr>
<td>ROMS</td>
<td>Regional Ocean Modeling System</td>
</tr>
<tr>
<td>COAWST</td>
<td>Coupled-Ocean-Atmosphere-Wave-Sediment Transport Modeling System</td>
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<td>NARR</td>
<td>North American Regional Reanalysis</td>
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<tr>
<td>CFSv2</td>
<td>Climate Forecast System version 2</td>
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<td>TRC</td>
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1.0 Introduction

The Pacific Northwest National Laboratory (PNNL) operates two AXYS WindSentinel lidar buoys for the U.S. Department of Energy’s (DOE’s) Wind Energy Technologies Office (Figure 1.1). These buoys are used to collect hub-height winds and supporting meteorological and oceanographic information to facilitate the development of offshore wind energy in the United States. In general, each buoy is deployed for a year or more at a given location in order to capture at least a full annual cycle of weather conditions. The initial deployment for one buoy was off the coast of Virginia beginning in 2015, and the other buoy was first deployed off the coast of New Jersey beginning in 2016. This report describes on-going analyses of the data collected during these two initial deployments.

Figure 1.1. The two AXYS WindSentinel buoys operated by PNNL for DOE. Note the second buoy in the distance.

This report identifies specific metocean conditions that lead to large errors in hub-height wind speed estimates from Monin-Obukhov Similarity Theory (MOST). Specifically, we examine how the error is affected of wind direction, atmospheric stability, wind-wave direction differences, and various measures of the wave state. The analyses presented here make use of the wide variety of sensors on board each buoy, as described in our previous quarterly report (Shaw et al. 2020). In Section 2.0 of the current report, we compare the non-dimensional wind shear and its stability dependence to that predicted by MOST using standard published similarity functions. This includes an examination of how the wave state impacts the relationship between wind shear and air–sea temperature difference. In Section 3.0 we examine wind-wave direction differences and identify specific conditions at each site where the errors in the MOST-predicted wind speeds are particularly large. This analysis also includes a decomposition of the wave field into wind-wave and swell contributions. Finally, Section 4.0 summarizes current efforts to run the Coupled-Ocean-Atmosphere-Wave-Sediment Transport (COAWST) system in order to simulate specific periods of interest identified in Section 4.0 and develop a robust model framework for future detailed evaluation.
2.0 Analysis of Wind and Wind Shear Differences between Observations and MOST

In this section we compare the wind speed and wind shear predicted by MOST to the buoy observations. We use a combination of surface and lidar measurements to examine the relationship between wind shear and air–sea temperature difference, and how the wind direction, wave age and swell effect that relationship. The non-dimensional wind shear and stability parameter, which were computed using fluxes obtained from a variant of the Tropical Ocean-Global Atmosphere-Coupled Ocean Atmosphere Response Experiment (TOGA-COARE) algorithm, are compared to several standard similarity functions. Finally, we examine the difference in wind speeds predicted from MOST to the lidar observations at the 70 m level, and how that error depends on stability.

2.1 Wind Shear vs Air–Sea Virtual Temperature Difference

We examine the relationship between wind shear and the air–sea virtual temperature difference. For this study, the wind shear is estimated from the difference in the lidar-observed wind speed at height $z_{\text{lidar}}$ and the surface anemometers on the buoy at height $z_s = 4.1$ m, i.e.,

$$\frac{\partial U}{\partial z} \approx \frac{(U_{\text{lidar}} - U_s)}{(z_{\text{lidar}} - z_s)}$$

(2.1)

The air–sea virtual temperature difference is computed using 10-min air temperature data at $z_s = 4.1$ m mean sea level (MSL) from a Pt RTD sensor (Rotronic Instrument Corp, model MP101A), and water temperature data from a YSI model 703. The air–sea virtual temperature difference is given by

$$\Delta T_V = T_V^{\text{air}} - T_V^{\text{sea}}$$

(2.2)

where

$$T_V^{\chi} = T_x (1 + 0.61 q_x)$$

(2.3)

$q_x$ is the water vapor mixing ratio in g g$^{-1}$, and “$\chi$” denotes either “air” or “sea.” At the 4 m level the mixing ratio is computed using

$$q_{\text{air}} = 0.622 \left( \frac{RH}{100} \right) \left( \frac{e_s}{P_{\text{air}}} \right)$$

(2.4)

where $RH$ is the relative humidity (in fractional form), $P_{\text{air}}$ is the atmospheric pressure in mb, and $e_s$ is the saturation vapor pressure in mb. At the sea surface we take $RH=1$, thus

$$q_{\text{sea}} = 0.622 e_s / P_{\text{air}}$$

(2.5)
The saturation vapor pressure is computed from

\[
es = 6.11 \exp \left( \frac{17.27}{1 + (237.3K / T_{air})} \right)
\]

(2.6)

where \(T_{air}\) is in K.

Ideally, in order to compare these observations with MOST, it is desirable to evaluate the wind shear in the lowest 20 to 30 m of the atmosphere, as the assumption of constant flux with height likely breaks down for heights above this level. Unfortunately, the lowest lidar level is 55 m MSL, which as we discovered during eXperimental Planetary boundary layer Instrumentation Assessment tended to produce wind speeds that are biased low due to poor signal-to-noise ratio. Results from eXperimental Planetary boundary layer Instrumentation Assessment showed that the wind speed slow bias was smallest (approximately 1% slow) near the 80 m to 90 m level. At the 70 m level, the slow bias was slightly larger at approximately 2%. Thus, in order to use the lowest reliable lidar level in our analysis, wind shear estimates in this study were computed based on the 70 m lidar level.

![Figure 2.1](image1.png)

**Figure 2.1.** Relationship between wind shear and \(\Delta T_v\) observed during a) the Virginia deployment, and b) the New Jersey deployment. Blue points indicate all wind directions. Red points indicate onshore flow only.

Figure 2.1 shows the relationship between wind shear and \(\Delta T_v\) as observed during the Virginia and New Jersey deployments. Although the scatter is significant, both buoys show a clear relationship between wind shear and \(\Delta T_v\). The Virginia buoy exhibits less scatter, particularly under stable conditions for \(\Delta T_v > 0\). The difference in the degree of scatter between Virginia and New Jersey is likely due to the site’s proximity to land. As mentioned in the introduction, the Virginia buoy was deployed approximately 40 km from shore, whereas the New Jersey buoy was deployed only 5 km from shore.

Figure 2.1 also shows the impact of filtering out offshore (i.e., land-affected) flow. For the Virginia buoy, onshore flow was defined for wind directions between 0° and 180°. For the New Jersey buoy, onshore flow was defined for wind directions between 35° and 215°. Filtering out the offshore flow significantly reduced the variance of the shear in unstable conditions for
$\Delta T_v < 0$. This effect is a bit more pronounced for the Virginia buoy. In the next couple of sections we examine whether the variance can be further reduced by filtering based on sea state, namely swell and wave age.

### 2.1.1 Wave Age Effects

Wave age is defined to be the wave phase speed, $c_p$, divided by the surface wind speed, i.e.,

$$\tau = \frac{c_p}{U_s}.$$  \hfill (2.7)

The phase speed was obtained from

$$c_p = \frac{g T_p}{2\pi},$$

where $g$ is the acceleration of gravity at the Earth’s surface, and $T_p$ is the significant wave period measured by the TRIAXYS system.

Wave age is a measure of the strength of the wind forcing and wave growth. For low values of $\tau$ the waves are strongly forced by the wind, and growth rates are high (Melville et al. 2004). Thus, wind waves tend to have smaller values of $\tau$; whereas swell tends to have larger values of $\tau$. Generally speaking, young waves (small values of tau) tend to be wind-driven and more locally generated waves, and old waves (larger values of tau) corresponding to swell, which are waves generated by distant storms that have traveled long distances.

Wave properties such as significant wave height, wave direction, and wave periods were measured with the TRIAXYS Next Wave II sensor. This sensor incorporates a 3-axis accelerometer, from which displacements in x (east), y (north) and z (vertical) are derived. Wave properties such as the average wave height ($H_{avg}$), significant wave height ($H_{sig}$), maximum wave height ($H_{max}$), and the average period ($T_{avg}$) are determined from analysis of the zero-crossings in the wave elevation ($z$-displacement) data (Mansard and Funke 1990). Additional wave properties are obtained from spectral analysis of the displacement data. Non-directional wave spectra are computed from the wave elevation ($z$-displacement) data. The non-directional power spectra are used to compute the zeroth moment ($H_{m0}$), which provides another measure of wave height, and the period ($T_p$) corresponding to the maximum of the non-directional power spectrum. Lastly, the directional wave spectrum is computed from the x-z and y-z cross-spectra and estimates of wave direction and spread are obtained using a modified version of the KVH method (Kuik et al. 1988).
Figure 2.2. Distributions of wave age for a) the Virginia buoy, b) the New Jersey buoy. The median wave age during the Virginia deployment was 2.02, and the median wave age during the New Jersey deployment was 2.15.

Figure 2.2 shows distributions of the wave age for both the Virginia and New Jersey deployments. Young waves occur with much greater frequency than old waves at both sites, as both distributions peak around $\tau \sim 1$ and then decrease monotonically with increasing wave age. Young waves with $t \sim 1$ occurred with greater frequency during the Virginia deployment than during the New Jersey deployment. We note that the median wave age during the Virginia deployment was 2.02, and the median wave age during the New Jersey deployment was 2.15.

Figure 2.3. Impact of wind direction and wave age filtering on the relationship between wind shear and $\Delta T_v$ for the Virginia buoy. Red points indicate data corresponding to onshore flow and a) wave age less than 2.02 (young waves), and b) wave age greater than 2.02 (old waves).
Figure 2.3 and Figure 2.4 show the impact of filtering based on both wind direction and wave age for the Virginia and New Jersey buoys, respectively. These plots show that under stable conditions the variance in the wind shear is reduced by rejecting samples corresponding to larger values of $\tau$, particularly for the Virginia buoy under stable conditions for $\Delta T_v > 0$.

Conversely, rejecting low values of wave age helps to reduce the variance in unstable conditions; however, the filtered wind shears tend to be evenly distributed about zero, whereas MOST predicts a small positive shear in this stability regime. These observations suggest that swell (high $\tau$) acts to suppress wind shear in moderate to strongly unstable conditions.

![Figure 2.3](image1)

**Figure 2.3.** Impact of wind direction and wave age filtering on the relationship between wind shear and $\Delta T_v$ for the New Jersey buoy. Red points indicate data corresponding to onshore flow and a) wave age less than 2.15 (young waves), and b) wave age greater than 2.15 (old waves).

2.1.2 Wave Partitioning Methodology

A watershed algorithm based on steepest ascent following Hanson and Phillips (2001) was used on the directional wave spectra from the TRIAXYS sensor in order to distinguish swell from wind waves. Wave spectra are estimated from the lidar buoy measurements using the maximum entropy method (more details in Shaw et al. 2020 and Garcia Medina et al. 2020). Following Hanson and Phillips (2001) and Hanson et al. (2009) the spectra are normalized and smoothed with an equally weighted eight-point averaging before being partitioned by the watershed algorithm. An undefined number of partitions can result because no limit is placed during the initial partitioning. Wind seas are identified based on the difference between the projected wind speed and the phase speed of the waves meeting the following criterion (e.g., Dobson et al. (1994), Pan et al. 2005, Hanson and Phillips (2001), Hanson et al. (2009)):

$$\alpha \frac{U_{10}}{c_p(f)} |\cos(\theta - \psi)| < 1$$

(2.8)

where $U_{10}$ is the wind speed at 10 m height, $c_p$ is the phase speed of the waves, $\theta$ is the wave direction, $\psi$ is the wind direction, and $\alpha$ is a calibration factor. The statistical properties of the partitioned spectra were not found to vary for $1.2 \leq \alpha \leq 1.5$, the former was chosen as a
The phase speed is computed based on linear wave theory for each spectral frequency:

\[
\sigma^2 = g k \tanh(kh)
\]  

(2.9)

where \( \sigma = \frac{\pi \omega}{g} \) is the radian wave frequency, \( h \) is the local water depth, and \( k \) is the wave number. The phase speed is \( \sigma / k \). If multiple partitions are being actively forced by wind, they are combined under a single wind sea partition.

A cap of 10 total partitions is applied; this is determined to be a sufficient number because more than 95% of the total spectral energy is on average contained within these partitions. If more than 10 partitions result from the watershed algorithm, then adjacent partitions are combined until the maximum number of partitions is met. Bulk wave parameters are computed for each partition for analysis. The significant wave height \( H_{m0} \) is defined as:

\[
H_{m0} = 4 \sqrt{\int E(f, \theta) \, df \, d\theta}
\]  

(2.10)

where \( E \left[ \frac{m^2}{Hz-deg} \right] \) is the frequency and directionally resolved variance spectrum. The peak period \( T_p \) is the peak wave period, defined as the inverse of the frequency corresponding to the maximum energy of the directionally integrated spectrum. These parameters are computed for the total spectrum and for each partition independently. Finally, for conservation of energy the total significant wave height \( (H_{m0,\text{tot}}) \) is related to the partitioned wave height as:

\[
H_{m0,\text{tot}} = \left( \sum_{i=1}^{10} H_{m0,i}^2 \right)^{0.5}
\]  

(2.11)

Figure 2.5. Partitioned spectrum example. Radial direction shown in Hz.

As an example, Figure 2.5 shows the wave spectrum measured during the Virginia deployment on 25 January 2015. The wind was blowing offshore at 10.0 m/s producing offshore directed waves with \( H_{m0} = 1.23 \) m. At the same time two swells are approaching from the southeast and the northeast. Those correspond to the two most energetic swells identified by the automated algorithm. The combined \( H_{m0} \) from partitions 3 – 9 is 0.1 m (not shown). As can be seen from
Figure 2.7 if only bulk spectral parameters are considered it could be reasonably concluded that the wind and the waves are aligned. That is because the most energetic component are the locally generated waves (i.e., the wind waves). However, there are two distinct swells that are misaligned with the wind seas by more than 100°. The effects of these wave conditions on the wind shear profile are discussed in Section 3.2. For the purposes of this document, the swells are numbered based on the energy content, where swell 1 is the most energetic spectral component not actively forced by the wind at any given time. The wind-wave misalignment will be evaluated based on the total wave spectrum, the wind-wave partition, and the most energetic swell partition. An analysis based on multiple swells where their combined effect on the wind profile is evaluated has not been performed at this time.

2.1.3 Characteristics of the Partitioned Wave Field

This section provides a brief description of the wind-wave and swell distributions at both deployments. A detailed description of the total sea state can be found in Shaw et al. (2020). Figure 2.6 shows probability density functions for total, swell, and wind-wave significant wave height for both deployments. During the measurement period 95% of the total swell significant wave height lies between 0.43 and 2.12, and 0.32 and 1.83 m for the Virginia and New Jersey deployments, respectively. These deployments experienced near constant swell approach where swells have a significant wave height of 0.25 m 99% of the time. Wind waves span a large range of wave height values which suggest that strong wind generation or reinforcement, where the wind forces previously developed waves, can drive large waves. Note the similarity between the wind-wave distribution of Figure 2.6 and the wave age distribution of Figure 2.2.

![Figure 2.6. Total, combined swell, and wind-wave significant wave height distributions.](image)

The directions from the wind seas (Figure 2.7 left) correspond well with the near-surface wind patterns at each location (Shaw et al. 2020, Figure 4.12). Where the largest wind-driven waves approach from the northeast in both deployments. This pattern contrasts with the distribution of the total swell (Figure 2.7 right), where the significant wave height is computed from the combined swells using Equation 2.11. Swells at the Virginia deployment approach from many directions from the east–northeast to the south. The New Jersey coast is sheltered from swells from the northeast and with swells only approaching between 90° and 180°. This suggests sheltering due to the change in shoreline orientation starting at Long Island filters the swell energy reaching the deployment area.
2.1.4 Effects of Swell

Here we use the results of section 2.1.2 to examine the effects of swell on the relationship between wind shear and air–sea temperature differences. The total wave energy is proportional to the following

\[ E_T \propto \sqrt{H_{\text{swell}}^2 + H_{\text{wind-wave}}^2} \]  \hspace{1cm} (2.12)

where \( H_{\text{wind-wave}} \) and \( H_{\text{swell}} \) are significant wave heights due to wind waves and swell, respectively. These parameters are obtained from wave partitioning analysis described in Section 2.1.2. We define the swell fraction to be the fraction of swell energy to total wave energy,

\[ s_r = \frac{H_{\text{swell}}}{E_T} \]  \hspace{1cm} (2.13)
Thus, $s_f$ can range from 0 for pure wind waves, to 1 for pure swell. We describe the wave field as wind-wave dominant when $s_f < 0.5$, and swell dominant when $s_f > 0.5$. Figure 2.8 shows an example time series from January 2016 for both buoys showing the swell fraction and wave age. The blue curves in the top panels represent the total energy, as given by Equation 2.7. The red curves in the top panels represent the swell contribution. The ratio between the red and the blue, i.e., the swell fraction, is shown in the middle panels of Figure 2.8. Finally, for comparison, the bottom panels show the wave age, $\tau$.

![Figure 2.8. Swell and wave age time series during January 2016 observed by the a) Virginia, and b) New Jersey buoys. Top panels show the total significant wave height (blue), and the significant wave height due to swell (red). Middle panels show swell fraction (ratio of the red to blue curves in top panels), and wave age is shown in the bottom panels.](image)

We should mention that there were significant periods of missing directional wave spectra during both the Virginia and New Jersey deployments. For the Virginia deployment this included the period from the end of May 2015 until 28 July 2015, i.e., roughly 2 months. For the New Jersey deployment, directional wave spectra are missing from mid-May 2016 until 30 June 2016, and again from mid-January until 7 February 2017. The issue we found was that the binary files containing spectral data were about half their normal size during the effected periods. In all cases, periods of missing data would start several weeks before the compact flash (CF) cards were retrieved from the buoys. Installing new CF cards seemed to fix the problem. Despite the apparent loss of directional wave spectra, the TRIAXYS system continued to produce valid estimates of the significant wave height, period and direction throughout the effected periods.
Distributions of swell fraction are shown in Figure 2.9. The bulk of these distributions occur for $sf > 0.5$, indicating that the wave field is dominated by swell most of the time at both sites. Wind waves were slightly more prevalent at the Virginia site than at the New Jersey site. At the same time, the Virginia site also saw a higher occurrence of nearly pure swell waves.

There is a general tendency for larger values of swell fraction to correspond to larger values of wave age, but the correlation is not that strong. This is seen more clearly in Figure 2.10, which shows wave age as functions of swell fraction for both the Virginia and New Jersey deployments.
Figure 2.11 and Figure 2.12 show the impact of filtering based on both wind direction and swell fraction for Virginia and New Jersey buoys, respectively. For these plots, the median value of swell fraction was used as the threshold. These values were 0.7 at the Virginia site, and 0.78 at the New Jersey site. Qualitatively, filtering based on swell fraction has much the same effect as filtering based on wave age. Swell-dominant wave fields are associated with a relatively tight clustering of the wind shear values about zero for moderate to strongly unstable atmospheric conditions. This is similar to the behavior we observed for larger values of wave age (see Figure 2.3 and Figure 2.4). Under neutral and stable conditions, we observe that wave age filtering results in a lower variance of the wind shear as compare to filtering based on swell fraction. This suggests that wave age may be a more robust parameter for evaluating the effects of the wave state on the wind speed profile. However, more work is needed to explore other metrics derived from the wave partitioning analysis.

![Figure 2.11](image)

**Figure 2.11.** Impact of wind direction and swell fraction filtering on the relationship between wind shear and $\Delta T_v$ for the Virginia buoy. Red points indicate data corresponding to onshore flow and a) swell fractions less than the median value of 0.7, and b) swell fractions greater than 0.7.
2.2 Comparison with Monin-Obukhov Stability Theory

In this subsection, we investigate the relationship between non-dimensional wind shear and the stability parameter as defined by MOST. We expect that the conditions for MOST to be best satisfied when the general flow is onshore, and when the observation height is sufficiently below the depth of the internal boundary layer, i.e., for \( \frac{z}{h} < \frac{1}{4} \), where \( h \) is the planetary boundary layer depth (Vickers and Mahrt 1999). The non-dimensional wind shear is given by

\[
\phi(\xi) = k \frac{z}{u_*} \frac{\partial U}{\partial z}
\]  

where \( \xi = \frac{z}{L} \) is the stability parameter, \( u_* \) is the friction velocity at the observation height \( z \), \( k \) is the von Karman constant (assumed to be 0.39 in this analysis), and \( U \) is the mean wind speed. Estimates of the friction velocity were obtained from a bulk flux algorithm (Fairall et al. 1996; Fairall et al. 2003; Edson et al. 2013) since direct measurements of momentum flux were not available from the buoy.

2.2.1 Flux Estimates

When turbulent fluxes are not directly measured, they can be estimated from the bulk method when near-surface measurements (generally within 10 m) of non-turbulent quantities are present. The bulk method relies on vertically integrated forms of Monin-Obukhov similarity equations to relate interfacial differences of temperature, moisture, and wind components to their vertical turbulent fluxes. Necessary inputs include air temperature, relative humidity, winds, and pressure (in order to compute air density), as well as the temperature of the ground or water surface. In general, the resultant bulk flux relations cannot be solved for the turbulent fluxes in closed form, since the Monin-Obukhov length is itself a function of those fluxes. Thus,
the bulk flux algorithm (except in idealized cases) becomes an iterative method to find a self-
consistent set of turbulent fluxes for given non-turbulent inputs.

Several factors preclude the creation of a unified bulk flux algorithm method. First, the method
assumes the validity of Monin-Obukhov similarity, and so would obviously not work in conditions
where the similarity theory is not valid, such as if turbulence is intermittent, or is not primarily
surface-based. It may also be possible that the spatial and temporal scales of measurements
may not be fully appropriate to the separation of turbulent and non-turbulent fields used in the
method. The difficulty of turbulence measurements over certain stability regimes means that
there is not universal acceptance of the form of the Monin-Obukhov formulas in all conditions.

In the offshore environment, additional complications to the bulk flux method arise. Over land, it
is usually assumed the air velocity goes to zero at a roughness height that is only a function of
land-use characteristics. Over the open water, the surface can have a current velocity that
should be subtracted out before applying the bulk formula, though this is often not taken into
account. Furthermore, the momentum drag at the surface is a function of wave state, which
causes the roughness length to become a complex function of the air velocity.

For offshore applications, a bulk flux algorithm has been developed based on observations from
the TOGA-COARE of 1992–1993. The algorithm, hereafter the COARE algorithm, has been
updated throughout the years based on new field data and/or theory (Fairall et al. 1996; Fairall
et al. 2003; Edson et al. 2013).

Initially version 2.5 of the COARE algorithm was used to compute the surface turbulent fluxes
that were in turn used to determine the Monin-Obukhov length applied in the lidar wind shear
calculations. Inputs to the COARE 2.5 algorithm were the 10-minute averaged cup anemometer
wind speed at 4 m and relative humidity, pressure, and temperature measured on the buoy at
3-m. Sea surface temperatures were obtained from the Acoustic Doppler Current Profiler
sensor.

To determine the sensitivity of the bulk method fluxes to the algorithm used, we recomputed the
fluxes using the COARE 3.0 algorithm, but with the same inputs as before. While there are quite
a few differences in the details of how the two algorithms are implemented, the main differences
between the two versions are the following:

1. COARE 3.0 assumes different forms of the Monin-Obukhov functions in both stable and
   unstable conditions compared to COARE2.5. In stable conditions, COARE 2.5 uses the
   standard Businger-Dyer equation, but imposes a minimum value on the Monin-Obukhov
   length to keep predicted fluxes from becoming zero. The COARE 3.0 algorithm in stable
   conditions is based on the Beljaars and Holtslag formula, which does not lead to zero fluxes
   at large stabilities and so does not need the bounding. In the unstable cases, COARE 3.0
   uses slightly modified similarity relations from COARE 2.5, and unlike COARE 2.5 uses
   different formulas for temperature and momentum in strongly convective conditions.

2. COARE 3.0 uses different forms of the thermal and momentum roughness lengths, which
   causes a different dependency of the drag coefficients on the wind speed.

3. COARE 3.0 includes options for parameterizing the roughness height on wave height and
   period, although we do not use that option for these baseline tests.
2.2.2 Non-dimensional Shear vs Stability

Flux estimates from the bulk algorithm are used to compute the non-dimensional wind shear as a function of stability parameter, \( \xi_i \), where \( i \) is a sample index. The non-dimensional wind shear is approximated according to

\[
\phi_i = \frac{kz}{u_{ij}} \left( U_{ij}^{lidar} - U_{ij}^s \right) / \Delta z
\]

(2.16)

where

\[
z = \left( z_{lidar} + z_s \right) / 2
\]

(2.17)

and

\[
\Delta z = z_{lidar} - z_s
\]

(2.18)

\( z_{lidar} \) is the height of the center of the lidar range gate, and \( z_s \) is the height of the surface anemometer on the buoy. In this case \( z_{lidar} = 71.0 \text{ m} \) and \( z_s = 4.1 \text{ m} \). The height that is used in the scaling of the vertical and horizontal (z/L) axes is the height of the midpoint between the lidar range gate center and the surface anemometer. This would seem appropriate since the wind shear is computed as the difference in wind speeds between these two levels.

Figure 2.13 and Figure 2.14 show non-dimensional wind shear as functions of stability parameter for the Virginia and New Jersey deployments, respectively. Also shown in each of the figures are results using COARE 2.5 and COARE 3.0. It is clear that there is virtually no difference in the results using either COARE 2.5 or COARE 3.0.

Red points in Figure 2.13 and Figure 2.14 show samples corresponding to onshore flow and younger waves (wave age < 2.02 for the Virginia buoy, and wave age < 2.15 for the New Jersey buoy). This filtering helps to delineate the relationship between the non-dimensional and stability parameter, particularly for the Virginia buoy. For z/L > 0 the filtered data exhibits a distinct linear trend with z/L. For the New Jersey buoy the situation is a bit more complicated, but a similar linear trend is also indicated.

For comparison, Figure 2.13 and Figure 2.14 also show three standard parameterizations. These include the Businger-Dyer (BD) (Businger et al. 1971; Dyer 1974), Beljaars and Holtslag (BH) (Beljaars and Holtslag 1991), and the Vickers and Mahrt (VM) (Vickers and Mahrt 1999). For reference we give their functional forms here. The BD function is given by

\[
\phi_{BD}(\xi) = \begin{cases} 
1 + 4.7\xi, & \text{for } \xi \geq 0 \\
(1 - 15\xi^{1/4}), & \text{for } \xi < 0
\end{cases}
\]

(2.19)

and the BH function is given by (Vickers and Mahrt 1991)

\[
\phi_{BH}(\xi) = \begin{cases} 
1 + \xi \left( a + b \exp(-d\xi)(1 + c - d\xi) \right), & \text{for } \xi \geq 0 \\
\phi_{BD}(\xi), & \text{for } \xi < 0
\end{cases}
\]

(2.20)
with \( a = 1, b = 0.667, c = 5, \) and \( d = 0.35 \). The VM function is given by

\[
\phi_{VM}(\xi) = \begin{cases} 
(1 + 16\xi) \nu/3, & \text{for } \frac{\nu}{\xi} \geq 0 \\
(1 - 35\xi) \nu/4, & \text{for } \frac{\nu}{\xi} < 0 
\end{cases}
\] (2.21)

The BD function comes closest to the current observations; however, for \( z/L > 0 \) the observed non-dimensional wind shear is larger than that predicted by any of the models. Also, the BH and the VM functions exhibit nonlinear behavior for \( z/L > 0 \) that is not suggested by the filtered data. On the unstable side, the BD, BH, and VM functions are nearly identical. In these cases, the models overestimate the shear when compared to the observations.

Figure 2.13. Non-dimensional shear vs stability parameter for the Virginia buoy using a) COARE 2.5 fluxes, and b) COARE 3.0 fluxes. Red points indicate samples where the flow is onshore and wave age is less than 2.02. Also shown are BD (solid), Belljaars and Holtslag (dashed), and the VM (dash-dot) models.
The New Jersey case (Figure 2.14) is notable for the prevalence of negative wind shear values for z/L < 0. These negative wind shears are real and not the result of noise in the measurement. In Section 2.3.2.1 we show that these features are associated with specific wind and wave directions.

2.2.3 MOST-Predicted vs Lidar-Observed Winds

If we assume the friction velocity to be constant with height, Equation (2.9) can be solved to yield estimates of wind speed at any desired height. Figure 2.15 and Figure 2.16 show the difference between the lidar-observed and MOST-predicted wind speed as a function of stability for the Virginia and New Jersey deployments, respectively. Here again the comparisons are done using the BD, BH, and VM functions. As indicated, all models produce large errors over the range of atmospheric stabilities that were observed, with larger errors occurring for stable flows. Both the Virginia and New Jersey results indicate that filtering based on wave age does little to improve the overall agreement with MOST. The VM model resulted in the largest overall bias and standard deviation, while BH model gave the smallest bias and standard deviation. As always, the results for New Jersey (Figure 2.16) exhibit more scatter than for Virginia (Figure 2.15) due to the influence of nearby land.

For unstable flows, all the models are essentially identical. For z/L less than -2 the models tend to overestimate wind speed by roughly 0 to 1 m s⁻¹. This is consistent with the observations in Figure 2.13 and Figure 2.14, which show the models overestimate wind shear in this stability regime.

Results shown Figure 2.15 and Figure 2.16 indicate that the error changes sign as one passes through neutral. For a narrow band about neutral stability the error in the Virginia buoy is nearly unbiased. By contrast, the New Jersey buoy shows a significant negative bias at neutral, indicating a tendency for MOST to overestimate wind speed under neutral conditions at the New Jersey site. As one moves away from neutral, the errors increase significantly under weakly stable or weakly unstable conditions. Under more strongly stable conditions the BD function
overestimates the wind speed at 70 m, and this overestimation gets worse with increasing stability. By contrast, the BH function produces a less biased result for \( z/L \) greater than about 1. In Section 2.3.1.1 we present scatter diagrams showing the correlations between the lidar measurements at 90 m and MOST predictions using the BD and BH functions. Specifically, Figures 2.17 through 2.19 show that the BH function results in improved correlation compared to the BD function due to its better performance under stable conditions.

Figure 2.15. Difference between the lidar wind speed at 71 m MSL and the wind speed predicted from MOST for the Virginia buoy using a) BD, b) BH, and c) VM. Red points indicate samples where the flow is onshore and wave age is less than 2.02.

Figure 2.16. Difference between the lidar wind speed at 71 m MSL and the wind speed predicted from a) BD, b) BH, and c) VM for the New Jersey buoy. Red points indicate samples where the flow is onshore and wave age is less than 2.15.

### 2.3 Wind-Wave Misalignment

In this section we examine the impact of wind-wave alignment on MOST predictions. Both buoys were deployed in an area known as the Mid-Atlantic Bight. This region is exposed to swells from the northeast and southeast with significant local wave generation. Locally forced waves are, by definition, aligned with the wind, but swells are independent of the local conditions. Recent studies have found that surface roughness is correlated with the swell component of the wave field (e.g., Pan et al. 2005). This motivates the examination of model performance based on wind-wave misalignment for total sea states and swells independently.
2.3.1 Metocean Conditions During Significant Wind-Wave Misalignment

The following discussion begins with an examination of the metocean properties during the Virginia and New Jersey deployments according to the divergence between the near-surface (4 m) winds and the total wave spectrum. The analysis in the previous section identified swells largely misaligned from the wind-driven seas and noted that these distinct features become obscured in the bulk wave spectrum. Therefore, this investigation of metocean properties is extended to consider the divergence between near-surface winds and the most energetic components of the wave spectra outlined in the prior section, namely wind-driven waves and partition 1 swell. Trends in the air–sea temperature difference and the wind shear between 4 m and 90 m according to the magnitude and sign of wave-wind misalignment are identified, and hub-height wind speed biases from similarity theory-based simulations are noted for different combinations of metocean conditions.

2.3.1.1 Metocean Conditions and Simulated Hub-Height Wind Speed Error

Before examining the relationships between wind-wave misalignment, metocean conditions, and simulated hub-height wind speed errors, it is necessary to recall from Figure 2.1 that two trends were observed during the initial DOE buoy deployments. Positive air–sea temperature differences tended to occur alongside strong positive wind shear, and negative air–sea temperature differences trended with minimal to negative wind shear. Thresholds, defined in Table 2.1, are applied to the extremes of these trends and provide metocean context for analysis on the performance of similarity theory-based simulations of hub-height wind speed according to wind-wave misalignment.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description and thresholds</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Positive hub height (90 m) to near-surface (4 m) wind speed differences ($U_{\text{Hub}} - U_{\text{Surface}} &gt; 5 \text{ m/s}$) with positive air–sea temperature differences ($T_{\text{air}} - T_{\text{sea}} &gt; 0^\circ\text{C}$)</td>
</tr>
<tr>
<td>2</td>
<td>Small to negative hub height (90 m) to near-surface (4 m) wind speed differences ($U_{\text{Hub}} - U_{\text{Surface}} &lt; 1 \text{ m/s}$) occurring in combination with large negative air–sea temperature differences ($T_{\text{air}} - T_{\text{sea}} &lt; -5^\circ\text{C}$)</td>
</tr>
</tbody>
</table>

It is of interest to examine how the two features of metocean conditions impact the performance of similarity theory-based enhancements to height adjustment techniques that are commonly employed in the wind energy industry. The wind speed at 90 m was computed using (Holtslag et al. 2014)

$$
\nu = v_{\text{ref}} \frac{\ln(z/zo) - \Psi(z/L)}{\ln(z_{\text{ref}}/zo) - \Psi(z_{\text{ref}}/L)} \quad (2.22)
$$

where $z_o$ is the roughness length, $z_{\text{ref}}$ is the height of the surface anemometer (4.1 m), and $z$ is the hub height. The function $\Psi(z/L)$ is given by

$$
\Psi(z/L) = \int_{z/L}^{z/L} \left( 1 - \phi(x) \right) dx \quad (2.23)
$$

and the function $\phi(z/L)$ is given by Equation 2.14 for BD, and Equation 2.15 for BH. Wind speed estimates using the BD and BH similarity functions are compared to 90 m wind speed.
observations from the lidar in Figure 2.17. As noted in earlier sections, for both deployments the BD formulation strongly overestimates the observed 90 m wind speed during stable conditions. These effects are mitigated by applying the BH similarity functions for stable conditions.

Figure 2.17. Comparison between observed (x-axis) and simulated (y-axis) 90 m wind speeds for the Virginia (left column) and New Jersey (right column) deployments. Simulated winds according to the log law incorporating the BD formulations for the stability correction function are shown in the top row, and those utilizing the BH correction function for stable cases are presented on the bottom row. Points are colored by the stability parameter $z/L$ estimated at 4 m.

The same observed vs simulated 90 m wind speeds are plotted in Figure 2.18, but data falling within the Feature 1 criteria are highlighted. Except under strongly stable conditions, BD estimates underpredict hub-height winds. In Feature 1, increasing wind speed is associated with a move from stable to neutral conditions. The BH formulations overall underpredict, in all atmospheric conditions, observed hub-height winds. For this feature, the correlation coefficients degrade relative to those from the overall deployments at Virginia and remain similar at New Jersey. The slopes deviate strongly from one using the BD formulations, but are 0.85 and 0.95 when using BH at Virginia and New Jersey, respectively.
Figure 2.18. Comparison between observed (x-axis) and simulated (y-axis) 90 m wind speeds for the Virginia (left column) and New Jersey (right column) deployments. Simulated winds according to the log law incorporating the BD formulations for the stability correction function are shown in the top row, and those utilizing the BH correction function for stable cases are presented on the bottom row. All points are plotted in gray, and those falling within the following criteria are colored by the stability parameter $z/L$: 90 m–4 m wind speed difference $> 5$ m/s, Air T–Sea T $> 0°C$.

Figure 2.19 displays the comparison of observed and simulated 90 m wind speeds using the BD formulations both with and without the BH correction, highlighting cases falling within the Feature 2 criteria. A tendency for the simulations to slightly overestimate the observed 90 m wind speeds exists but mostly under neutral conditions. In Feature 2 cases, an increasing wind speed is associated with a move from unstable to neutral conditions. Since Feature 2 conditions represent primarily unstable and neutral conditions, both BD and BH formulations provide the same subset of data. The correlation coefficients for Virginia and New Jersey formulations are 0.98 and 0.96, respectively. A relatively small bias and slope near 1 is observed, for both formulations.

When the air–sea temperature difference is non-zero, heat is transferred between the air–sea interface due to conduction. When the ocean temperature exceeds the air temperature, buoyant plumes form in the heated air, transferring heat away from the ocean surface through convection. If the ocean were colder than the atmosphere (as in Feature 1) the air in contact
with the ocean would cool, becoming denser and hence more stably stratified. In this case, the conduction process does not carry the atmospheric heat into the cooler ocean as effectively. Results shown in Figure 2.19 indicate that the BD and BH formulations perform best under strongly unstable conditions when conduction processes play a more important role in the transfer of heat. There are, however, several other factors at play such as wind-wave direction alignment, wind-driven vs. swell conditions. These will be discussed in the coming sections.

Figure 2.19. Comparison between observed (x-axis) and simulated (y-axis) 90 m wind speeds for the Virginia (left column) and New Jersey (right column) deployments. Simulated winds according to the BD formulations are shown in the top row, and those utilizing the BH correction function for stable cases are presented on the bottom row. All points are plotted in gray, and those falling within the following criteria are colored by the stability parameter $z/L$: 90 m–4 m wind speed difference < 1 m/s and Air T–Sea T < -5°C.

2.3.1.2 Wind – Total Wave Misalignment Effects on Simulated Hub-Height Wind Speed Errors

The study continues with an examination of the directional divergence between the total wave spectrum (i.e., swell and wind-driven waves) and the near-surface winds along with the impact
of divergence on the simulated hub-height wind speed errors, with a particular focus on cases exhibiting Feature 1 and 2 metocean conditions. Figure 2.20 shows the distributions of difference between the total wave directions and near-surface wind directions for both deployments. Positive differences indicate that the wave direction is ahead of the wind direction, in a clockwise manner; negative differences indicate the total wave direction behind the near-surface wind direction. The Virginia deployment shows a distribution of directional divergence that peaks around +20°, while the frequency peak around -55° at the New Jersey site. Therefore, near the Virginia buoy winds are more aligned with the waves, while near New Jersey, wind-wave misalignment occurs mostly due to the proximity of the buoy to the coast.

![Figure 2.20](image)

Figure 2.20. Distributions of total wave and near-surface wind directional divergence for the Virginia and New Jersey deployments. Positive differences indicate that the wave direction is ahead of the wind direction in a clockwise manner; negative differences indicate that the wave direction is behind the wind direction.

Figure 2.21 shows hub-height wind speed errors between the observed and extrapolated winds (using both BD and BH formulations) as a function of divergence between the total wave direction and the near-surface winds. For both deployments, the largest errors are produced using the BD formulations and tend to occur for negative wave-wind misalignments, when the total wave direction is behind the wind direction in a clockwise manner. The largest concentrations of cases where the observed hub-height wind speeds deviate most strongly from the simulated speeds that incorporate the BD formulations correlate with total wave-wind misalignments between -70° and 0° for the Virginia deployment and -120° and -30° during the New Jersey deployment.

BH formulations exhibit decreased variability in error as compared to BD formulations. Figure 2.21 shows that the BH wind speed estimates deviate within ±5 m/s from the observed 90 m wind speeds. For both deployments, more variability in the error is exhibited for negative total wave-wind misalignments.

Instances exhibiting the Feature 1 characteristics of strong positive wind shear and positive air–sea temperature difference are colored by the stability parameter $z/L$ in Figure 2.21. Feature 1 characteristics, which are associated with neutral to stable environments, are mostly concentrated with negative wind-wave misalignments for both New Jersey and Virginia. As noted in Section 2.2.3, the hub-height wind speed simulations based on the BD formulations produce large positive deviations from the observed hub-height winds during strongly stable conditions, which are mitigated using BH similarity formulations. BH estimates of extrapolated wind speed at hub height tend to overall underestimate for Feature 1 instances.
Figure 2.21. Simulated 90 m wind speed error (y-axis) from the log law in conjunction with the BD (top row) and BH (bottom row) stability correction functions according to total wave and near-surface wind directional departure (x-axis) during the Virginia and New Jersey deployments. All points are plotted in gray, and those falling within the Feature 1 criteria of 90 m – 4 m observed wind speed difference > 5 m/s and air–sea temperature difference > 0°C are colored by the stability parameter $z/L$.

Figure 2.22 shows simulated hub-height wind speed errors according to total wave-wind misalignment as in Figure 2.21, for instances exhibiting Feature 2 characteristics of small to negative observed wind shear and strongly negative air–sea temperature differences colored by the stability parameter $z/L$. Strongly unstable Feature 2 occurrences appear across all total wave-wind misalignments, and the associated simulated hub-height wind speed error is near 0 m/s. More neutral environments with Feature 2 characteristics occur for specific ranges of total wave-wind offsets, and the simulated hub-height wind speeds for these cases tend to overestimate the observed winds. For the Virginia deployment, the concentration of neutral conditions combined with Feature 2 characteristics falls between total wave-wind misalignments of -40° and +100°. For the New Jersey deployment, neutral conditions occurring in conjunction with Feature 2 characteristics are found for all total wave-wind offsets except for when the waves and winds are aligned (offsets between ±15°) and severely misaligned (offsets less than -140° or greater than +170°). Similar tendencies in wind speed errors as a function of wind-wave misalignment are observed in both locations for BH estimates, i.e., an average negative bias of 1-2 m/s in Feature 1 conditions and near zero bias during Feature 2 conditions. This is indeed interesting, as one would expect coastal sea breezes and internal boundary layers (causing large wind shear and higher thermal gradient between sea surface and air) to invalidate Monin-Obukhov-theory assumptions. A meso-scale and micro-scale modeling effort is a part of future work to understand some of these inconsistencies and dynamics.
The analysis in the Section 2.1.2 identified swells largely misaligned from the wind-driven seas and noted that these distinct features become obscured in the total wave spectrum. Therefore, the investigation of metocean properties and the performance of hub-height wind speed simulations incorporating the BD and BH formulations is extended in Section 2.3.2 to consider the divergence between the near-surface winds and the most energetic components of the wave spectra outlined in Section 2.1.2, namely wind-driven waves and partition 1 swell.

### 2.3.1.3 Wind – Wind-Driven Wave Misalignment Effects on Simulated Hub-Height Wind Speed Errors

The discussion continues with an examination of the directional divergence between wind-driven waves and the near-surface winds themselves. Figure 2.23 depicts the distributions of the difference between the wind-driven wave directions and the near-surface wind directions for both deployments. The Virginia deployment shows a normal distribution of directional divergence centered around 0°, while the peak using the total wave spectrum was shifted somewhat into positive values. The wind-driven wave to wind misalignment frequency peaks in descending order centered around -40°, +5°, and +60° at the New Jersey site. A similar, yet more variable pattern by misalignment was noted for the distribution based on the total wave spectrum at New Jersey, due to its proximity to the coast.
Figure 2.23. Distributions of wind-driven wave and near-surface wind directional divergence for the Virginia and New Jersey deployments. Positive differences indicate that the wave direction is ahead of the wind direction in a clockwise manner; negative differences indicate that the wave direction is behind the wind direction.

Figure 2.24 shows the hub-height wind speed errors from BD and BH formulations as a function of misalignment between wind-driven waves and the near-surface winds. For the simulated winds speeds that incorporate the BH formulations, which more appropriately represent the observed 90 m wind speeds under stable conditions, the sign of the error does not exhibit a noticeable trend according to wave-wind misalignment, while the variability in the errors does. For the Virginia deployment, variability in the simulated wind speed errors follows the pattern of the distribution of wind-driven wave to wind offsets, with the largest variability occurring when the waves and wind are aligned to minimally offset. For the New Jersey deployment, concentrations of the most variable wind speed errors are greatest between wind-driven wave to wind offsets of -180° and +90°.

Figure 2.24. Simulated 90 m wind speed error (y-axis) from the log law in conjunction with the BD (top row) and BH (bottom row) stability correction functions according to wind-driven wave and near-surface wind directional departure (x-axis) during the Virginia and New Jersey deployments. All points are plotted in gray, and those falling within the Feature 1 criteria of 90 m – 4 m observed wind speed difference > 5 m/s and air–sea temperature difference > 0°C are colored by the stability parameter \( z/L \).
Instances exhibiting the Feature 1 characteristics of strong positive wind shear and positive air–sea temperature difference are colored by the stability parameter $z/L$ in Figure 2.24. Feature 1 characteristics associated with strongly stable conditions occur in conjunction with all possible wave-wind misalignments for the Virginia deployment, and correspond to large positive errors in simulated hub-height wind speed using the BD methodology and zero to small negative wind speed errors when employing the BH corrections. Feature 1 occurrences in more neutral environments are concentrated between offsets of -60° and + 50° and are associated with simulated winds speeds that are similar to or underestimate the observed wind speeds.

Figure 2.25 provides a look into the origination of the wind-driven waves and winds that are associated with the Feature 1 attributes during the Virginia deployment. Conditions of strong positive wind shear and positive air–sea temperature difference are associated with winds sourced from the south and wind-driven waves coming from the south–southeast.

![Figure 2.25](image)

Feature 1 occurrences for the New Jersey deployment are largely confined to wind-driven wave to wind offsets between -150° and +40°, with the largest concentration of near neutral condition cases occurring between -60° and +40°. South–southwesterly winds and wind-driven waves from the south are associated with Feature 1 conditions for the New Jersey deployment, as seen in Figure 2.26. The warmer winds relative to the cooler waves results in neutral to stable conditions near the surface, as seen in the final column of roses in Figure 2.25 and Figure 2.26. In turn, these conditions allow for the strong positive wind shear observed, which the simulations either accurately represent or underestimate, excepting the BD simulations under strongly stable conditions.
Concentrations of the Feature 2 attributes of neutral to slightly negative wind shear occurring in combination with very cold air relative to the ocean are recognized in Figure 2.27 for both deployments. As in the total wave analysis, it is seen that strongly unstable Feature 2 occurrences appear across all wind-driven wave to wind misalignments, and the associated simulated hub-height wind speed errors are near 0 m/s. Concentrations of Feature 2 characteristics under neutral conditions, which are associated with zero to positive simulated wind speed errors, occur for wind-driven wave to wind offsets between -30° and +60° for the Virginia deployment. Two concentrations of Feature 2 characteristics under neutral conditions according to wind-driven wave to wind misalignment appear for the New Jersey deployment, between ±90° and 0°.
For the Virginia deployment, as seen in Figure 2.25, the Feature 2 characteristics of minimal wind shear and very cold air relative to the sea tend to occur with north–northwesterly winds and wind-driven waves sourced from the entirety of the northern quadrant, with a particular concentration in the north–northeast. For the New Jersey deployment, two peaks were noted that are dominated by the Feature 2 large negative air–sea temperature differentials and minimal wind speed difference. The first occurs when the wind direction is ahead of the wind-driven wave direction in a clockwise manner for directional offsets between -90° and 0°. As shown in Figure 2.26, the wind-driven waves for these misalignments tend to be sourced from the west–southwest, while the near-surface winds are west–northwesterly. For the second peak, the sign is flipped, and the wind-driven wave direction is ahead of the wind direction and is concentrated for directional offsets between 0° to +90°. Under these circumstances, the winds tend to be northerly and the wind-driven waves source from the east–northeast.

This section highlighted the dominant influence of wind-driven waves within the total wave spectrum. The misalignments of the total waves and wind-driven waves relative to the near-surface winds are similar in their distributions and concentrations of the Feature 1 and 2 attributes. Next, the more obscure partition 1 swell is isolated and assessed relative to the wind for impacts on the distributions of Feature 1 and 2 attributes and the corresponding performance of similarity theory-based simulations of hub-height wind speed.
2.3.1.4 Wind – Partition 1 Swell Misalignment Effects on Simulated Hub-Height Wind Speed Errors

The metocean conditions and simulated hub-height wind speed errors are now examined according to divergence between the wind and partition 1 of the swell or surface gravity waves, which is the most energetic of the swell categories. The distributions of directional divergence, shown in Figure 2.28, are bimodal for each deployment, with peaks centered around ±80° for Virginia and ±90° for New Jersey. The partition 1 swell to wind misalignment distributions have a different form than those shown for the total wave to wind misalignments in Figure 2.20, which each feature a solitary peak. Since swells are mostly driven due to large-scan synoptic weather systems, the similarity in distributions between the two sites is expected.

Figure 2.28. Distributions of partition 1 swell and near-surface wind directional divergence for the Virginia and New Jersey deployments. Positive differences indicate that the wave direction is ahead of the wind direction in a clockwise manner; negative differences indicate that the wave direction is behind the wind direction.

Figure 2.29 shows the simulated hub-height wind speed errors from the log law in conjunction with the BD and BH stability correction functions according to misalignment between the partition 1 swell and the near-surface winds. For both deployments and stability correction techniques for the simulated wind speeds, greater variability in the simulated wind speed error occurs for negative swell-wind offsets, or cases when the wind is ahead of the swell in a clockwise manner. This sign dependency is enhanced for simulations incorporating the BD methodology and minimal for simulations using the BH technique.
Figure 2.29. Simulated 90 m wind speed error (y-axis) from the log law in conjunction with the BD (top row) and BH (bottom row) stability correction functions according to partition 1 swell and near-surface wind directional departure (x-axis) during the Virginia and New Jersey deployments. All points are plotted in gray, and those falling within the Feature 1 criteria of 90 m – 4 m observed wind speed difference > 5 m/s and air–sea temperature difference > 0°C are colored by the stability parameter $z/L$.

Instances exhibiting the Feature 1 characteristics of strong positive wind shear and positive air–sea temperature difference are colored by the stability parameter $z/L$ in Figure 2.29. Feature 1 characteristics occur for all possible swell-wind misalignments for the Virginia deployment, but are most concentrated for negative swell-wind offsets. For the New Jersey deployment, Feature 1 occurrences are largely confined to swell-wind offsets between -150° and 0°.

Figure 2.30 provides a look into the origination of the partition 1 swell and winds that are associated with the Feature 1 attributes during the Virginia deployment. Conditions of strong positive wind shear and positive air–sea temperature difference are primarily associated with southerly winds and all predominantly occurring partition 1 swell origins, which encompass the eastern quadrant. For the New Jersey deployment, Feature 1 occurrences are correlated with south–southwesterly winds and all predominantly occurring partition 1 swell sources, which fall into the southeastern quadrant, as shown in Figure 2.31. As in the total and wind-driven wave analyses, the warmer winds relative to the cooler waters and strong positive wind shear are associated with neutral to stable conditions near the surface and zero to negative hub-height wind speed biases, with the exception of the BD simulations under strongly stable conditions.
Figure 2.30. 90 m – 4 m wind speed difference (left column), air–sea temperature differential (middle column), and stability parameter $z/L$ estimated at 4 m (right column) by 4 m wind direction (top row) and partition 1 swell direction (bottom row) for the Virginia deployment.

Figure 2.31. 90 m – 4 m wind speed difference (left column), air–sea temperature differential (middle column), and stability parameter $z/L$ estimated at 4 m (right column) by 4 m wind direction (top row) and partition 1 swell direction (bottom row) for the New Jersey deployment.
Feature 2 attributes of neutral to slightly negative wind shear occurring in combination with very cold air relative to the ocean are common for strongly offset swells and winds, as shown in Figure 2.32. Feature 2 is rare and dominated by strongly unstable conditions for swell-wind offsets between -50° and 0° for the Virginia case and for swell-wind offsets between -70° and +50° for the New Jersey case. As in the total and wind-driven wave analyses, it is seen that strongly unstable Feature 2 occurrences are associated with simulated hub-height wind speed errors near 0 m/s, while occurrences of this feature during more neutral conditions correlate with zero to positive simulated wind speed errors.

Figure 2.32. Simulated 90 m wind speed error (y-axis) from the log law in conjunction with the BD (top row) and BH (bottom row) stability correction functions according to partition 1 swell and near-surface wind directional departure (x-axis) during the Virginia and New Jersey deployments. All points are plotted in gray, and those falling within the Feature 2 criteria of 90 m – 4 m observed wind speed difference < 1 m/s and air–sea temperature difference < -5°C are colored by the stability parameter $z/L$.

Though variable, the largest concentrations of Feature 2 attributes during the Virginia deployment occur for north–northwesterly winds paired with partition 1 swells from the northeast and east, as shown in Figure 2.30. Feature 2 conditions also occur for very rare reversals of the partition 1 swell from its predominant easterly flow to a west–northwesterly flow. For the New Jersey deployment, events exhibiting Feature 2 attributes tend to be associated with near-surface winds from across the northwestern quadrant and partition 1 swells from all possible origins, which lie in and around the southeastern quadrant.

Therefore, regardless of swell or wind-driven waves conditions exhibiting Feature 1 are less predictable and the BH formulations exhibit a bias in estimated winds. Therefore, the applicability of MOST should be centered around Feature 2 type offshore atmospheric conditions.
2.3.2  Assessment of Time Rate of Change of Wind and Wave Direction

Given the trends in metocean properties and similarity theory-based simulation biases by alignment of wind and waves identified in the previous sections, it is of interest to explore these variables according to the time rate of change (TRC) of the wind with respect to the waves. Figure 2.33 displays the distributions of the TRC of wind-driven wave and near-surface wind misalignment over the time periods of 20 minutes, one hour, and three hours for both deployments. As expected, the frequency of large magnitude changes in wave to wind offset increases with length of time.

![Histograms of the time rate of change of wind-driven wave and near-surface wind misalignment for the Virginia (top row) and New Jersey (bottom row) deployments for Δ time = 20 minutes (left column), 1 hour (middle column), and 3 hours (right column).](image)

Figure 2.33. Histograms of the time rate of change of wind-driven wave and near-surface wind misalignment for the Virginia (top row) and New Jersey (bottom row) deployments for Δ time = 20 minutes (left column), 1 hour (middle column), and 3 hours (right column).

Figure 2.34 displays the TRC of the air–sea temperature differential and the 90 m – 4 m wind speed difference according to the TRC of wind-driven wave and wind misalignment for each deployment over the time periods of 20 minutes, one hour, and three hours. The variability in TRC of air–sea temperature differential and wind shear increase with increasing length of time and with decreasing rates of change of wave-wind departure.

No dependency of the TRC of air–sea temperature differential or wind shear on the sign of the TRC of wave-wind misalignment is noted, with the exception of the Virginia study over three hour periods. For this case, instances of the largest positive rates of change of wind shear occur for negative rates of change of wave-wind misalignment.
Figure 2.34. Time rate of change of the air–sea temperature difference (y-axis) and 90 m – 4 m wind speed difference (color spectrum) by the time rate of change of wind-driven wave and near-surface wind misalignment (x-axis) for the Virginia (top row) and New Jersey (bottom row) deployments for $\Delta$ time = 20 minutes (left column), 1 hour (middle column), and 3 hours (right column).

The TRC of the Beljaars-Holtslag simulated 90 m wind speed error and the stability parameter $z/L$ estimated at 4 m are examined against the TRC of the offset between wind-driven waves and the near-surface wind in Figure 2.35 for both deployments. An increase in the variability of the TRC of simulated hub-height wind speed error and the stability parameter is associated with an increase in length of time. The greatest variability in TRC of simulated wind speed error is also correlated with the smallest magnitude rates of change in wave-wind offset. Interestingly, the opposite is true for the TRC of the stability parameter. For the hour+ lengths of time, the greatest variability in the TRC of the stability parameter occurs when large magnitude increases in wave-wind offset happen during those time periods.

A sign dependency is noted between the variability in the TRC of simulated hub-height wind speed and the TRC of wave-wind offset. Greater variability in the TRC of simulated wind speed error exists for wave-wind offsets switching between 0° and -100° than for wave-wind offsets switching between 0° and +100°.
A final sign dependency is noted for the Virginia three hour analysis. Positive changes in wind speed error over three hours tend to be associated with moves to a more stable regime over the same time period. Negative changes in wind speed error over three hours show correlation with moves to less stable conditions over the same time period. This trend is subtly, though inconclusively, noted for the New Jersey three hour analysis.

Next, the TRC of the most energetic swell and near-surface wind misalignment is assessed to identify any associated trends in metocean properties. As in the wind-driven wave analysis, the frequency of large magnitude changes in swell to wind offset depicted in Figure 2.36 increases with length of time.
Figure 2.36. Histograms of the time rate of change of partition 1 swell and near-surface wind misalignment for the Virginia (top row) and New Jersey (bottom row) deployments for $\Delta$ time = 20 minutes (left column), 1 hour (middle column), and 3 hours (right column).

Figure 2.37 displays the TRC of the air–sea temperature differential and the 90 m – 4 m wind shear according to the TRC of swell-wind misalignment for each deployment over the time periods of 20 minutes, one hour, and three hours. The variability in TRC of air–sea temperature differential and wind shear increase with increasing length of time and with decreasing rates of change of wave-wind departure.

Sign dependencies are noticeable in Figure 2.37. For both deployments, greater variability in the TRC of air–sea temperature differential exists for negative change in swell-wind misalignment than for positive rates of change in swell-wave misalignment over lengths of time one hour or greater. For the Virginia case, larger variability in the TRC in wind shear also exists for negative swell-wind misalignments over one and three hours.
Figure 2.37. Time rate of change of the air–sea temperature difference (y-axis) and 90 m – 4 m wind shear (color spectrum) by the time rate of change of partition 1 swell and near-surface wind misalignment (x-axis) for the Virginia (top row) and New Jersey (bottom row) deployments for ∆ time = 20 minutes (left column), 1 hour (middle column), and 3 hours (right column).

The TRC of the Beljaars-Holtslag simulated 90 m wind speed error and the stability parameter \( z/L \) estimated at 4 m are examined against the TRC of the offset between partition 1 swells and the near-surface wind in Figure 2.38 for both deployments. An increase in the variability of the TRC of simulated hub-height wind speed error and the stability parameter is associated with an increase in length of time. The greatest variability in TRC of simulated wind speed error is also correlated with the smallest magnitude rates of change in swell-wind offset. Unlike the wind-driven wave and wind misalignment assessment, the opposite is not true for the TRC of the stability parameter. No feedback between the variability in the TRC of the stability parameter and the magnitude of the TRC of swell-wind offset is discernable.

As in the wave-wind assessment, a subtle sign dependency is noted between the variability in the TRC of simulated hub-height wind speed and the TRC of swell-wind offset. Greater variability in the TRC of simulated wind speed error exists for well-wind offsets switching between 0° and -180° than for swell-wind offsets switching between 0° and +180°.
Figure 2.38. Time rate of change of Beljaars-Holtslag 90 m wind speed error (y-axis) and $z/L$ estimated at 4 m (color spectrum) by the time rate of change of partition 1 swell and near-surface wind misalignment (x-axis) for the Virginia (top row) and New Jersey (bottom row) deployments for $\Delta$ time = 20 minutes (left column), 1 hour (middle column), and 3 hours (right column).
3.0 Coupled Ocean–Atmosphere Framework

One potential cause of the hub-height wind speed errors of some of the commonly used atmospheric model analysis products is their relatively coarse horizontal, vertical, and temporal resolution. For instance, the North American Regional Reanalysis is at 32 km horizontal resolution and 3 hr temporal resolution; Rapid Refresh model (RAP) is available at 13 km spatial resolution and up to 1 hr temporal resolution. Applying these scales to hub-height offshore wind prediction may lead to large errors in cases of large meteorological spatial and temporal variability, such as frontal systems or land-sea circulations, and poor predictions of ramp characteristics. It is therefore advantageous to run in-house simulations downscaled from larger-scale analyses, to determine if the model errors can be reduced.

Previous work by García Medina et al. (2020) showed the advantage for wave characteristic prediction of running a downscaled wave generation model (WAVEWATCH III (WW3)), driven by winds the Climate Forecast System version 2 (CFSv2; Saha et al. 2010; Saha et al. 2014). The CFSv2 is an analysis system with intermittent data assimilation that uses forecasts of fully coupled atmosphere / land / ocean / models in the assimilation step, thus making it a good choice to investigate oceanic / atmospheric coupling. However, while the CFSv2 product has good temporal resolution (1 hr), its atmospheric component is still relatively coarse in spatial resolution (0.5 degrees). We thus describe here our configuration for performing our own in-house downscaled atmospheric simulations, and how we will optimize it for use in the offshore environment.

We will use the Weather Research and Forecasting (WRF) atmospheric model (Skamarock et al. 2008) for our purposes. WRF has been used in the worldwide community for both operational and research atmospheric applications, at scales from the turbulence scale to the global scale. It will allow us to model the structure of marine boundary layer wind profiles at higher resolution than available in existing reanalysis datasets, although with a set of physical parameterizations (including that of boundary layer vertical mixing) similar to that used in some of the analysis products we have investigated, such as the RAP.

One shortcoming of the standard WRF configuration for offshore wind applications, however, is the absence of the explicit effect of sea state on momentum transfer to the lower atmosphere. In WRF, the roughness height over water is parameterized as a function of the surface momentum stress, as quantified by the friction velocity; this parameterization is based on that of Charnock (1955), as are the forms used in the COARE algorithms. In practice, using these parameterizations essentially assumes the effect of waves on the surface drag is a given function of near-surface wind speed, based on observations and theory. But in reality, as suggested by Taylor and Yelland (2001) and others, the effect of waves on surface drag is also a function of their significant height and mean wavelength. Some of the boundary layer parameterizations in WRF do include options for including more sophisticated marine surface drag formulations, such as that of Taylor and Yelland (2001). Even then, however, the formulations in WRF resort to parameterizing wave significant height and mean wavelength from observationally derived functions of wind speed, so again there is no explicit dependence on actual wave characteristics in the simulation and the dynamic wind-wave interaction is not considered.

An example of how these wave parameterizations can deviate from the dynamically modeled waves is shown in Figure 3.1. Surface roughness was estimated using the Taylor and Yelland (2001) formulation with waves inferred parametrically from the CFSv2 wind field (left) and from a WW3-based hindcast (right). More details of the wave model development and calibration can
be found in Shaw et al. (2020) and García Medina et al. (2020). The parametric surface roughness (left) is more spatially homogeneous than that derived from simulated waves (right). This can happen because the parametric surface roughness is estimated from local wind conditions. This is not necessarily a good assumption when the wave field includes swells, which is not a local property. In addition, as waves enter intermediate waters they are affected by the bathymetry where their steepness is altered; this effect is dynamically included in the wave models. Wave steepness (i.e., the ratio of wave height to wavelength) is one of the inputs to the Taylor and Yelland (2001) model. Apart from the distribution, the magnitude of the surface roughness can also be significantly different depending on the modeling approach taken – surface roughness derived from the wave modeling approach in an order of magnitude greater than that from near-surface wind field. This is only a snapshot showing the differences that can be expected from the inclusion of realistic waves to estimate the surface roughness but serve to highlight the differences in the approaches.

Figure 3.1. Parametric derived surface roughness from CFSv2 (left) and from WW3 (right) using the Taylor and Yelland (2001) relationship. Cyan triangles show the locations of the lidar buoys. Note that the color scales differ between plots.

In terms of surface heat transfer with the ocean, the standard WRF configuration simply assumes the sea surface temperature is externally prescribed, with no coupling. Options do exist in WRF to use either a 1-D oceanic mixed-layer model, or a 3-D Price-Weller-Pinkel 3-D oceanic model. However, neither of these options include bathymetry or the possibility of non-heterogeneous initialization, restricting their usefulness on the continental shelf.

To take full advantage of the WRF atmospheric model, while also making use of our wave modeling and observational capabilities, we are proceeding with simulating selected cases from the Virginia and New Jersey buoy deployments with the COAWST system (Warner et al. 2010). This system was developed by the United States Geological Survey and consists of a tailored set of models for investigating the mutual interactions between the atmosphere, ocean, wave state, sediment transport, and sea ice, along with coupling software (Figure 3.2). The atmospheric component of the system is WRF version 4.0.3, while the oceanic component is the Regional Ocean Modeling System (ROMS) version svn 934. Wave processes may be represented either through the Simulating Waves Nearshore model version 41.20, or WW3,
version 5.16. COAWST may be run in fully coupled mode, or individual components may be run uncoupled, or some combination of the two may be performed.

Our plan is to use COAWST to perform high resolution modeling experiments of the selected case studies of increasing interactive complexity. We begin by performing stand-alone WRF and WW3 simulations over the Mid-Atlantic continental shelf region. The WW3 configuration is based on that used in the simulations described in García Medina et al. (2020). Those simulations considered the effects on waves of analyzed surface currents from the large scale HYbrid Coordinate Ocean Model (HYCOM) (Halliwell 2004) provided by the Naval Research Laboratory. The initial WRF configuration is chosen to have a similar horizontal resolution and spatial extent as the WW3 simulations. Two nested domains were constructed for WRF, one at 15 km horizontal grid spacing, the second at 5 km, corresponding to the spacing of the WW3 high resolution domain (see Figure 3.3). The meteorology used for the initial and boundary conditions were updated from CFSRv2 every 3 hrs, so that these wind fields are consistent with those used to drive WW3. The sea surface temperatures (as well as those of the land surface) was also updated every 3 hrs from the CFSRv2. However, away from the surface and the lateral boundaries, no external forcing was applied to the internal WRF model tendencies. WRF model output itself we will save every 30 minutes. The main WRF physics specifications are shown in Table 3.1 and are generally chosen to either be consistent with the default COAWST configuration, or with those of the WRF model configuration used to generate the RAP analysis. Surface drag was computed in WRF from its own near-surface atmospheric wind field, which uses the Taylor and Yelland (2001) parameterization of marine roughness height but formulated as a function of parameterized wave height and period rather than actual wave height and period.
Figure 3.3. WRF 15 km domain and 5 km domain (d02) used for high resolution simulations.

Table 3.1. Selected namelist options for initial WRF configuration.

<table>
<thead>
<tr>
<th>WRF namelist option</th>
<th>Value</th>
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<tr>
<td>Horizontal Dimensions</td>
<td>134 x 134, 121 x 133</td>
</tr>
<tr>
<td>Horizontal Grid Spacing (km)</td>
<td>15, 5</td>
</tr>
<tr>
<td>Vertical Dimension</td>
<td>72</td>
</tr>
<tr>
<td>Timestep (s)</td>
<td>90, 30</td>
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<td>Boundary Layer Parameterization</td>
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<td>Radiation</td>
<td>RRTMG</td>
</tr>
<tr>
<td>Cumulus Parameterization</td>
<td>Kain Fritsch</td>
</tr>
<tr>
<td>Land Surface Model</td>
<td>Noah</td>
</tr>
<tr>
<td>Data Assimilation</td>
<td>None</td>
</tr>
</tbody>
</table>
In parallel to this effort, a stand-alone oceanic configuration was constructed using the COAWST ROMS model to improve the spatial resolution and frequency of output storage from the HYCOM model used as input in our previous work as noted above (García Medina et al. (2020), Shaw et al. (2020)). The model resolution has been preliminarily set at 5 km, which is twice as resolved in both the zonal and meridional direction as those used to drive the wave model. Example results showing the model domain are shown in Figure 3.4. For consistency with the WW3 calibration, the boundary conditions will come from the same HYCOM model used previously.

Figure 3.4. Preliminary result of simulated sea surface temperature from the refined ROMS model for the Mid-Atlantic Bight. Cyan triangles show the locations of the lidar buoys.

The high resolution WRF and coupled WRF systems will be used to investigate: 1) cases of interest from the previous WW3 studies, such as the Jan 2016 and Jan 2017 nor’easters, for which the wave characteristics should have a substantial impact on the predicted wind fields in the vicinity of the buoys; and 2) a set of the previously identified cases for which large discrepancies exist between the lidar-derived hub-height winds and those derived from combining buoy measurements with MOST. One example case (whose initial period falls into both categories) of the nor’easter event from 18-24 Jan 2016 is shown in Figure 3.5. The main low pressure system moved from the coast of the Carolinas to Hampton Roads by the morning of 22 Jan, after which it moved away from the coastline south of the New Jersey buoy deployment location.
Figure 3.5. WRF-predicted wind speeds (in m s\(^{-1}\)) at 10 m height within the WRF 5 km domain on 12 coordinated universal time (UTC) 23 Jan 2016.

The Jan 2016 nor’easter case happens to coincide with both the Virginia and New Jersey buoy deployments. A comparison of the anemometer wind speed at both the Virginia and New Jersey buoys with the WRF model output is shown in Figure 3.6. It can be seen that, at least at timescales greater than a few hours, the WRF forecasts of the observed wind speed variability throughout most of this period are quite good, with the exception of the period coinciding with the passage of the main system at the Virginia buoy location. We will further analyze the reasons for the existing model discrepancies and quantify the WRF forecast skill for wind speed at heights of interest.
After initial analysis of the stand-alone WRF and ROMS simulations are completed, the next step will be to conduct one-way coupled simulations. First, explicit wave characteristics from the previously generated WW3 simulation will be used as input to a new WRF simulation that will use them in the surface drag calculation. In turn, the high resolution winds from the WRF simulation will be used to drive a new WW3 simulation. As a further step, the WRF simulations will utilize sea surface temperatures that are explicitly predicted by the parallel ROMS simulations; additionally, the WW3 wave characteristics will need to be updated to be consistent with the ROMS-predicted ocean currents. As a final step, a fully two-way coupled system between WRF, WW3, and ROMS will be created, in which WRF-predicted wind and temperature fields could in turn affect wave field prediction and surface turbulent fluxes in ROMS and WW3.
4.0 Summary

The analysis presented in this report focuses on understanding the metocean conditions that lead to large errors in hub-height wind speed estimates from MOST. Specifically, we examined how those errors depend on wind direction, atmospheric stability, wind-wave direction differences, and wave state. A combination of surface and lidar measurements were used to examine the relationship between wind shear and air–sea temperature difference during the Virginia and New Jersey deployments. Although the scatter is significant, both buoys show a clear relationship between wind shear and air–sea temperature difference. The Virginia buoy exhibits less scatter because it was deployed farther from shore than the New Jersey buoy. Filtering out samples corresponding to offshore flow helped to reduce the scatter, particularly under unstable conditions. We also explored the impact of filtering based on wave age and swell fraction and found that filtering based on wave age results in a lower variance of the wind shear as compared to filtering based on swell fraction. In our analysis we applied a simple filtering criterion in which the threshold was set to the median value of wave age over the entire campaign. This filtering, however, did not significantly reduce the overall agreement between the lidar-observed and MOST-predicted wind speeds.

Comparisons between lidar-observed and MOST-predicted wind speeds and wind shears were facilitated using flux estimates from two different versions of the TOGA-COARE algorithm, as described in Section 2.2.1. We found no significant difference in the results using these two versions of the COARE algorithm.

The observed non-dimensional wind shear versus stability data were compared with the BD, the BH, and the VM functions. For stable flows, the observed non-dimensional wind shear exhibits a much steeper slope (with respect to z/L) than that indicated by either the BD, BH or VM functions. The BD function, which is linear, comes closest to the observations. On the unstable side, the errors are much less. However, all of the functions still systematically overestimate the shear compared to the observations.

Integrated forms of the BD, BH and VM functions were used to compare lidar-observed wind speeds to the MOST predictions. For both the Virginia and New Jersey deployments, the VM function resulted in the largest overall bias and standard deviation, while BH function gave the smallest bias and standard deviation. For z/L less than about -2 the functions tend to overestimate wind speed by roughly 0 to 1 m s⁻¹. Under more strongly stable conditions the BD function overestimates the hub-height wind speed, and this overestimation gets worse with increasing stability. By contrast, the BH function produces a less biased result for z/L greater than about 1.

In the analysis of wind-wave misalignment we identified specific conditions in which the errors in wind speed from MOST are particularly large. Feature 1 events occur under stable conditions with strong positive wind shears. At the Virginia site Feature 1 events are associated with southerly winds, and south–southeasterly wind-driven waves, as well as southeasterly partition 1 swells. Under these conditions we found that MOST significantly underestimates the wind speed when compared to the lidar measurements at 70 and 90 m MSL. Feature 1 occurrences for the New Jersey deployment tended to involve south–southwesterly winds and southerly wind-driven waves and southeasterly partition 1 swells. For both sites, the winds associated with Feature 1 flow parallel to the coastline.

Feature 2 events are characterized by moderately to strongly unstable flows with negative wind shears. Incidents of Feature 2 events during the Virginia deployment tended to occur during
periods with north–northwesterly winds and north–northeasterly wind-driven waves and northeasterly partition 1 swells. Feature 2 occurrences for the New Jersey deployment tend to be sourced from west–northwesterly winds and west–southwesterly wind-driven waves and east–southeasterly or south–southwesterly partition 1 swells. Feature 2 also occurred during the New Jersey deployment when the winds were northerly or north–northwesterly (i.e., onshore) and when the waves of each of the most energetic partitions were east–northeasterly.

Given the apparent sensitivity of the wind speed errors to wind-wave alignment, Section 3.3 explored how the TRC of the wind-wave direction difference is correlated with the rates of change of other metocean observations. We found that negative rates of change of wave-wind offsets exhibited slightly more variability in the rates of change of the metocean properties and simulated wind speed errors than did positive rates of change of wave-wind offsets.

Finally, in Section 4.0 we describe our framework for using COAWST to perform high resolution modeling experiments of selected cases identified in our research.
5.0 Data Availability Statement

The buoy observations discussed in this work are publicly available at a2e.energy.gov.
6.0 References


