Potential of Offshore Wind Energy off the Coast of California

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***Abstract*— Two buoys equipped with lidars owned by US Department of Energy were deployed off the coast of California in fall of 2020 by Pacific Northwest National Laboratory. The buoys are scheduled to collect data for an entire annual cycle at two offshore locations proposed for offshore wind development by Bureau of Ocean Energy Management. One of the buoys was deployed approximately 50 km off the coast near Morro Bay in central California in 1100 m of water. The second buoy was deployed approximately 40 km off Humboldt County in northern California in 625 m of water. The buoys provided the first-ever continuous measurements of hub-height winds off the coast of California. The atmospheric and oceanographic characteristics of the area and estimates of annual energy production at both Morro Bay and Humboldt lease areas show that both locations have a high wind energy yield and are prime locations for future floating offshore wind turbines.**

Keywords—offshore wind energy, lidar, West Coast, wind resource characterization, Buoy

I. Introduction

An unprecedent growth in offshore wind energy is expected off the coast of California by 2030. This is primarily due to the high wind resource offshore and favorable regulatory changes to achieve net-zero emissions by 2050. The Bureau of Ocean Energy Management (BOEM) recently put forth two offshore wind call areas near Humboldt and Morro Bay. These two areas are expected to support most of the offshore wind energy development over the coast of California. Several model-based resource assessments have shown the high potential of wind energy off the coast of California [1,2]. Recent surface buoy climatological analysis using National Data Buoy Center (NDBC) buoys along the Californian coast showed seasonal and diurnal variability observed at several sites [3]. So far, to the best of the authors' knowledge, there have been no wind observations at hub-height (typically at 100 m above sea level) collected over an annual cycle off the coast of California. The U.S. Department of Energy (DOE) procured two buoys to facilitate meteorological and oceanographic data collection using validated methods to support the U.S. offshore wind industry. Pacific Northwest National Laboratory (PNNL) manages the two lidar-equipped buoys for offshore wind resource characterization on behalf DOE [4]. Therefore, to estimate the annual wind resource at those potential development areas in California, the two DOE buoys equipped with Doppler lidars were deployed at those locations for a year. These freely available data will provide wind farm developers with much needed information on the available wind resource at these locations. The data is currently uploaded in near real-time on the DOE Data Archival Portal managed by PNNL. The DOE lidar buoy loan program provides opportunities for the wind industry and other interested parties to apply to use the lidar buoys for resource characterization. Fig. 1 shows the location of the two buoys deployed within the Morro Bay and Humboldt call areas. Multiple NDBC buoys are also located several kilometers away from the buoy sites. The NDBC buoy data are a good reference to confirm the DOE buoy data are consistent in near surface atmospheric and oceanographic variables. The spatial variability of the atmospheric and oceanographic variables can be assessed by comparing the measurements from these stations. In this manuscript, the atmospheric and oceanographic characteristics and potential of wind energy off the coast of California as measured by the lidar-buoys will be discussed.

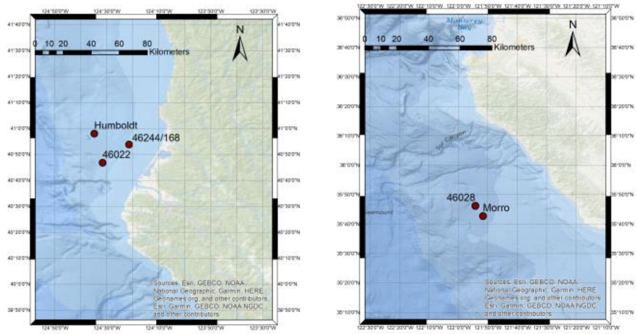

Fig. 1. Location of DOE buoy deployed at (left) Humboldt and (right) Morro Bay. Nearest NDBC buoy (46022, 46244, 46028) locations to the deployment are also shown.

II. Deployment and Instrumentation

A. Field Deployment

The two buoys were deployed in the Fall of 2020 offshore of Humboldt County and Morro Bay. The Humboldt buoy was affected by a large wave event in December 2020, wherein the power supply of the buoy was disabled. The buoy was repaired, redeployed and is back into full operation in May 2021. The Humboldt buoy will be stationed another year up to May 2022. The Morro Bay buoy was deployed on September 29, 2020 and has been collecting data since the time of deployment. Approximately 10 months of wind speed profiles, wind direction, atmospheric stability, and turbulence estimates for the region over typical offshore wind turbine hub-heights were collected. The Morro Bay buoy was deployed in approximately 1100 m of water depth and the Humboldt buoy was deployed in approximately 625 m water depth. The DOE buoys are located within the call areas defined by BOEM and are inside a Rossby radius of deformation from the coast. The buoys therefore would feel the steering effect of the coastal topography but are adequately far away from the coast that they are not significantly impacted by microscale land features. The Morro Bay and Humboldt buoys are approximately 43 kilometers and 39 kilometers away from the coast, respectively.

To make sure the data collected by the buoys are consistent and to detect issues with the data, quick look plots are being complied on the Data Archival Portal (DAP) when the data is uploaded. The quick look plots are uploaded on the DAP website: https://a2e.energy.gov/data/viz#.

B. Buoy Instrumentation

The instrumentation package is mirrored on both buoys and includes a Doppler lidar vertical wind profiler (Windcube 866 Offshore), which measures the horizontal wind vector from 40 m to 250 m above sea level (ASL) with a vertical resolution of 20 m. In addition to the wind profiles from the lidars, the buoys collect near-surface measurements of wind speed and direction (4 m ASL), air temperature, relative humidity, barometric pressure, and solar irradiance. Oceanographic variables measured include the two-dimensional wave spectrum, sea surface temperature, ocean conductivity, and ocean current profiles. Fig. 2 shows the location of various instruments on the DOE buoys [5].

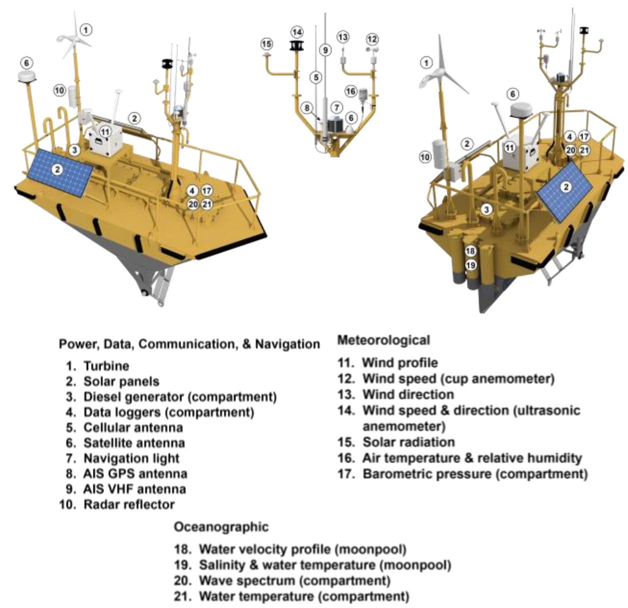

Fig. 2. Various instruments mounted on the DOE buoys deployed at Morro Bay and Humboldt.

III. California Wind Resource

Central California has attracted significant interest in offshore wind energy due to its proximity to the existing grid and consistent winds through the day. The data collected to date by the buoys deployed off California have confirmed several modeling hypotheses but have also provided new insights into the atmospheric and oceanographic conditions at these areas. Data from October 2020 to June 2021 was used for the Morro Bay data analysis and October 2020 to December 2020 was used for the Humboldt data analysis. A climatological analysis of the data collected is provided in the following sections.

A. Hub-height Weibull Distributions and Wind Rose

Fig. 3 shows the distribution of winds at typical offshore hub-heights (100 m above sea level) at both the Morro Bay and Humboldt sites. Winds at Morro Bay at hub-height are more evenly distributed from 5 m/s to 10 m/s from October 2020 to June 2021. The Weibull scale factor (*c*) for Morro Bay is 9.8 and the shape factor (*k*) is 1.86. The scale factor is a measure of the characteristic wind speed of the distribution. The shape factor provides details on the wind behavior, i.e., small *c* values represent weak winds while high value indicates that the site observes equal distribution of high and low wind

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speeds. Most sites typically have a shape factor of 2. The peak load operating range of the wind turbines are generally from 3 m/s to 12 m/s, and the cutoff is at 25 m/s. The winds at Morro Bay exceeded 3 m/s 85% of the time and 12 m/s 25% of the time. Therefore, offshore wind turbines at Morro Bay can expect high probability of continuous wind production to support the California grid. At Humboldt, being data was only available from October to December 2020 owing to buoy power issues, the wind exceeded 3 m/s 82% of the time and 12 m/s 27% of the time. Additional data at Humboldt is being collected to provide a complete annual cycle of winds at that site.

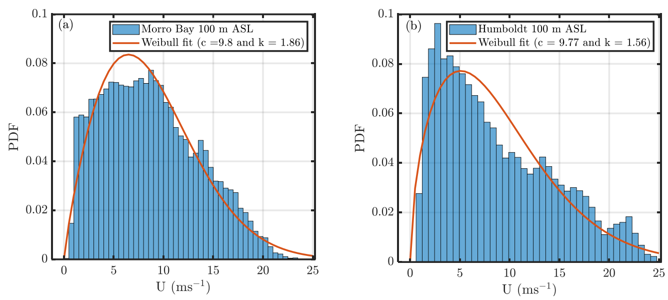

Fig. 3. Wind speed distributions at 100 m ASL from a Doppler lidar at a) Morro Bay from October 2020 to June 2021 and b) Humboldt from October to December 2020. The Weibull fit, scale and shape factors are also displayed.

Fig. 4 shows the wind rose from the surface anemometer on the buoys at Morro Bay and Humboldt for the period of deployment. Winds near the surface at Morro Bay are almost always from north west and are parallel to the California coastline. At Humboldt, the equatorward winds are predominant, but a small component of winds are south easterly. The coastline at Humboldt is oriented north – south and northwest – southeast at Morro Bay.

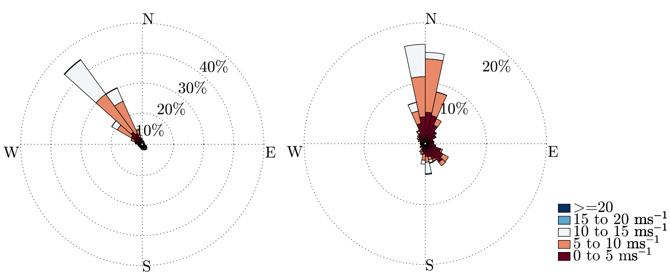

Fig. 4. Wind rose at 4 m ASL at (left) Morro Bay from October 2020 to June 2021 and (right) Humboldt from October to December 2020.

Fig. 5 shows the wind rose at 100 m ASL from the Doppler lidar mounted on the buoys for the deployment period at Morro Bay and Humboldt. Winds at 100 m ASL are consistent with those observed from the surface anemometer, as the winds are predominantly northerly at Humboldt and northwesterly at Morro Bay. At Humboldt, strong winds are also occasionally observed from the south. At Morro Bay it was observed that the winds are lighter in fall and stronger in spring (by approximately 10%).

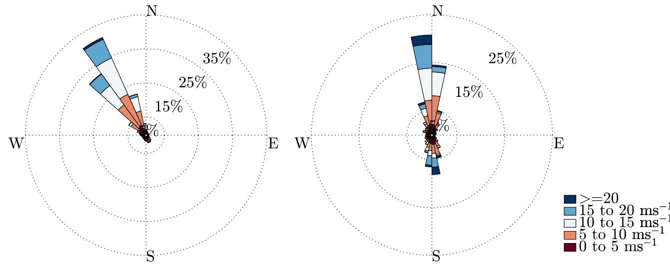

Fig. 5. Wind rose at 100 m ASL at (left) Morro Bay from October 2020 to June 2021 and (right) Humboldt from October to December 2020.

B. Atmospheric Stability

The atmospheric stability at Morro Bay and Humboldt were determined by calculating the bulk Richardson number from the surface buoy atmospheric measurements and sea surface temperature estimates. The bulk Richardson number (Ri_b) is given by

$$Ri_b = -\frac{g}{T}\frac{z\Delta\theta_v}{U^2} \tag{1}$$

Where, g is acceleration due to gravity, T is the temperature, U is the mean wind speed, z is the reference measurement's height and $\Delta\theta_v$ is the gradient virtual potential temperature. At Morro Bay, due to a faulty relative humidity sensor, the virtual potential temperature was approximated by potential temperature. A negative Ri_b indicates unstable atmospheric conditions and a positive Ri_b indicates stable atmospheric conditions. Stable atmospheric conditions result in higher near-surface wind shear. Fig. 6 shows the bulk Richardson number at Morro Bay and Humboldt for the period of observation. During the winter months, the atmosphere is more frequently unstable along the Californian coast and the inversion is not well defined [6]. Therefore, at Humboldt since the measurements were made only during the winter period, the atmosphere is dominated by unstable atmospheric conditions. During summer months, a stable marine boundary layer is typically observed within the lower atmosphere [7]. At Morro Bay, an even distribution of stable and unstable conditions is observed, as the data spans through both winter and spring time periods. Future work on classifying the stability with additional data being collected at both the sites will be conducted.

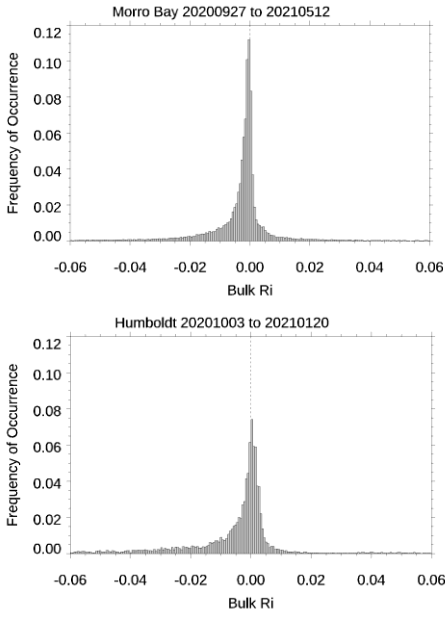

Fig. 6. Bulk Richardson number at (top) Morro Bay and (bottom) Humboldt for the period of observations.

C. *Rotor Layer Winds*

Fig. 7 shows the Doppler lidar diurnal winds at Morro Bay from October 2020 to June 2021. Measurements of Doppler lidar were collected from 40 m to 240 m above sea level. The data availability was high consistently through the deployment period, with greater than 95% availability at 200 m. Winds are parallel to coast at all hours in the mean and significant daily wind speed variability is observed especially in upper part of the rotor layer. Winds are 1.5 times stronger at night compared to daytime conditions at 150 m ASL. Nighttime winds also exhibit significantly higher wind shear compared to daytime conditions. Conclusions from previous modeling studies and surface buoy observations have not shown the high wind shear and an elevated nocturnal wind layer at Morro Bay [1-3]. Therefore, these measurements are unique and would be extremely helpful to the offshore wind industry.

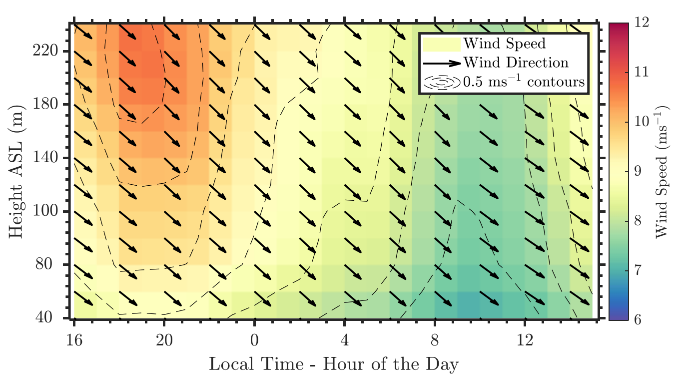

Fig. 7. Doppler lidar daily wind variability at Morro Bay from October 2020 to June 2021.

Fig. 8 shows the Doppler lidar diurnal winds at Humboldt from October to December 2020. Slightly lower availability (>90%) is observed at Humboldt, but the duration of data analyzed was shorter. An onshore wind component is observed in the afternoon and steady wind speeds are observed at each altitude through the rotor layer at Humboldt. The winds in Morro Bay are stronger than Humboldt at 200 m in the evening and weaker during mid-morning. This could also be due to the smaller sample of data at Humboldt. Further analysis will be conducted to characterize the wind conditions at Humboldt in future studies.

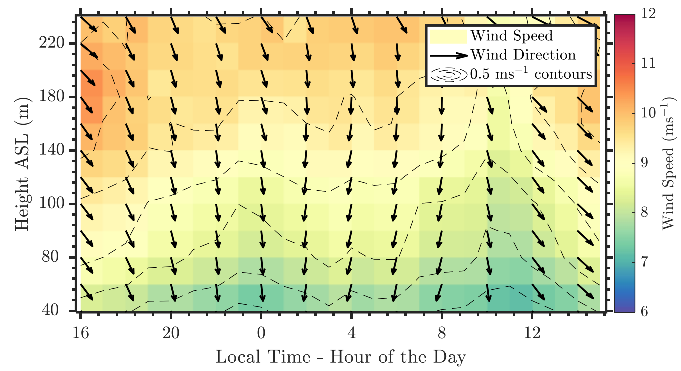

Fig. 8. Doppler lidar daily wind variability at Humboldt from October to December 2020.

D. *Wave Characteristics*

Additional analysis was conducted on the oceanographic data collected on the buoys, especially with the context to understand the importance of wind-wave misalignment for offshore resource assessment. The description of wave climate at a local scale is of paramount importance for offshore and coastal engineering applications. Conditions influencing wave characteristics at a specific location cannot, however, be fully understood by studying only local information. It is necessary to consider the dynamics of the ocean surface over a large 'upstream' wave generation area. To understand this better at the sites, results from the ESTELA model is shown in Fig. 9. ESTELA is a method for evaluating the source and travel time of the wave energy reaching a local area [8]. Fig. 9 below shows the origin of wave energy arriving at the Humboldt and Morro Bay buoy locations. They show the potential for significant decoupling between wind and waves in the region. Winds are equatorward while the wave conditions are predominantly from west at both sites. When the winds and waves are decoupled, it leads to increased air-sea interaction effects and can impact the local conditions significantly. Mesoscale and high-fidelity models also do not perform well when the wind-wave misalignment is large. The California coast has been described as a traditional upwelling region, which modifies the wind stress near the region and can influence the dynamics of air-sea circulation. Further research is undergoing to understand the sources of error due to such decoupling in the wind profile.

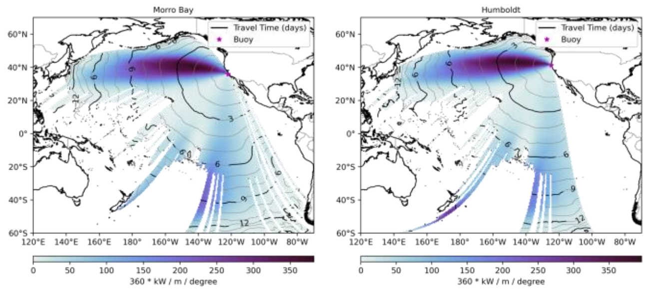

Fig. 9. Origin of wave energy arriving at the buoy location (left) Morro Bay and (right) Humboldt based on peak period, direction, and wave energy. Results are compiled using the ESTELA model.

Fig. 10 and Fig. 11 shows the significant wave height and peak wave periods at Morro Bay and Humboldt, respectively. Measurements from the DOE buoy were compared to the nearest NDBC buoy estimates. For the several months at Morro Bay and three months at Humboldt, the agreement is very good. Close comparison shows Humboldt County significant wave heights are greater and periods are shorter than at Morro Bay. This suggests increased surface roughness at the Humboldt deployment compared to the Morro Bay deployment. Comparison with longer term data collected at nearby NDBC buoys show that larger wave heights than those measured during the campaign have occurred historically. These events should be considered for turbine survivability.

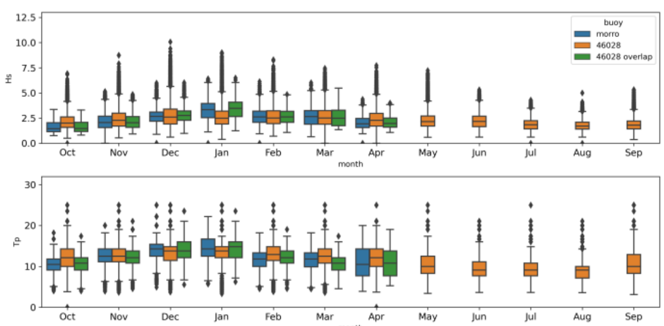

Fig. 10. Box plots comparing significant wave height (top; m) and peak wave period (bottom; sec) by month between the DOE buoy and a nearby NDBC buoy at Morro Bay. Overlap refers to periods when both buoy data are available.

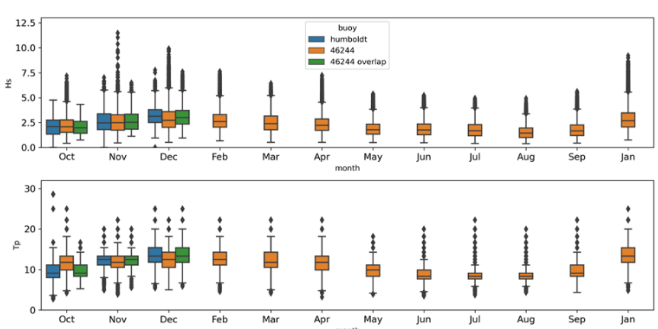

Fig. 11. Box plots comparing significant wave height (top; m) and peak wave period (bottom; sec) by month between the DOE buoy and a nearby NDBC buoy at Humboldt. Overlap refers to periods when both buoy data are available.

E. Ocean Characteristics

Fig. 12 shows the ocean current speeds at Morro Bay and Humboldt. The Acoustic Doppler Current Profiler (ADCP) at Morro Bay suffered a loss of signal below 125 m depth and resulted in much lower data availability. While at Humboldt, the ADCP worked well and showed good range through the deployment period. The lower current speeds at Morro Bay at depths below 125 m are a result of averaging low percentage of data and should not be necessarily misconstrued as a rapid drop in current speeds at Morro Bay. The ocean mixed layer depth at Morro Bay is crudely observed to be deeper than at Humboldt. The ocean current speeds are also faster near the surface at Morro Bay compared to Humboldt. Within the lowest 100 m below sea level, the ocean currents more rapidly decrease at Morro Bay compared to Humboldt. The reason for this needs to be investigated further. Overall, the ocean currents data provides valuable information for the possibility of installing floating offshore wind turbines and studying the impact of upwelling/downwelling along the California coast.

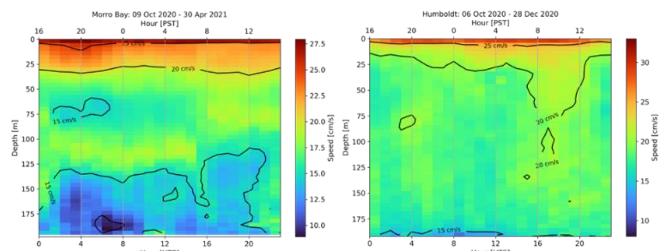

Fig. 12. Ocean current speeds at the (left) Morro Bay and (right) Humboldt County.

IV. Conclusions

The year-long buoy deployments off the coast of California provide unprecedented data to developers and researchers on the potential of offshore wind resource in the region. The publicly available data also helps answers some of the fundamental questions on air-sea interaction effects and its impact on the offshore wind profile. Preliminary evaluation of the lidar-equipped buoy data collected at both Morro Bay and Humboldt show distinct flow patterns which are influenced by the coastal topography. Winds are predominantly northwesterly at Morro Bay and from the north at Humboldt, parallel to coastline at the respective locations. The winds at Morro Bay exceeded 3m/s 85% of the time and 12 m/s 25% of the time, while at Humboldt the wind exceeded 3 m/s 82% of the time and 12 m/s 27% of the time. At Humboldt, steady-state wind speeds are observed at each altitude through the rotor layer. At Morro Bay significant diurnal variability was observed especially in the upper part of the rotor layer. Winds at nighttime are 1.5 times higher than winds during daytime at Morro Bay with high wind shear conditions at night. Unstable conditions prevailed at the Humboldt site during the period of observation (winter), while at Morro Bay an even distribution of stable and unstable conditions was observed. During summer months, a higher percentage of conditions are expected to be stable within the lower atmospheric boundary layer. A preliminary comparison of the wave characteristics with the nearest NDBC buoy showed good correlations between the two sensors. It was observed that the Humboldt County significant wave heights are greater, and periods are shorter than at Morro Bay. With deeper mixed layer depth and rapid decrease of ocean currents within the lowest 100 m at Morro Bay, sea state conditions at Morro Bay are expected to be vastly different than at Humboldt. Further research will be conducted to examine the impact of sea state conditions on the wind profile within the marine boundary layer. Wind profiles at the leased areas will help offshore wind farm developers to validate their existing models, advance on improving surface layer parameterization schemes, and provide an accurate estimate of the annual energy production. The data collected so far is extremely interesting and will lead to unearthing valuable science and help advance on air-sea interaction theories relevant to offshore wind energy. Further analysis of the data will be conducted as the campaign continues.

Acknowledgment

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