Impact of Stability on the Atmospheric Boundary Layer

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Abstract—**We present an investigation of the impact of stability in a coastal environment's wind resource estimate. The site, near Cape Hatteras, is interesting because of its proximity to an open sound condition to the north and west, as well as its oceanic boundary to the south and east. Early exploration of wind profiles collected during 2012-2014 from the surface to 200 m with a Scintec XFAS SODAR wind profiler revealed distinct characteristics unique to winds coming from the sound, as compared to those coming from the ocean. "Steady-state" cases were defined in order to examine time periods where the winds might be more readily compared with simple theory. While wind profile cases from the sound exhibited low level shear that reached a constant wind speed within instrument height, the oceanic profiles were characterized by shears higher in both magnitude and elevation that had not yet reached their maximum at 200 m. Although this feature of the oceanic profiles is typical of a stably stratified wind regime, further study of the environmental conditions affecting each case was necessary to determine the specific impact of the stability on the profiles.**

An aggregation of ancillary data was collected, including surface sea and air temperature, surface humidity, and vertically-distributed air temperature and humidity from surrounding airports, meteorological stations and ocean buoys. The COARE algorithm was utilized to calculate a Monin-Obukhov Similarity (MOS) scaling parameter, L, a stability parameter appended to a neutral logarithmic layer. An internal boundary layer algorithm is used to determine the height over which the MOS theory should reproduce the structure of the wind profiles. The nested boundary layers identified include those created by changes in roughness as well as those induced by thermal effects of the sea and land surface. Upwind topography and local aerodynamic roughness length values are used to assess the impact of roughness on the measured wind profiles, and the height to which this impact should remain significant. The high shear at low altitude observed in the sound cases is mostly explained by this process.

After controlling for roughness induced shear, thermal effects will be integrated. The level of stability or instability gleaned from the sign and magnitude of L will be used to assess the differences in wind profile structure across the sound and ocean cases identified, and the seasonal changes associated with both. This work is part of a larger effort to improve upon the wind resource estimate off the Outer Banks of North Carolina. The results will be incorporated into the larger scale study of wind energy in order to adjust for the effects of atmospheric stability in this dynamic region.

Keywords—meteorology; atmospheric boundary layer; wind energy; coastal processes

I. Introduction

A. *Application to Wind Resource Studies*

An initial wind resource assessment of coastal North Carolina, prepared for the North Carolina General Assembly in 2009 [1], quantified the feasibility of offshore wind energy generation in the area. More recently, surface wind measurements from satellite sources were used to extend the assessment offshore [2]. The adjustment of winds to turbine hub height did account for atmospheric stability. However, no validation of stability-impacted wind profiles have been collected. In a typical power-law height extrapolation of wind speed, the shear present in the wind profiles proves to be an important element in the wind power estimates. The validity of this estimate is questionable when there is non-neutral stability in the lower atmosphere. Especially in this dynamic region, where variation in sea surface temperature significantly

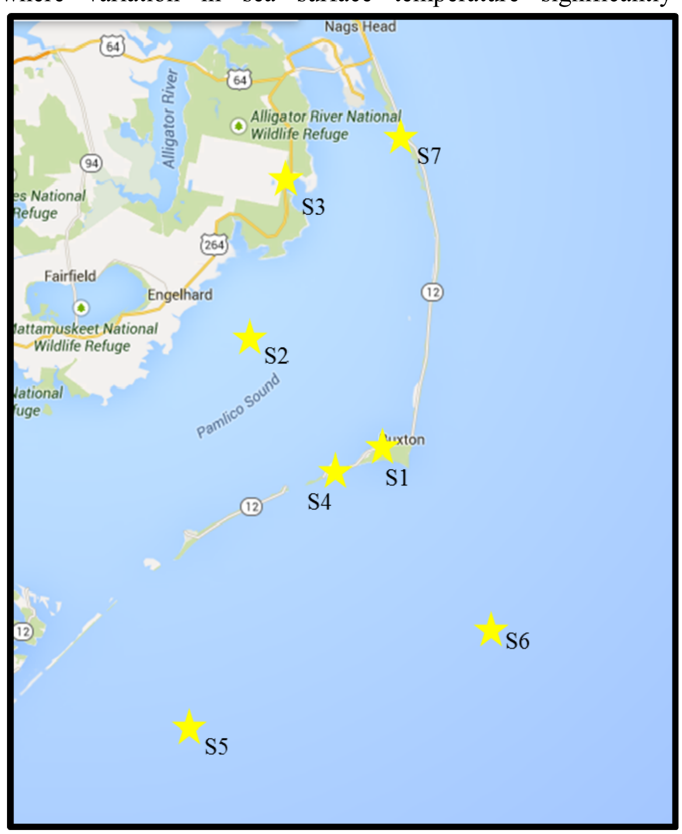

Fig. 1. Coastal North Carolina, Study Location and Associated Ancillary Data Sources

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impacts oceanic heat flux, stable or unstable conditions could play a large role in the estimation of wind speed at turbine height [2]. Explicit measurement of wind profiles and the impact of the stability of the atmospheric boundary layer (ABL) as well as the seasonal and diurnal changes in the profile structures, is crucial to estimating winds at height for use by wind turbines.

B. *Location*

The location in this study, on a thin barrier island separating two distinct water bodies permits an investigation of directional variation. To the northwest of the measurement location near the Billy Mitchell weather station (Fig. 1, S1) is the Pamlico Sound, as well as significant land and foliage cover (an important factor in any surface roughness calculation). To the south and east is the Atlantic Ocean and Gulf Stream. The persistent warmth of the Gulf Stream is in stark contrast to the highly varying temperatures of the sound and the cooler ocean water to the northeast. The comparison of wind profiles from the NW and S form one of the bases of analysis in examining the impact of stability on the measured wind profiles. The stability of the ABL is not only affected by the degree of thermal stratification in the air – the air-sea temperature difference is also important in the ocean-air heat flux and resulting momentum flux through the wind profile. Utilizing both of these methods of characterizing atmospheric stability through comparison of both oceanic and sound cases will be used to assess the momentum in a directionally varying wind field.

C. *Boundary Layer Theory – MOS*

In order to analyze how stability influences the atmospheric boundary layer, wind profiles are modeled using a Monin-Obukhov Similarity correction of functional form Ψ appended to a neutral log-layer where the mean wind speed, M

$$\bar{M} = \frac{u_*}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) + \Psi_M\left(\frac{z}{L}\right)\right] \quad (1)$$

(m/s), is calculated as

MOS Theory allows for a stability parameter, L, to induce a change in the wind profile according to the degree of stability or instability, in this study calculated using the COARE algorithm [3] based largely on air-sea temperature differences. The additional parameters in the MOS formulation include: (1) the friction velocity, u_*(m/s), (2) the von Karman constant, κ=0.4, (3) the height from the surface, z (m), and (4) the aerodynamic roughness length, z_0 (m). This model indicates that in an unstable environment, known as a "convective" boundary layer, shear is generally higher near the surface, but decreases rapidly with height. In a stably stratified atmosphere, the wind profile will generally look more linear, indicating a lower maximum shear, but with stronger shear aloft as compared to the unstable wind profile. Regarding the placement of a wind turbine in this environment, this variability in magnitude and height dependence of the wind shear makes a simple power-law height extrapolation an oversimplification. A more complex method of wind profile modelling like MOS would improve on the wind resource assessment, if stability is found to be a major factor in changing the wind profile's structure.

D. *Roughness*

The surface roughness found in a typical offshore wind environment is small relative to land environments. Water's roughness can vary with wave height but is usually assumed to be constant and significantly small in studies of this type. At the Billy Mitchell weather station, winds out of the north and west (most typically those associated with a "sound" case) encounter significant surface roughness, due to either longer fetches over land, or even a few maritime forest areas surrounding the measurement station. Several different methods exist to assess the impact of local roughness on the wind profile that is not sufficiently approximated by the COARE algorithm. The first utilized in this study was a relation used by several authors, found in Stull, [4] where a height to which a wind profile would be influenced by a surface roughness is calculated as

$$\frac{\delta}{z_{01}} = a_{IBL}\left(\frac{x}{z_{01}}\right)^{b_{IBL}} \quad (2)$$

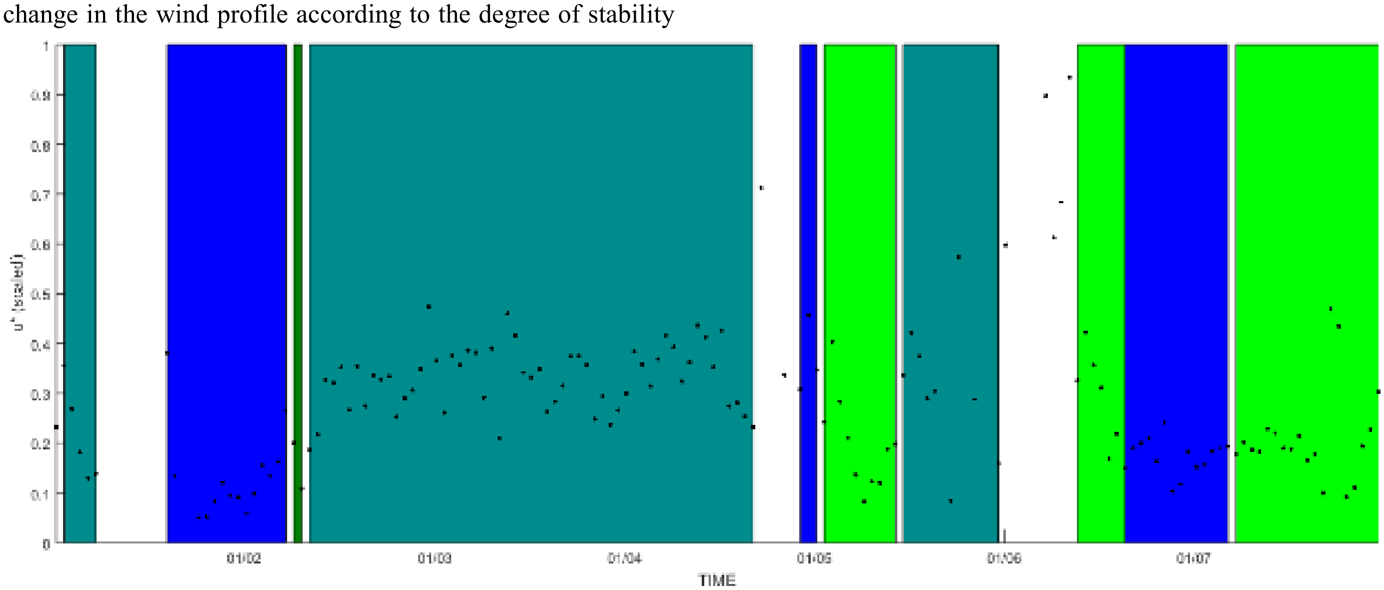

Fig. 2. Scaled friction velocity in the first week of January, 2012; colors indicate direction of wind (blue – from ocean; teal – from sound; green – from land)

Where

$$a_{IBL} = 0.75 + 0.03 \ln\left(\frac{z_{02}}{z_{01}}\right) \quad (3)$$

And b_{IBL} is an empirically derived, stability influenced constant ranging from 0.2-0.8. The surface roughness element change – from surface 1 to 2 – is represented by the two z_0 parameters (z_{01} and z_{02}, respectively), and x represents the horizontal fetch across an individual surface. The height, δ, to which the wind profile is influenced by the surface roughness over land is significant in certain directions of Hatteras Island, and this internal boundary layer theory (IBL) growth is used to investigate how much of the profile measured at the interior of the island is affected by the roughness elements it passes over. This method is a valuable first step in partitioning the measured wind profile into vertical elements that might individually reflect the properties of their respective surfaces.

II. Methods

A. Instrumentation

This meteorological study aggregates data from a variety of different sources, the most valuable of which is the Scintec XFAS SODAR wind profiler located at the Billy Mitchell weather station. This instrument provides a wind speed measurement at high temporal (half-hourly measurements) and altitudinal (up to 200 meters with 5 meter bins) resolution. For stability and shear analysis in the sound cases, weather towers to the west and north of the Billy Mitchell weather station (at Stumpy Point, Fig. 1, S3 and in Pamlico Sound, Fig. 1, S2) give wind measurement and air temperature measurement. At Stumpy Point, values are obtained at 47, 72, and 93 meters. The Pamlico Sound weather mast provides these measurements at 13 meters. A water temperature measurement for the sound was obtained from a coast guard station on Hatteras Island (Fig. 1, S4) and from an Oregon Inlet station (Fig. 1, S7) during a data gap of the former in 2013. Similarly, water temperature, humidity, wind, air temperature, and other various parameters necessary for execution of the COARE algorithm were obtained from buoys in Raleigh Bay and Diamond Shoals (Fig. 1, S5 and S6 respectively) for the ocean cases.

B. Steady State Cases

Wind profile measurements were available from the SODAR at half-hourly intervals, starting from June 2009 to present with several significant periods of instrument downtime or spotty height coverage. Analysis was begun with the data from 2012 as this year was determined to be the period of time where the measurement coverage started to be relatively consistent both temporally and spatially. A neutral logarithmic function for predicted wind speed, U, of the form

$$\widehat{U} = \beta_1 \ln[z] + \beta_0 \quad (4)$$

Where

$$u_* = \kappa\beta_1 \quad (5)$$

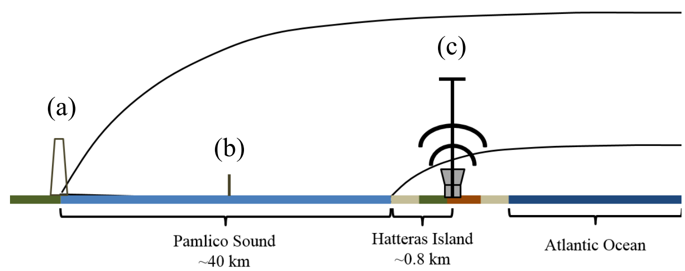

Fig. 3 The Billy Mitchell SODAR (c) site is located on Hatteras Island, between Pamlico Sound and the Atlantic Ocean. A wind regime measured by the SODAR coming from the sound side would display elements characteristic of wind flowing over the sound water, possibly up to and above the measurement height of the SODAR, as well as a developing land boundary layer that begins as the wind reaches the island. The IBL theory used in this study will attempt to use the Stumpy Point tower (a) and the Pamlico Sound weather mast (b) to assess stability, and resulting boundary layer growth rates. This method will aid in characterizing the vertical structure of the measured wind profiles and evaluating the best method of MOS theory use in these cases.

And

$$z_0 = e^{-\frac{\beta_0}{\beta_1}} \quad (6)$$

was regressed against an hourly average of the measured wind profiles to obtain an analytically derived value for friction velocity and roughness for each, from the regression constants, β. The friction velocity was scaled by the mean speed of each time point for comparison purposes. In order to identify periods of time where the profiles could be compared against each other and the MOS theory, "steady-state" cases were defined based on several stipulations. First, the direction of the wind remained constantly sourced from either the sound (15° E of N - 100° W of N) or oceanic (65° E of N - 140° W of N) direction. A second constraint on the "steady-state" cases was that the scaled friction velocity remained relatively small, and consistent (below 0.5 for the length of the case). Lastly, any time periods where the height of the boundary layer, as defined by the height of the log-layer fit, maintained a growth rate of less than 40 meters/hour. From the periods of time meeting these constraints, specific cases were selected that met the stipulations for over a 24 hour period in order to capture any diurnal cycle evident in the wind behavior. For example, in Fig. 2, the scaled friction velocity is plotted as a function of time. The colors indicate the direction from which the measured wind came, blue indicating ocean, teal indicating sound, green indicating the small ranges of Hatteras island to the west and north east of the SODAR site, and white indicating periods of time where the numerical constraints were not met. The first steady-state sound case of the year starts on January 2, and continues to January 4, as can be seen in the swath of teal during those dates.

C. COARE

The COARE algorithm [3] has been a useful tool in independently calculating the Monin-Obukhov length scale and friction velocity for use in the MOS theoretical functional form. After inputting the necessary data (wind speed, surface

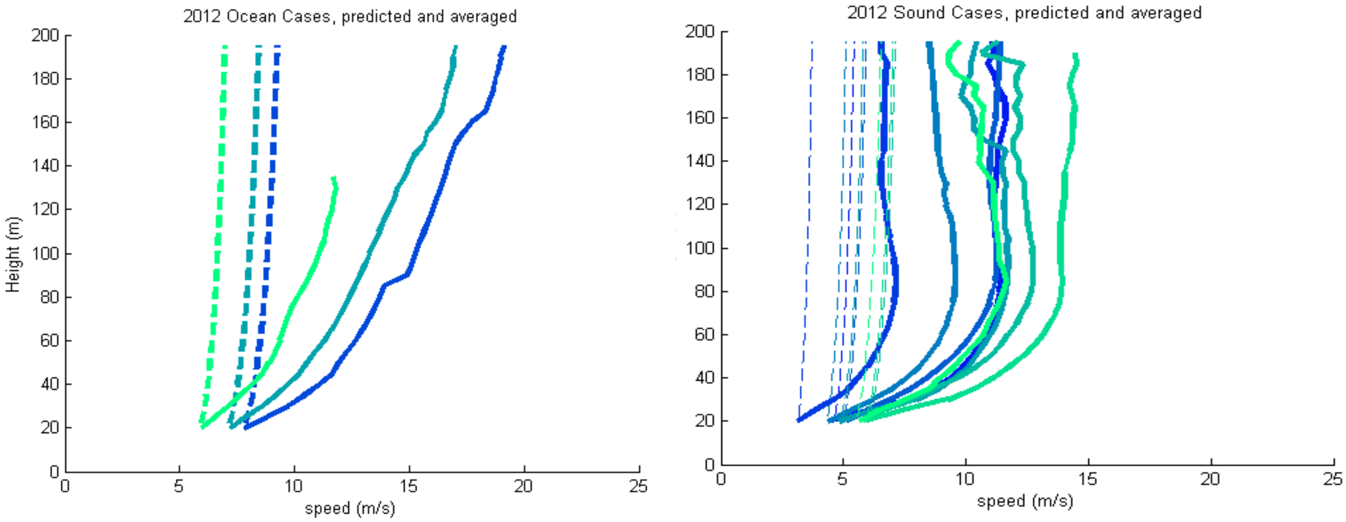

Fig. 4. Ocean and sound cases from 2012. The measured profiles are presented as solid lines, each color indicating a different day-long case, averaged over the time period of the case. The dashed lines indicate a power law extrapolation typical of these types of studies using neutral log-layer speed shift [5]. In both instances this extrapolation would greatly underestimate the wind speed at turbine height. Clear shapes are also evident for both ocean and sound sourced winds. Winds from the sound exhibit high shear near the surface, perhaps as a result of the induced roughness of the island, as winds from this direction in general encounter more land before reaching the SODAR. Winds from the ocean are characterized by slightly higher, linearly increasing winds, and shear that has not yet reached its maximum at the highest measurement.

water current speed, water temperature, air temperature, specific humidity of air and water, PBL depth, atmospheric pressure, and location), either from the Raleigh Bay buoy or the assorted weather stations available on the sound side, COARE uses a bulk air-sea flux iterative method to calculate several relevant parameters for MOS theory. Anytime the COARE algorithm was used in this study, the input parameters specified remain completely independent from the SODAR wind profile measurements, often using the wind measurements from the Pamlico Sound weather mast (Fig. 1, S2), or the ocean buoy in Raleigh Bay (Fig. 1, S5). The COARE parameterization is therefore based on conditions significantly upwind of the SODAR instrument, and several different boundary layers can develop over this distance. The nested IBL theory detailed below is graphically represented in Fig. 3. The COARE outputs remain indicative of the conditions upwind of the SODAR, but the extent to which they are found in the measured wind profile depends on the growth rate of these nested boundary layers. The COARE results will be used in order to characterize the vertical structure of the measured wind profile based on a nested boundary layer theory.

D. Internal Boundary Layer Theory and Algorithm

During the exploratory data analysis phase, using both regression methods and the COARE algorithm, it seemed that the analytically derived values for surface roughness lengths (z_0) varied significantly from what are generally accepted values for terrain of this type. While a change in roughness values does not significantly impact the shape of the wind profile, roughness elements would induce an increase in shear, and therefore friction velocity of the profile, a factor that can greatly affect the structure and temporal variation of the wind. Initial model development also indicated that the wind profile was not being accurately depicted at lower elevations, possible due to the effect of higher surface roughness values of the land surrounding the site. Especially in the sound cases, the fetch over which the wind must travel, including beach, forest, or even urban buildings, could be impacting the lower shape of the wind profile. A geospatial visualization of roughness values for the Billy Mitchell site was obtained and the values extracted for a directionally varying scheme of roughness elements that a wind path would encounter before meeting the SODAR.

The IBL theory described above was used iteratively to determine the height to which the profile should be theoretically impacted by the roughness elements. This height was utilized to define a portion of the modelled profile that would use the roughness values from the geospatial map rather than the roughness output from the COARE algorithm. This method went through several iterations to determine what best reproduced the wind profile measured by the SODAR, including only assessing the roughness at its maximum point, and also only at the first element encountered by the wind.

III. Results

A. Vertical Characterization of the Atmospheric Boundary Layer

The IBL algorithm developed to analyze the wind profiles was used in conjunction with outside data sources, including ASCAT satellite wind measurements and COARE outputs in order to identify which elements best represented the measured wind profiles at the Billy Mitchell SODAR. The wind profiles were shown to be best modeled by the COARE outputs, while ASCAT wind stresses inaccurately predicted wind speed at height, so further steps only included the COARE-based model. The sound cases were investigated first, and were

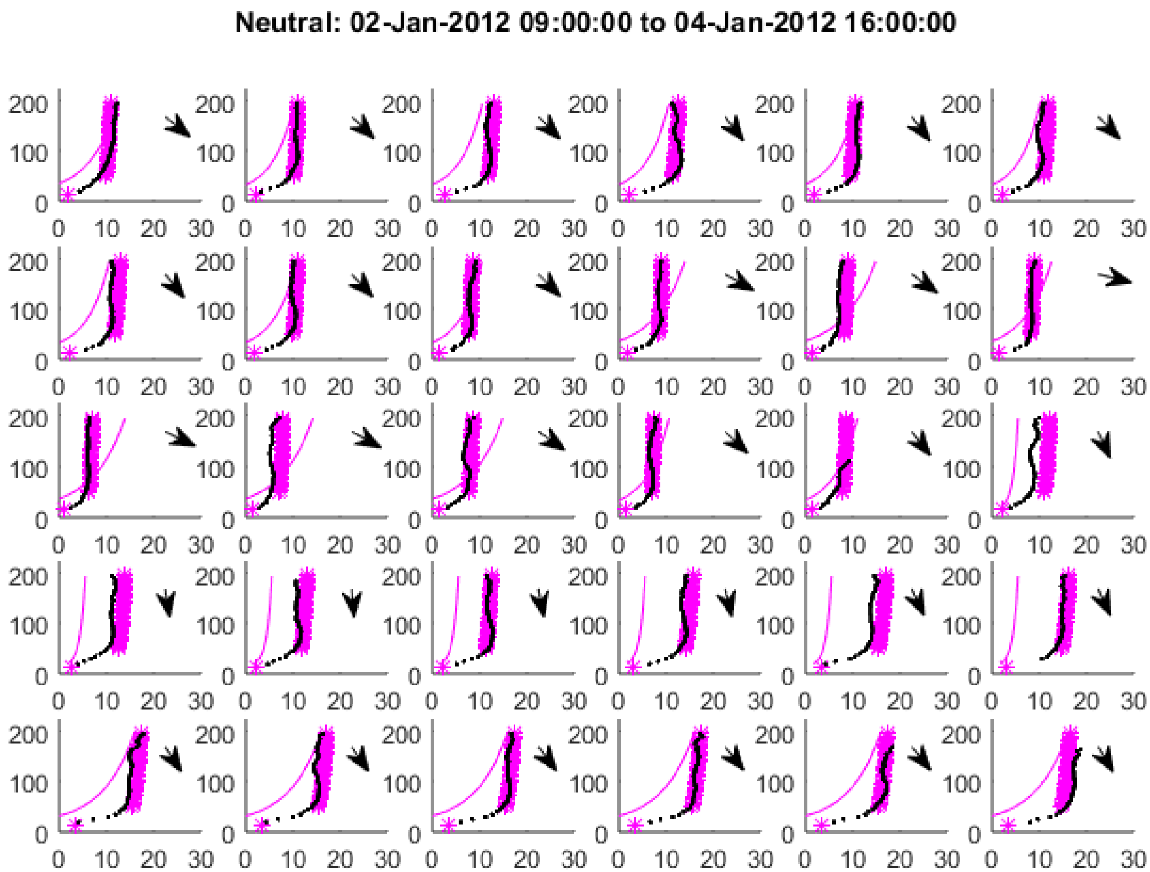

Fig. 6. The first few hourly time increments across the first sound case in 2012, with wind direction shown with a black arrow. Black dots indicate measurements from Billy Mitchell SODAR (wind speed, m/s, with height, m). Pink stars above 75 m are the profiles constructed from COARE output parameters. Pink star at 10 m is the wind speed expected from the Billy Mitchell geospatial roughness value. The pink line shows a nonlinear fit attempted through these two data regimes, using a log layer functional form.

closely associated with cold air outbreaks from the continental cold fronts during the winter months. Initial model development using an iterative IBL algorithm stepping through the changes

in roughness elements proved inadequate to accurately describe the effect of roughness on the wind profile at the SODAR location. The model's next iterations were to associate the COARE output with the maximum roughness element encountered by the wind, rather than a summation of all the roughness elements in the wind's path. This method of breaking the wind profile into distinct vertical layers, each affected by differing surfaces, will be helpful in further characterizing the boundary layer growth rates, and how that may relate to atmospheric stability.

B. Assessment of Stability Impact

Early exploration of the dataset showed distinct wind profile shapes of sound sourced winds as compared to ocean sourced winds. The sound cases were characterized by low shear that reached a maximum around 50-75 meters, and were generally associated with cold air outbreaks from the continent in the winter months. The ocean cases exhibited more constant shear with altitude that had not yet reached its peak even at maximum measurement height (Fig. 4). These findings seem to corroborate the results from [2] that distinct regimes are found under conditions of relatively cooler water from the sound, or relatively warmer water from the Gulf Stream. Further steps in the stability analysis will attempt to determine if a difference in atmospheric stability and/or oceanic heat flux in these differing environments might contribute to these variations in profile structure.

An iterative estimate of the Monin-Obukhov Length scale parameter for use in MOS Theory is one of the output parameters of the COARE algorithm. This provided a useful first estimate in quantifying the stability of the atmosphere at a fine temporal resolution. The profiles constructed from the COARE algorithm outputs (u_*, z_0) using a neutral formulation were generally similar to those measured at the Billy Mitchell SODAR (Fig. 5) throughout a variety of environmental conditions. The model performs well in the upper portions of the boundary layer, providing a good independent estimate of the shape and magnitude of the wind profile. Below about 75 meters, the profile is characterized by high shear that is not captured well in the COARE outputs. This feature could be a result of the roughness encountered by the wind, coupled with a variable boundary layer growth rate influenced by stability. In some cases, the δ height found through the Stull formulation offered an accurate estimate of the height at

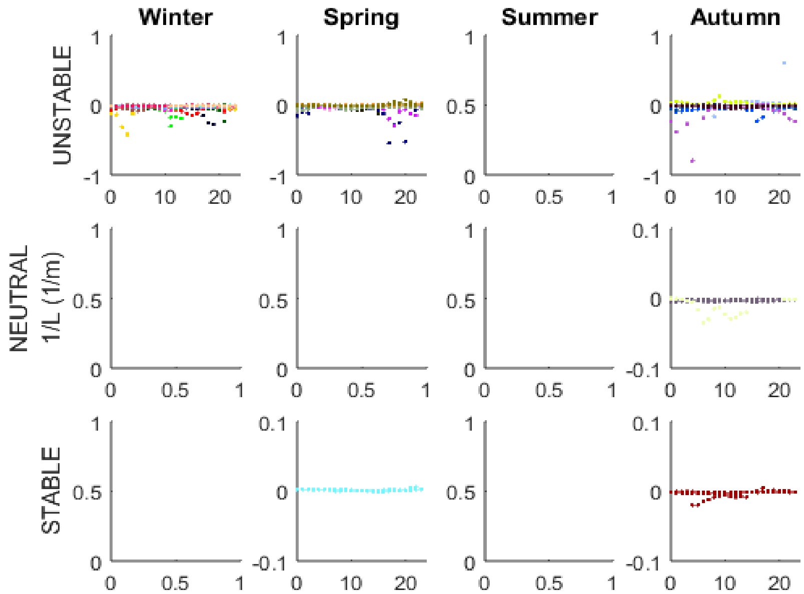

Fig. 6 Inverted Monin-Obukhov Length scale (1/L) to quantify stability throughout the sound cases of 2012, 2013, and 2014. Each color represents a different case, and the Length scale is plotted against the hour of the day (UTC) to show diurnal as well as seasonal trends.

which this 'roughness affected layer' would end. However, a simple log layer, and even a MOS log layer with added stability parameter struggled to resolve the coupling of these two conditions, as shown by the pink lines in Fig. 6.

C. *Seasonal and Diurnal Trends*

Several distinct seasonal trends were observed in the Billy Mitchell SODAR data. Most of the steady-state cases were pulled from late winter/early spring, as well as mid to late autumn, indicating, on average, a more consistent wind regime during these months. The sound cases were generally found to be unstable regimes, with the most strongly unstable conditions found in the winter. More weakly unstable conditions occurred in the spring and autumn months, while a few neutral and weakly stable cases were also found in these warmer months. There were no summer cases out of the sound, but further analysis of oceanic winds should bring a few cases from those months for comparison. A few slight diurnal patterns were found, including high instability during mid-day (see Fig. 6, spring, at UTC 19:00). During the winter and autumn, by contrast, higher levels of instability occurred often during the night and throughout the day.

IV. Conclusions and Future Study

It remains clear that the stability of the atmosphere has the potential to impact the profile of the wind regime in sound cases. The COARE algorithm, a stability based method for predicting a given wind climate, generally matches the structure of the wind profile at height measured from the SODAR. The calculations from this algorithm are much closer in magnitude to SODAR measurements than other popular estimates, like power law estimations or a neutral log-layer using surface wind speed measurements. Insofar as the atmospheric boundary layer structure is used for wind power feasibility studies, the extrapolation of wind to turbine height has the potential to be greatly underestimated if the effect of stability is omitted. The nested boundary layers developing from a change in surface roughness, or even temperature, can cause high wind shear in the lower wind profile, where wind speed measurements are typically made. Further study will expand this method to the ocean cases. The thermal internal boundary layer induced by warmer waters (especially important when looking at locations near the Gulf Stream and similar) is another element worth considering in the context of the IBL theory, rather than a simple stability based parameter obtained from temperature differences. These added cases should also show the differing structures of the wind climate during the summer months, and will provide valuable information about the wind resource in the offshore environment of North Carolina.

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