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Contract Title: Staff Support to Prepare for MD Offshore Wind Resource Assessment Using Modeling, Marine-based LiDAR and Conventional Wind Observations
UMBC Project #00008532, DNR award # KOOP3400400
Sponsor: MD Department of Natural Resources

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I. INTRODUCTION AND BACKGROUND

The complexity of the Mid-Atlantic coast, Chesapeake Bay and Appalachians leads to a variety of low-level wind phenomena along the coast and offshore (*Rabenhorst, 2012*), that are poorly understood due to the sparse observational record and the lack of long-term wind profile measurements. Quantifying uncertainty inw ind measurements is critical because of the cubic dependence of available wind power density on windspeed. Low level wind phenomena include downslope winds, bay/sea breezes, frontal passages, low-level jets (LLJ) and nor'easters that are due to a combination of synoptic forcings, such as the location of the subtropical jet, and terrain-induced forcings due to topography and contrasting land-sea thermal structure and surface roughness (*Rabenhorst, 2012; Weldegaber,et al 2009; Zhang et al, 2006*; *Lange et al, 2004*). The extent to which the winds in the MD WEA[1] are influenced by the processes occurring in these coastal transition zones is not currently known. This is particularly true during synoptically quiescent weather patterns when terrain-induced local forcings are likely to control potential wind resource regimes such as the Mid-Atlantic LLJ. It is critical to understand the forcings that drive the low-level wind regimes in the region in order to provide a context to interpret wind measurements, to develop measurement and sampling strategies, to assess resource predictability on different time scales, and to better understand any possible linkages between the long record of land/sea surface wind observations and the offshore wind climatology at turbine height.

This project was a "Phase I" project to prepare for a more comprehensive wind resource assessmentThe work under this contract encompassed a range of activities aimed at characterizing the offshore wind in the MD WEA and assessing current modeling and measurement uncertainties. . It included participation in a offshore wind measurement campaign and the configuration of a regional mesoscale model and development of expertise with offshore wind lidar measurements. The methodology used an iterative combination of models to interpret measurements, and measurements to test models.A combination of NWP modeling together with the existing multi-platform database of wind observations and lidar wind observations was used to characterize the variability in the coastal and offshore low level wind and its dependence on height.

UMBC research conducted under this DNR contract has revealed higher uncertainty in existing NWP models and data sets than previously estimated, including some significant biases. Offshore wind measurements showed a number of important features such as winds decreasing with height, strong cross-rotor wind shear, rapid turbulent breakdown and strong inter-turbine variability. Some of these features are related to the unique physiography near the coast and other ocean processes such variations in SST, as coastal cold water upwelling. This suggests that mesoscale models for offshore wind may require coupling to an ocean model.
This uncertainty can negatively impact the viability of an offshore wind project since project finance costs depend not only on the estimate of the available annual resource, but

[1] Maryland Wind Energy Area. A complete list of acronyms can be found at the end of this report.

on the confidence level of that estimate. By exposing (and addressing some of) these weaknesses, UMBC has laid the groundwork for a more comprehensive and confident resource assessment and better forecast models.

II. SUMMARY OF DELIVERABLES AND OTHER PRODUCTS

The research goals for the work under this contract were to lay the groundwork for a more comrehensive wind resource assessment of low level wind regimes in the coastal and marine atmospheric boundary layers (ABL), with emphasis on the MD coastal and WEA region. Modeling studies were aimed at improving model skill and achieving a better understanding the regional wind patterns in coastal and offshore MD. Extensive analysis of model simulations, data analysis and model/data comparisons were used to improve understanding of the origns of model and measurement uncertainties which is necessary for further work on resource assessment and future data assimilation efforts. The work included preparation for a Summer 2013 MEA-sponsored met/ocean/geophysical survey of the MD WEA to gather the first hub-height wind measurements in that region, processing the Lidar data to compensate for vessel motion, and analysis of the data and other measurements and comparison to models. An extensive archive of data gathered during the measurement campaign, historical coastal and offshore data from a variety of sources was prepared and will be a valuable resource for further work. The work was presented at conferences, a conference paper was submitted, and a draft of a peer-reviewed journal articles prepared.

II.1. Summary of Deliverables Submitted to DNR

• *First quarterly report (QR1)*: analysis and meteorological interpretation of lidar measurements from the August 17, 2012 UMBC/USNA pilot study in Chesapeake Bay aboard a USNA YP training vessel. The full analysis was not possible due to inconcistencies and insufficient information about the vessel and lidar coordinate systems, the placement of the lidar with respect to the vessel frame of reference, and the lack of measurements of vessel heave (vertical motion) in the YP IMU system. Nevertheless, this experience was extremely valuable in planning the requirements and set-up for the wind lidar measurements in the MD WEA during the Summer 2013 offshore campaign, as detailed in later reports. QR1 also detailed the preparations for the Summer 2013 measurement campaign, and analyzed seasonal and diurnal variability for a multi-decadal wind dataset from the Chesapeake Light Tower as part of the data archive analysis.

• Meeting with DNR to report on preparations for Summer 2013 MD WEA wind/geophysical measurement campaign.

• *Second quarterly report (QR2):* model configuration testing of horizontal and vertical resolution, topography smoothing to increase model numerical stability and a case study of a low level jet (LLJ). The model simulations were compared to near-surface wind data from NDBC buoy 44009, a few km from the MD WEA, and to wind profiles from the MDE radar wind profiler data at Horn Point .

• *Third quarterly report (QR3):* A post measurement campaign synopsis, including a summary of wind lidar and several other in situ measurements. Attempts to gather thermal and water vapor profiles, which are important for interpreting the wind data, were described. A comprehensive analysis of pre and post mission microwave radiometer thermal and water vapor profiles required an extensive post-mission field study at several locations to obtain comparisons with weather balloon profiles and other radiometer instruments. QR3 also included an analysis of the representativeness of the summer 2013 measurement period relative to the long-term climatology. The skill of NOAA's RAP and other operational met fields and high resolution WRF simulations was assessed by comparison with radiosonde data from balloons launched from the vessel and data from the HPLMD an BLTMD wind profilers. This report also included a summary of the theoretical basis of the motion compensation algorithm for the ship-based lidar and an outline of the numerical implementation.

• *Fourth quarterly report (QR4):* analysis of data from the Summer 2013 measurement campaign and comparison to WRF model simulations. Work during this quarter also included a more in-depth look at vessel motion for motion compensation of the wind lidar measurements that revealed biases in the orientation angles of the platform that were related to the asymmetric mass distribution on the vessel. A forward model to simulate a lidar-sampled wind field was also developed. In other modeling work, the North American Mesoscale (NAM) model, the North American Regional Reanalysis (NARR) model, and the Rapid Refresh (RAP) operational forecast models were compared to profiler data to assess uncertainties in the initial and boundary conditions for the high resolution WRF simulations.

• *Fifth quarterly report (QR5):* Meeting with DNR and MEA to report on the modeling and interpretation of measurements gathered during the Summer 2013 MD WEA wind/geophysical measurement campaign and other research outcomes. The powerpoint presentation was delivered to DNR.

• *The current, final report*. A summary of work completed and accomplishments under this contract, including some additional results obtained since the QR5.

• *Conference presentation:* "Measurement and modeling challenges to wind resource assessment in the Mid-Atlantic", L. C. Sparling, S. Rabenhorst and R. Delgado, American Solar Energy Society Conference, (SOLAR 2013),(session on wind energy), Baltimore, MD, April 2013. (See Appendix in QR2).

• *Conference presentation and paper:* "Building a Science-Based Foundation for Assessing the Offshore Wind Resource of Maryland", L. C. Sparling, S. Rabenhorst, B. Williams, R. Delgado, E. Strobach, B. Boicourt and B. Bailey, EWEA 2013 Offshore Wind Conference, Frankfurt, Germany, November 2013. The conference paper was submitted to DNR, and drew considerable attention to MD's offshore wind energy efforts.

• *Peer-reviewed journal article on complexity of midatlantic wind*. A peer-reviewed publication for the journal *Wind Energy* on the subject of uncertainty in wind resource assessment is being prepared that will be a reduced version of this final report.

II.2. Summary of Specific Products/Outcomes

This section is a summary of products/utcomes that addressed the stated goals, with a brief discussion of the methodology used. Discussion of specific outcomes and results in later section.

- **Summer 2013 offshore measuremet campaign:** Preparation and participation in intensive 6 week field campaign that surveyed winds over the entire MD WEA.Preparation for campaign, testing instrumentation, data gathering during campaign, post-mission field measurements for quality control, lidar motion compensation.

- **Model/Data Archive:** compilation of a data archive of wind measurements from satellites, rawinsondes, bouys, anemometer towers, wind profilers and other platforms. Includes hourly RAP forecast fields that are not archived at NOAA for forecast sensitivity studies and future data assimilation efforts and WRF simulation model output. After sufficient quality control and concerns about server security, the archive will be made available to all interested stakeholders. The contents of the archive are outlined in Appendix xx.

- **Analysis of archived data**; statistical analyses of historical data, analysis of data gathered during field campaigns, case studies

- **Wind LiDAR** - development of expertise in meteorological interpretation of lidar observations and uncertainties. Motion compensation algorithms were developed to compensate for the motion of the lidar on a moving platform; and lidar simulation algorithms were developed for uncertainty analysis and initial tests conducted.

- **WRF Model Configuration and Comparative Analysis** - configuration and testing of a NWP model that can be used to aid resource assessment and form the model component of a reanalysis dataset based on data assimilation. The methodology included numerous simulations and testing of spatial resolution, variation of boundary layer parameterizations, testing of input boundary conditions for regional downscaling, extensitve model evaluation by comparison to lidar and other observations and several in-depth case studies to understand forcing mechanisms.

III. MODELING SUMMARY

UMBC Modeling studies were aimed at understanding the regional wind patterns in coastal and offshore MD in order to interpret observational data correctly and configure NWP models. UMBC research outlined in this report demonstrates that by carefully selecting the optimal model, setup, configuration, and initial/boundary condition input data sets for a specific region of interest, model skill offshore can be improved significantly.

III.1 WRF Model Configuration, Testing, and Optimization

The NWP simulations used a state-of-the-art numerical weather prediction model, WRF-ARW, v. 3.5 (Weather Research and Forecast, Advanced Research) model [Skamarock et al., 2008]over a region that includes the MD WEA and mid-Atlantic coast. High-resolution (100m) surface data was also incorporated to accurately model land/water roughness and thermal contrasts that lead to internal boundary layers with complex thermal stability profiles. The NWP model configuration includes several vertical layers that span the turbine rotor at heights 50-200m. Simulations were performed on a range of horizontal resolutions down to a few hundred meters, and different land surface and marine boundary layer parameterization options were tested. A variety of observations (locations shown in Figure III.1) were used to evaluate model performance and to optimize the model configuration for future long-term high-resolution simulations of marine boundary layer winds. These studies will build confidence in the model and will be used in future modeling work to target key uncertainties in the offshore wind resource

III.1.1 Horizontal Resolution

WRF was set up and run using several different horizontal resolutions. Good results were found for the placement of the outer domain with the southern edge located near the Gulf Coast, the western edge located west of the Mississippi River, the northern edge above the Great Lakes region, and the eastern edge located far enough into the Atlantic Ocean to capture high/low pressure centers along the eastern seaboard. Additionally, we have found running high-resolution simulations greater than 72 hours tends to introduce excessive drift. It is best practice to keep high-resolution simulations relatively short, counting output as valid after a 3-6 hour model spinup time period. Grid spacing was chosen to roughly match that of higher resolution operational models, ranging from 13.5 to 10 km.

Experiments were run with varying nest resolutions of 4.5, 4, 2, 1.5, 1.33, 0.66, 0.5, and 0.44 km. Fine nest placement was chosen to cover the entire wind energy area and as much of the Delmarva peninsula and DC metro area as possible, but computational limitations curtailed the spatial extent to the immediate MD WEA and Atlantic coast for nest domains with very low grid spacing values (< 2 km). Every effort was made to mitigate parent-to-nest domain boundaries along large topographic features, such as the Appalachian Mountains. These steps were taken to minimize artificial artifacts generated by terrain discontinuities between domain resolutions. Results show that nests with higher resolutions

(<2 km) are able to better resolve features in topographic gradients and landuse (water, urban, wooded, cultivated, etc) that can force local winds.

III.1.2 Vertical Resolution

WRF was also run with several vertical resolutions, which are the number of layers between the surface and a specified pressure level, 100 hPa in our case. Current operational models use various numbers of levels. For example, GFS (Global Forecast System), NAM (North American Mesoscale Model), RAP (Rapid Refresh), and HRW (High Resolution WRF) use 64, 60, 50, and 35 vertical levels, respectively. Operational models tend to focus on storm development, precipitation, and aviation forecasts, which are all focused well above ground level. As a result, they are not well-configured for studying low-level winds at turbine heights.

UMBC's modeling tests ran WRF with 50, 61, 69, and 100 vertical levels. The default distribution of model levels is linear with pressure, leading to deep vertical layers near the surface. This was undesirable due to our need for more information across the rotor span. Therefore, we found the best result used custom vertical level placement that concentrated layers at wind turbine heights. While in theory using more vertical levels should better resolve the lower atmosphere, the side effect was to generate instability at coarser grid resolutions in regions with sharp topographic gradients. Therefore, we found the best results were to run WRF with 69 vertical layers approximately centered at 12, 30, 45, 60, 75, 90, 105, 120, 140, 160, 185, and 212 m above the surface throughout the lower atmosphere. This configuration provided more information that was calculated on vertical levels, and more thin layers that effectively reduces interpolation errors to specific heights. This also allows WRF the ability to better resolve low-level shear layers.

III.1.3 Resolution of Surface Data

The highest resolution geographic datasets provided by WRF are 30 arc seconds (nearly 1 km grid spacing). For many forecasting applications, this resolution is sufficient. However, for low-level wind simulations it is important to accurately represent the terrain features and landuse that force winds. For example, parts of Ocean City, MD are only 0.4 km wide. This means that parts of the barrier islands are completely unresolved and appear as open water. Additionally, there are mountain ranges in Western Maryland that are barely 1 km wide, and often averaged out into a small knoll by neighboring grid cells. Unrealistic representation of surface features can significantly impact low-level winds. Furthermore, the default USGS landuse dataset in WRF does not account for different urban intensities, and therefore will assign the same roughness factor to a suburban neighborhood as a downtown skyscraper.

Since these details are very important at high resolutions, UMBC converted the National Land Cover Dataset (NLCD) 2006 (and the NLCD 2011 as of this year) into an ingestible form for WRF. This dataset provides detailed information at 30m resolution for WRF. High resolution (30m) topographic data from the USGS National Elevation Dataset (NED) was also adopted for WRF. This improves the surface resolution in WRF runs to resolve smaller features than would otherwise be accounted for.

The combination of adopting the NLCD and NED datasets for high resolution WRF simulations reduces the uncertainty associated with poor surface representation. This is particularly for the complex geography of the Midatlantic region.

III.1.4 PBL Schemes

One of the functions of planetary boundary layer (PBL) physics schemes in mesoscale models is to parameterize vertical mixing caused by unresolved sub-gridscale turbulence. The stable nocturnal PBL is notoriously difficult to model (*Sukoriansky, et al., 2005*) because the shear-induced turbulence in the stable layer occurs on small horizontal scales and is intermittent, thus has less statistical regularity relative to the convective daytime PBL. The newer MYNN PBL scheme was used since it was designed to perform better under a range of stability conditions. The model is configured with a total of 63 unequally spaced vertical levels, with 11 levels below 200m in order to sufficiently resolve the wind profile across the turbine rotor layer (50-150m The current WRF configuration is summarized in Table III.1.

III.2 Evaluation of Weather Forecast and Climate Reanalysis Data Sets - Reducing Uncertainty in Model Initial and Boundary Conditions (QR2, QR3)

Variability and uncertainty in the offshore wind resource has a variety of origins including measurement errors or temporally and spatially sparse or biased sampling [4, 5]. Small scale variability due to local forcing is not resolved in currently available climatological datasets, and winds forced by larger scale mesoscale or synoptic features can have strong local finescale variability which requires high resolution modeling. High resolution numerical models require lower resolution meteorological model input data to provide initial and boundary conditions on the higher resolution inner domains. A significant portion of this research was devoted to evaluating these input datasets.

The data sets chosen for analysis were the North American Mesoscale (NAM) model, the North American Regional Reanalysis (NARR) model, and the Rapid Refresh (RAP) model. The model resolution relative to the size of the MD WEA is shown in Figure III.1. The frequency of the model analysis and forecasts are significantly different between the three models. There has been a long-held belief that the analysis state should be closest to the observed state of the real atmosphere, since all subsequent forecasts will drift further away with time. The analysis process tends to smooth over fine-scale features and structures present in the real atmosphere, especially near the surface. However, after a short spin up period, the model will quickly regenerate these realistic structures and features. One of the largest sources of uncertainty in running high-resolution regional models is obtaining an accurate initial state of the atmosphere.

One aim of these investigations was to identify which analysis state (what forecast time) best represents mid-Atlantic wind observations. This must be balanced by how frequently the optimal time appears in a given dataset. This is largest for the RAP dataset which thus has an advantage over the other two datasets. This was verified by observations from the Radar Wind Profiler (RWP) located at the Horn Point Lab (HPLMD) near the Chesapeake Bay in Cambridge, MD. RAP output is therefore used as a 1st-order investigation of meteorological conditions during case studies of interest.

III.2.1 RAP, NAM, NARR: Biases v. Radar Profilers (HPLMD, BLTMD), July 2013 (QR3?)

For this study we examined data for the whole month of July 2013. The NAM, NARR, and RAP models were compared to RWP observations from Beltsville, Maryland (BLTMD) and Horn Point Maryland (HPLMD). The horizontal resolutions of NAM grid 218, NARR grid 221, and RAP grid 130 are approximately 12, 32, and 13 km, respectively. Since the exact location of the RWPs are not centered within individual model grid cells, we explored different horizontal interpolation methods and found little sensitivity.We also explored the differences between using linear and second order interpolation of model data to observation levels. Generally speaking, the second order interpolation showed closer agreement with observations. It should also be noted that the vertical resolution for the NAM and NARR datasets are on standard pressure levels, starting at 1000 hPa with intervals of 25 hPa. The RAP data, on the other hand, is on terrain-following native model levels. During high pressure regimes, RAP demonstrates there can be as many as 3-4 model levels between the sea surface and the first 1000 hPa pressure level. A statistical analysis of the height of the 1000mb surface (QR5) from 30 years of data from buoy 44009 showed that the 1000 hPa height near the MD WEA can extend above 200m during the summer, which is well above hub height. A preliminary study of the climatology of the 1000mb height over the North Sea on the other hand, based on NCEP/NCAR Reanalysis data, showed it to be much lower and closer to hub height.

III.2.2 Wind Speed – Input Data Sets - Model Biases vs Radar Profilers (HP and BLT)

The overall wind speed errors were evaluated from probability distributions (PDFs) of wind speed error (model subtracted from observation) between all three models at a land-based site (BLTMD) and in a more coastal environment at HPLMD. Part of this study was to assess the accuracy of the RAP forecast fields for forecast times from 0 to 12 hours. Wind speed values were found to be chronically underestimated at the analysis time (t=0) and must "spin up" to observation values. Our findings show that wind speed values are best represented around the 2-3 hour forecast time (F02-F03), as opposed to using the traditional analysis time (F00). All three models show a significant underestimation of wind speed (1-2 m s^{-1}) at the analysis time at BLTMD. Wind speed errors are lower at HPLMD. A possible reason is the flatter terrain in a coastal environment, which has smaller spatial variance. Similarly, the implication is that more spin up time is necessary in order to accurately represent wind speed over land as opposed to coastal environments.

Comparisons of the profiles of median wind speed error at HPLMD to the RAP, NAM and NARR wind products indicate a significant amount of model uncertainty below 1 km. The forecast time with the least error for both NAM and RAP is 2 hours (F02). Overall, the NAM data shows a tighter agreement in wind speed throughout the lowest 2 km of the atmosphere. NARR, on the other hand, performs the worst with a chronic underestimation of wind speeds throughout the entire lower 2 km.

We also examined wind speed errors during low-level jet (LLJ) events. A comparison of the median wind speed error profiles between the three models (RAP, NAM NARR) for LLJ cases during July showed that model wind speeds are greatly underestimated (2-3 m s^{-1}) around 500 m above the surface, a height where LLJ core wind speeds are the strongest. Above 1 km, RAP and NAM wind speeds above the LLJ are overestimated. The net effect of this pattern means that the models will show weaker, less defined LLJ features compared with RWP observations. This could imply that turbine-height wind speeds are greater than the model simulations of LLJ cases. However, this may not necessarily be the case offshore. More research over a greater set of LLJ cases is needed.

A study of wind shear from the RAP model across wind turbine heights was conducted during JULY 19-21 case study (QR3). The RAP data has approximately three model levels below 200m. A strong sensitivity of computed cross rotor wind shear on the order of the vertical interpolation across the rotor span was found. Using a 2^{nd} order vertical interpolation, wind shear values greater than 4 m s^{-1} across the rotor were not uncommon. If RAP was underestimating the LLJ strength, these values could be significantly greater. This highlights the importance of wind lidar (or conventional) observation profiles for model validation. An important feature in the RAP data is the substantially larger wind shear across the bottom half of the rotor span compared to the top half. Because this was also observed in the lidar data, it gives some confidence that RAP is capable of representing the observed cross-rotor variation in shear. Additional studies will be required to evaluate whether the RAP and WRF models can give reliable and realistic information about wind shear under other meteorological conditions.

A comparison between the RAP and RWP wind speed time-series showed that the model captures the overall timing and vertical structure of the jets, but significantly underestimates the LLJ strength. By comparison, the RAP wind speed magnitude over the MD WEA agrees more closely with the RWP observations, roughly 120 km inland. It is not apparent whether RAP simply underestimated the LLJ core at Horn Point, or whether the model incorrectly translated the jet axis too far east. More observations would be needed to make this determination.

III.2.3 Wind Direction – Input Data Sets - Model Biases in Wind Direction vs Radar Profilers (HP and BLT)

Tests of the WRF (Weather Research and Forecast) mesoscale model were conducted for different model physics and boundary layer options. There is increasing evidence that some model configurations do not adequately represent the Ekman turning of low-level winds. A study by MMI Engineering showed a bias in wind direction when comparing NARR and buoy windroses[1]. Similar biases in WRF simulations using the MYJ planetary boundary physics option have shown that winds over land were rotated 5-10 degrees counter-clockwise[2]. Such wind direction errors are not uncommon and must be understood due to their impact on wind farm design simulations. (QR3)

Wind direction error for NAM, NARR and RAP were analyzed vs. HPLMD. These forecast error profiles are very significant (ranging between 18-35°) for both NAM and RAP, and exhibit a chronic negative (counterclockwise) model bias. The wind direction errors throughout the lowest 500 m are typically biased between -40° to 0° counterclockwise. NARR shows significantly less wind direction error at HPLMD (ranging between 5-8°) but with a positive (clockwise) model bias throughout the lower atmosphere. Wind direction errors are shifted significantly further inland at the BLTMD site, and NARR error increased to a 15-20° clockwise bias. However, the rougher topography and terrestrial boundary layer effects bring the NAM and RAP into much closer agreement with observations, with median error profiles ranging between a 8-15° counterclockwise bias

III.3 WRF Case Studies: May 21-22 – Low Level Jet (QR3)

The May 21-22, 2013 case was selected for in-depth studybecause of the unusually high winds speeds observed at the lowest profiler observation level (171m AGL). This case was also chosen because these low-level jet (LLJ) features can be challenging for models to accurately simulate.
The simulated WRF profiles were compared to the HPLMD measurements because another objective of this case study was to investigate whether observations with the Horn Point wind profiler on the eastern shore of MD allowed anything to be inferred about the wind in the offshore WEA. The profiler is the only nearby source of information about the continuous time evolution of the wind vertical profile, but it may not be representative of the offshore wind, given its proximity to the Chesapeake Bay and possible influence from small scale local forcing. Nevertheless, the profiler is an excellent model validation data source, and together with a high resolution model, can lead to insights about the winds offshore. The models agreed qualitatively with the observations, but failed to reproduce the intensity and height of the jet core, which may have been displaced in the model. Nevertheless, the simulation showed a strong correlation in the time evolution of the windspeed vertical profile between Horn Point and the WEA and also showed how the wind profile changed along a transect across the Delmarva peninsula. The study also showed that data sources of this type are valuable diagnostic tools for model validation. Models will continue to be important for wind resource assessment, but model uncertainties must be taken into account.

The RAP wind field for May 21-22 in the larger region surrounding the WEA showed that the height and strength of the jet varies across the region; at lower levels the jet is strongest over the WEA with turbine height windspeeds of about 14-15 m/s. This case study illustrated the impact of the mountains, which appeared as a leeside trough west of the Chesapeake Bay at 1000hPa that becomes centered over the Bay at higher levels. It is not uncommon for downslope winds associated with leeside troughs to lift the LLJ to higher levels [*Rabenhorst*, 2012]. Downwind, a wave in the geopotential heights can be seen that is associated with a ringlike structure in the windspeed. The RAP wind speeds over Horn Point were found to underestimate the 23 m/s wind speed from the profiler. One possibility is that RAP has the jet shifted too far east.

Comparison of WRF LLJ Profiles to observations: buoys and Horn Point Profiler

Continuous vertical wind profiling would be extremely useful to fully understand coastal wind variability. The Horn Point wind profiler data is the only available data of this kind that may be relevant for the WEA, but it is over 100km away and situated on the Eastern Shore.

A modeling study was performed to evaluate whether this could be a useful data source for offshore wind studies. The observations were compared to the RAP analysis and to a high resolution WRF simulation during a LLJ event in May 2013. The model agreed qualitatively with the observations, but failed to reproduce the intensity and height of the jet core, which may have been displaced in the model. Nevertheless, the simulation showed a strong correlation in the time evolution of the windspeed vertical profile between Horn Point and the WEA and also showed how the wind profile changed along a transect across the Delmarva peninsula. The study also showed that data sources of this type are valuable diagnostic tools for model validation. Models will continue to be important for wind resource assessment, but model uncertainties must be taken into account.

Overall, WRF correctly represents the vertical structure of the LLJ, however, it significantly underestimates the core wind speed by roughly 5 m/s. It is not likely a resolution issue because the horizontal grid spacing was 1.5 km (actual pixels in domain figure) and there were 68 vertical levels spaced at: 30,45,60,75,90,105,120,135,150,175, 200..etc. meters AGL. Possible other sources of the discrepancy such as initial/boundary conditions, surface temp, or PBL scheme were investigated and results are discussed in later sections. The model and data agree with respect to the southwesterly wind direction of the LLJ and the downward penetration of SW winds to the surface during jet formation. The timing of the onset of the jet is also approximately correct. This illustrates why it is so important to have continuous vertical profile measurements of winds in order to verify the model results, even if the observations are outside the main region of interest.

Other comparisons with buoy 44009 showed good qualitative agreement with the model. This indicates that the LLJ extends offshore into the WEA, which is a potentially important result for evaluating the wind resource in the warm season.

IV. SUMMARY OF WORK: MEASUREMENTS AND DATA ANALYSIS

A major source of uncertainty in wind resource assessments is the lack of detailed information on the variation of the wind across the rotor span. Wind shear has been shown to affect turbine power output [1], and variations in shear across the rotor can lead to repetitive (cyclic) stresses and fatigue. Measurements of cross-rotor shear variation are not possible from tower anemometers which cannot reach rotor-top heights. In addition, the coarse vertical resolution of many mesoscale models have not allowed quantitative analysis of cross-rotor shear. This has led to the widespread use of logarithmic or power-law extrapolations of measurements to estimate winds above hub height, introducing significant uncertainty. Lidar allows a much better understanding of shear profiles and stability regimes, reducing this uncertainty. Offshore measurements showed significant departures from simplified statistical extrapolations of wind speed to hub height based only on surface observations.

IV.1 NASA Airborne Lidar Scans of the WEA

The NASA/LANGLEY airborne wind lidar surveyed the MD WEA on June 24 and June 26, 2013. Some results for this survey were given in QR1 and QR5, and some additional analysis has been done since QR5. Figure IV.1 shows windspeed profiles from the June 24 overfly, with every other profile for clarity. The main result here is that this case demonstrates that maximum winds can occur near the surface; in this case, the wind speed decreased with height for the first 300m ASL, and was relatively constant above that up to about 1.5 km, which was the likely height of the boundary layer, as this was a warm, cloudless summer day. This suggests that some low level forcing mechanism is at work. This result prompted an analysis of the anemometer winds at the Chesapeake Light Tower (z=43m ASL) to the 3m winds at a buoy located about 1 km away (buoy 44010) during a brief period from August 1994 - June 1995. The results (QR5) showed that winds at 43 m ASL are weaker than near surface winds over one-third of the time. It is not clear at this time whether that location is representative of the Mid-Atlantic region as a whole due to its proximity to the mouth of the Chesapeake Bay or to meanderings of the Gulf Stream. Preliminary analysis shows that the negative wind shear does not appear to be correlated with wave height or season, thus it does not appear to be a sea breeze effect or associated with wave forcing. It is also possible that the higher speeds at 3m may be due to averaging of higher gusts near the surface, but this must be investigated further.

IV.2 Offshore Lidar: Measurements and Methodologies

The offshore measurements during the Summer 2013 MD WEA measurement campaign were made with a Leosphere wind lidar, model WindCube^{TM} v2 Offshore, that measures the wind profile in the height range 40-220 m. The instrument was designed for a buoy platform and included compensation for orientational motion only, thus it was necessary to return to the uncorrected line-of-sight wind and include corrections to both orientational and translational motion using the motion compensation algorithm discussed in QR3. High precision 10 Hz data were available during this time from the ship differential GPS and inertial navigation system (INS). Important lessons were also learned regarding the effective use of motion compensation for lidar data collected from a moving vessel.

IV.2.1 Case Study July 19 – 21, 2013: Lidar and WRF Comparisons

A series of strong LLJs occurred during the week of July 18. The jet axis for the July 19 event was located above the MD WEA site at 0700 UTC, and was stronger further northward. The spatial characteristics suggested a local forcing mechanism, and this LLJ may have been partially governed by low-level heating differentials. The model showed a pattern of alternating warm and cool surface temperatures as the transect traverses the cool highlands, the warm Bays, the cool coastal water and finally the warmer ocean offshore. The LLJ evolution and scope appear to be governed by an amalgam of thermal forcing, lee trough intensity, stability, and synoptic arrangement.(QR4) (*Sparling et al, 2013*).

The important findings include observations of much stronger shear in the rotor plane (40-100 m) below hub height (100 m) compared to the upper half of the rotor plane (100-160m), and an abrupt decrease in wind near 0700 UTC that was associated with a downward turbulent cascade of momentum that occurred in less than 20 minutes. Shear instability is one possible reason for the rapid breakdown of the jet, however other observations point to a larger scale event. Other factors such as downwind propagation of a lee trough generated by flow over the Appalachians or Cool water upwelling along the coast could also have played a role.

During the campaign, lidar scans were made "underway", ie. the ship was continually moving at a speed of about 3 m/s. The scans thus show a mix of spatio-temporal variability as the ship moves along the ship tracks. A space-time comparison of the WRF simulation for the July 19 LLJ is compared to the wind speed observed along the ship track in Figure IV.2. The latitude vs time track of the ship is superimposed, colored according to windspeed with the same color scale as the WRF plot, and the latitude-time plots are shown for three heights across the turbine rotor (60, 100, 160m). During this 00-11:00 UTC period, the ship covered less than 600 meters E-W, but approximately 20 km N-S, thus the distance in longitude is less than the 4 km model grid spacing. The plot shows how the simulated field evolves in time in the N-S direction. Exact agreement cannot be expected, since at high model resolution small features can easily be displaced, nevertheless the figure shows good qualitative agreement.

IV.2.1 Offshore Lidar Statistics: July 18 – Aug 4 2013

Figure IV.3 is a more comrehensive statistical study of the offshore lidar data for the portion processed for motion compensation, showing pdfs of the windshear across the upper half (160 – 100 m), lower half (100 – 40m) and entire rotor (160 - 40m). The legend in each plot gives the fraction of observations for which the shear ΔV was negative.

(ΔV = wind at higher level – wind at lower level) Negative wind shear occurs somewhat less frequently during the day, which is not surprising given that momentum mixing during the day reduces wind shear. The windspeed decreases from hub height to rotor top a substantial fraction of the time during this period.

IV.2.2 Horn Point RWP and Offshore Lidar Comparisons: July 18 – Aug 4 2013

An important question is the extent to which the HP RWP gives info about offshore wind. RWP observations at the lowest profiler height (170m) were compared to 170m winds observed offshore for the period July 18-Aug 4 2013. The timeseries comparison in Fig IV.4 contains some daytime gaps in the Lidar due to overheating during the day. The LLJs offshore are generally stronger during this time, but more general conslusions will require much more offshore data. The extent to which the two data sets agree is not completely clear for this limited time period. Instances where there is close agreement suggests larger scale forcing, so this is a possible way to evaluate synoptic vs local forcing.

V. OUTCOMES AND CONCLUSIONS

- Potentially more low-level vertical information is contained within native-level model datasets (RAP) as opposed to model data that has already been interpolated to standard pressure levels (most other model datasets) and potentially omitting important turbine-height wind information.

- Input data from low resolution models is required for climate downscaling to obtain higher resolution wind climatologies on wind farm scales or smaller. The standard levels are frequently above hub height in the Mid-Atlantic which means that fine scale wind features and local climatologies due to terrain, SST or other regional forcing must be generated by the dynamics of the interior nest. This in turn requires high resolution land surface data and SSTs which can drive these local circulations.

- The F02 forecast time appears to be an optimal forecast time that best represents both sites. Longer forecast times tend to overestimate wind speeds. Models often underestimate wind speeds during strong LLJ events. This has direct consequences for resource assessment which includes estimates of ramp rates for grid integration. In addition, accurate marine forecasting is essential for wind farm O&M.

- Wind direction biases were found in commonly used model datasets used for initial and boundary conditions. NAM and RAP performed better inland and worse in the coastal environment, while NARR performed better in the coastal environment during the period of study. Biases in wind direction are serious sources of uncertainty in wind farm planning because turbine layout depends on the prevailing wind direction in order to minimize wake effects.

- The model sometimes showed strongest winds offshore and over the Ches Bay, rather in coastal plain, which suggests local land-sea thermal forcing. The nocturnal LLJ actually appeared to be strongest offshore, extending out into the WEA as a larger scale coastal/offshore meteorological wind regime. This illustrates the complexity of the wind field, especially when synoptic forcing is weak and the winds are driven by a combination of influences that arise from the complex coastal terrain.

- The impact of the mountains, together with local thermal contrasts, can lead to complex behavior along the coast that can “break” long range correlations in the wind along the coast and further offshore. This can lead to considerable uncertainty when coastal land-based data is used to make inferences about offshore winds.

- The wind lidar data gave an unprecedented small scale view of the wind dynamics on the turbine scale and demonstrates that simple statistical extrapolations of surface winds to hub height can be drastically different from the wind that is actually hitting the turbine.

- The use of lidar on a moving platform thus has potential to reveal both spatial and temporal variability, and suggests that lidar scanning from a translating platform is a promising sampling strategy, and opens the door to new, adaptive sampling strategies.

- Quantifying wind shear is important for wind reource assessment. These results show that the extrapolation of buoy or other surface wind observations to hub heights assuming a logarithmic or power law profile is not valid.

- The complexity of the coastline along the eastern seaboard, and its impact on what onshore observations imply about the hub height offshore wind resource, is an important area for further study.

VI. REFERENCES

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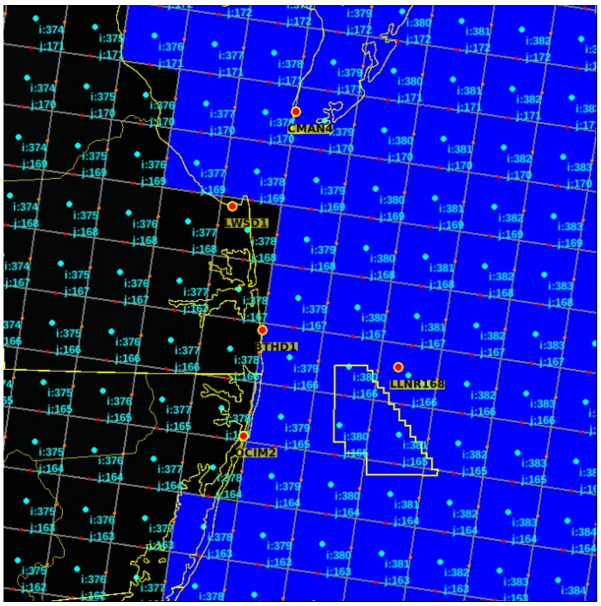
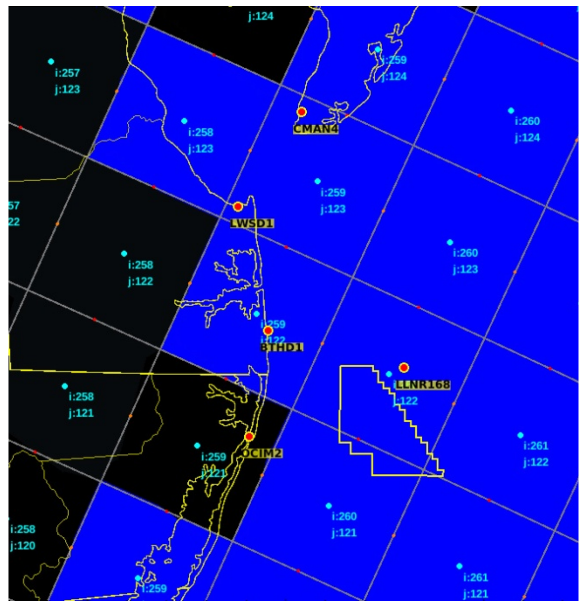
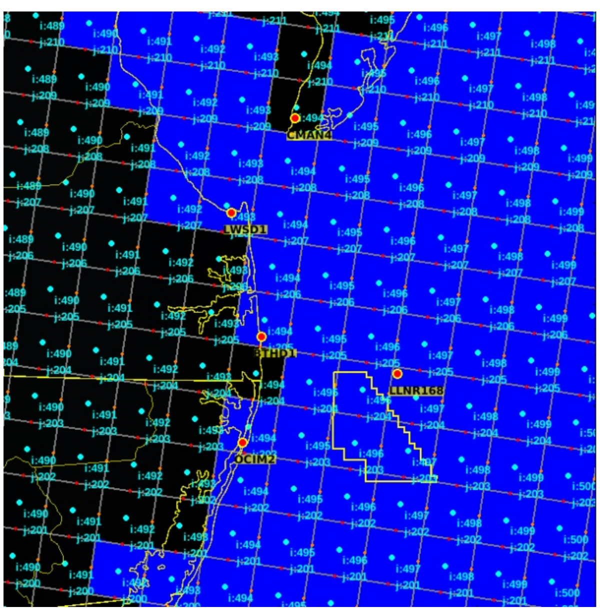
VII. FIGURES



(a) RAP Grid 130: ~13 km grid spacing



(b) NARR Grid 221: ~32 km grid spacing



(c) NAM Grid 218: ~12 km grid spacing

Figure III.1: Comparison of the horizontal resolution of three models analyzed in this investigation. Blue shading indicates grid cells that represent open water, while the dark shading indicates land areas. Coarse, jagged coastal resolutions are often not representative of fine-scale wind observations.

Table II.2: Configuration for WRF-ARW v. 3.5 numerical simulations*. MYNN=Mellor-Yamada-Nakanishi-Niino, RRTMG=Rapid Radiation Transfer Model.	
Model Option	**Option used for simulations**
Surface layer/PBL	MYNN (TKE-based) *Nakanishi and Niino, 2006*
Land surface model	NOAH Land Surface Model/ Urban Canopy Model (UCM)
Cumulus parameterization	N/A for high resolution
Shortwave radiation	RRTMG
Longwave radiation	RRTMG
Microphysics	WRF double moment, 6-class scheme
Horizontal and vertical resolution/	1.5 km horiz grid ; 68 vertical levels; (30,45,60,75,90,105,120,135,150,175, 200...)m AGL
Initial/boundary conditions	RAP (http://rapidrefresh.noaa.gov/) (hourly update assimilation system)
(*) -WRF Model architecture and physics schemes are described in http://www.mmm.ucar.edu/wrf/users/wrfv3.2/wrf_model.html	

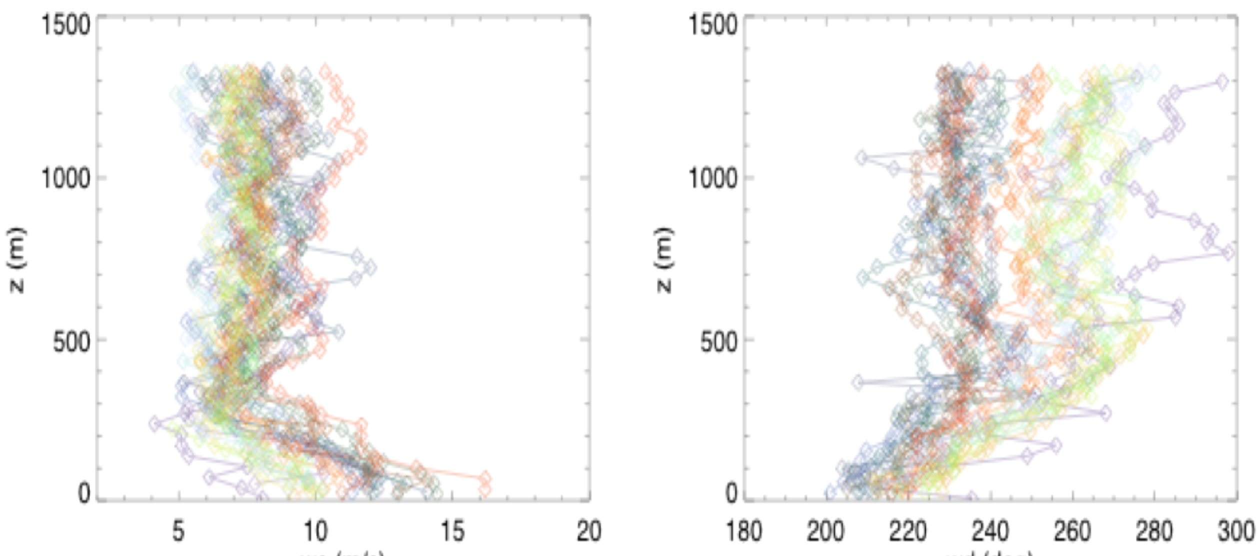


Figure IV.1: Windspeed vertical profiles over the MD WEA, June 24, 2013. Data taken by the NASA/Langley DAWN airborne lidar wind profiler.

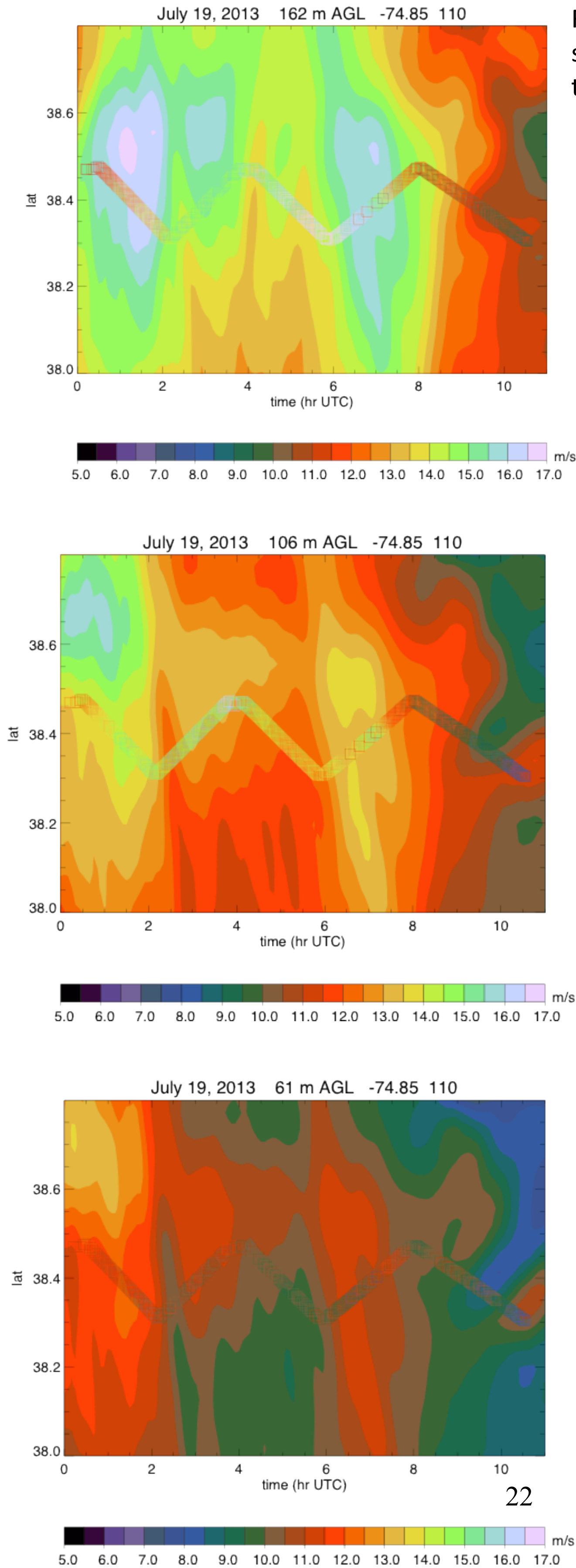


Figure IV.2: Latitude vs height wind speed contours from the model, with the flight track superimposed.

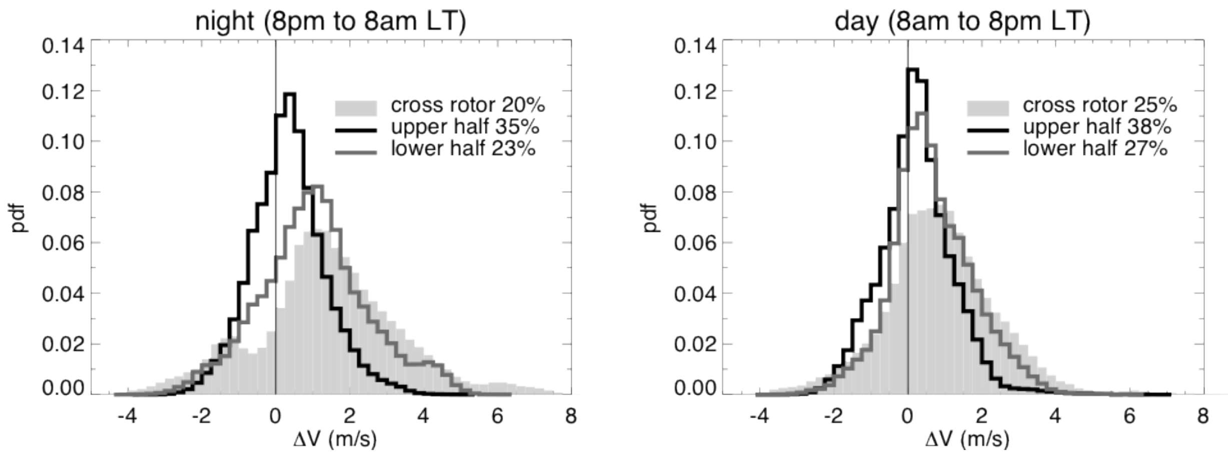


Figure IV.3: Pdfs of windshear across the bottom half, top half and across the rotor. Data from the wind lidar in the MD WEA, July 17-Aug 4, 2013.

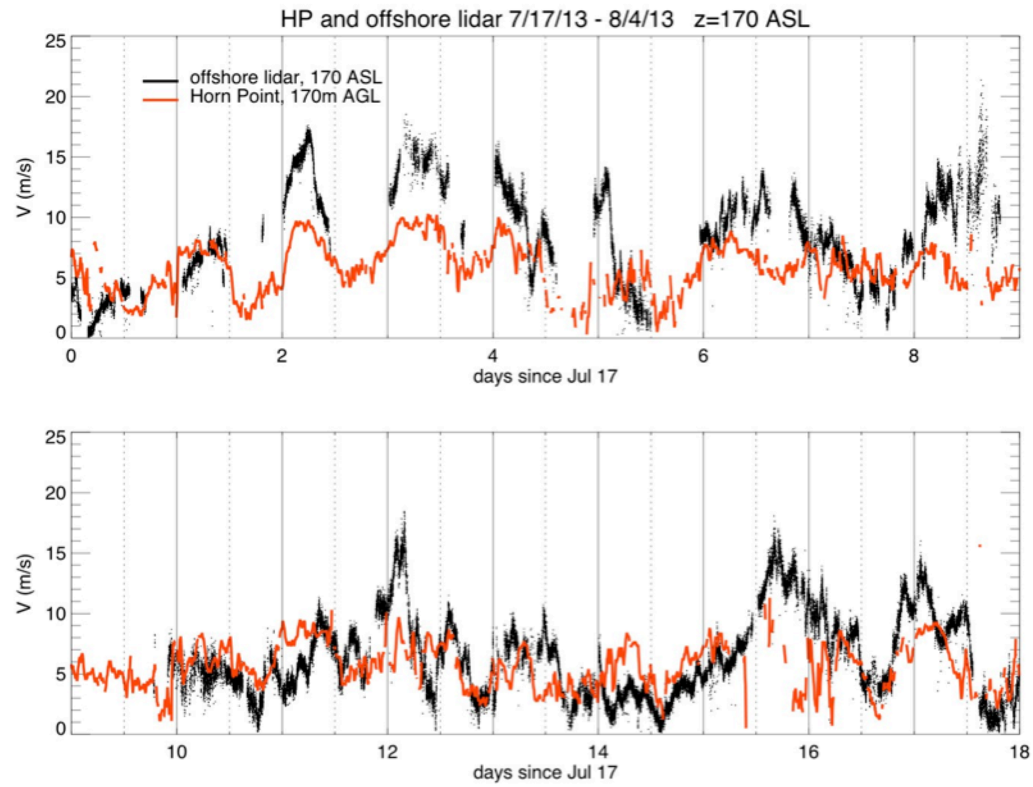


Figure IV.4: Timeseries comparison of offshore lidar in the MD WEA to a RWP located in Horn Point, MD, over 100 km away.

APPENDIX 1. LIST OF ACRONYMS

Acronym	Definition
ABL	Atmospheric Boundary Layer
AGL	Above Ground Level
ASL	Above Sea Level
BLTMD	Baltimore, MD
DNR	Department of Natural Resources
EWITS	Eastern Wind Integration and Transmission Study
EWRW	Eastern Winds Regional Wind
F02	2-hour Forecast
GFS	Global Forecast System
GPS	Global Positioning System
HP	Horn Point
HPLMD	Horn Point Lab (Maryland)
HRW	High Resolution WRF
HUBRC	Howard University Beltsville Research Center
IBL	Internal Boundary Layer
INS	Inertial Navigation System
LIDAR	Light Detection and Ranging
LLJ	Low Level Jet
MDE	Maryland Department of the Environment
MEA	Maryland Energy Administration
MYJ	Mellor Yamada Yanic
NAM	North American Mesoscale
NARR	North American Regional Reanalysis
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NDBC	National Data Buoy Center
NED	National Elevation Dataset
NLCD	National Land Cover Dataset
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Lab
NWP	Numerical Weather Prediction
OCIM2	Ocean City NDBC buoy
PBL	Planetary Boundary Layer
PDF	Probability Distribution
RAP	Rapid Refresh
RWP	Radar Wind Profiler
SAR	Synthetic Aperture Radar
SST	Sea Surface Temperature
UCM	Urban Canopy Model
UMBC	University of Maryland at Baltimore County
USGS	U.S. Geological Survey

Acronym	Definition
WEA	Wind Energy Area
WRF-ARW	Weather Research and Forecast Advanced Research

APPENDIX 2: CONTENTS OF DATA ARCHIVE

UMBC Data Server for Maryland Wind Energy Project – Summary/Directory Listing

-Observations

-Summer 2013 – Data taken aboard the Scarlett Isabella, June to August 2013 in Maryland Wind Energy Area

Directory: LaCie/sftpusers/campaign_wea2013/umbc_measurements – See table.

CTD Sea Surface Temperature, Wind and Aerosol Lidar, Temperature/Pressure/Humidity Sensors, Radiometer, Radiosondes, INU motion data

-Historical – Data taken by outside sources during Summer 2013 and previous years

Directory: LaCie/sftpusers/campaign_wea2013 – See table

Satellite Imagery, Buoys, Synthetic Aperture Radar (SAR), Meteorological Assimilation Data Ingest System (MADIS) – data from ground stations, aircraft, satellites across entire U.S., Moderate-resolution Imaging Spectroradiometer (MODIS) Satellite, NASA Overfly

-Models

-Weather Research and Forecasting (WRF) Model Simulations

Directory: LaCie/wrf - See table

Simulations for week of July 18, 2013 during Low Level Jet event in MD WEA. Simulations carried out with a variety of forecast models.

-Reanalysis – Forecast Model Data for 2013 and 2014 for different models of different resolutions and parameters

Directory: LaCie/model_data, LaCie/nwp_data, LaCie/sftpusers/dataAnalysis – See table

Raw data from North American Mesoscale (NAM), Rapid Refresh (RAP), High-Resolution Window (HIRESW), and Real-Time Mesoscale Forecast (RTMA) models for 2013 and 2014.

Comparisons between forecast models and wind profilers/observations for 2013. Probability Distribution Functions for wind speeds at various locations in Maryland in 2013.

LaCie/sftpusers/campaign_wea2013/umbc_measurements/data_level-0

Directory Name	Measurements	Location	Dates	Description
CTD	SST	MD WEA	7/5 - 8/22, 2013 (sporadic)	Taken to depths of 20-25 meters by CBI on campaign
EasyLogger	T, RH, DP	MD WEA	6/30, 7/1, 7/2 2013	Data sensor used by UMBC on SI
elastic_lidar	WSPD, WDIR	MD WEA	6/24 – 8/14, 2013	Raw data from Leosphere Lidar aboard SI
INU	LAT, LON, Velocity, Heading, Pitch, Roll, etc.	MD WEA	7/8 – 8/20, 2013 (sporadic)	Raw data about SI's orientation along the campaign
Anemometer	WSPD, WDIR	MD WEA	8/20, 2013	Used one day during campaign for comparison data
Photos	Actual photos	MD WEA	Summer 2013	Various photos taken during the campaign showing location of sensors and SI layout
MicroLite	T	MD WEA	7/24 – 8/26, 2013	Approximately 1 meter above sea level
OMCP	T, RH, P	MD WEA	7/26 – 8/26, 2013	Approximately 6 meters above sea level
microstation	T	MD WEA	8/19 – 8/31 (sporadic)	
radiometer	T, WVMR, P	MD WEA	7/26 – 8/29	Profiles taken up to 10km
radiosonde	T, RH, P	MD WEA	8/16, 8/18, 8/29 – 8/31	Radiosondes released on board the SI at the end of campaign, profiles up to 20km
videos	Actual videos	MD WEA	Summer 2013	Various videos taken during the campaign on SI
windcube	WSPD, WDIR	MD WEA	6/29 – 8/30, 2013	Raw Data taken from Leosphere Windcube, corrected for motion (uncorrected available too)

LaCie/sftpusers/campaign_wea2013/umbc_measurements/data_level-1

Directory Name	Measurements	Location	Dates	Description
CBI IMU	LAT, LON, Velocity, Heading, Pitch, Roll, etc.	MD WEA	7/8 – 8/20, 2013 (sporadic)	Processed IMU data
WindLIDAR	WSPD, WDIR	MD WEA	7/18 – 8/3, 2013	Processed and Corrected wind lidar data

LaCie/sftpusers/campaign_wea2013/

Directory Name	Measurements	Location	Dates	Description
sfc_analysis/lrgnamsfc	Isobars, various T, P	U.S.	6/1 – 9/3, 2013	Surface Analysis satellite images
sfc_analysis/ussatsfc	Isobars, various T, P	U.S.	6/1 – 8/31, 2013	Surface Analysis satellite images
satellite_imgs/GOES_imgs/[dates]	Infrared Black and White Images, Infrared Color Images, and Visual Images from satellites	CONUS – Entire Continental U.S. and regional data focused around ALB (Albany, NY), BWI (Baltimore, MD), CLT (Charlotte, NC), DTW (Detroit, MI), MGM (Montgomery, AL)	7/29 – 9/3, 2013	Images from NOAA Geostationary satellites
satellite_imgs/ Satelllite_Wind_Retrievals_1	25KM WSPD	MD WEA	7/19 –	Retrieved from

Directory Name	Measurements	Location	Dates	Description
9-21jul_2013_MEA	and WDIR	and surrounding area	7/21, 2013 at various times	satellite
satellite_imgs/sst	SST	MD WEA and surrounding area	6/19 – 8/31, 2013 at various hourly intervals	Retrieved from satellite, Rutgers Coastal Ocean Observation Lab
madis_data/LDAD/crn	DP, RH, Q, DPD, AH, WVMR, T, TV, WSPD, WDIR, ELEV, LAT, LON, PRECIP, SOIL, GUST	U.S.	6/1 – 9/3, 2013	Meteorological Surface Dataset – Climate Reference Network
madis_data/LDAD/hcn	T, WSPD, WDIR, GUST, ELEV, LAT, LON, PRECIP	U.S.	6/1 – 9/3, 2013	Meteorological Surface Dataset – U.S. Historical Climatology Network
madis_data/LDAD/hydro	PRECIP, ELEV, LAT, LON	U.S.	6/1 – 9/3, 2013	Hydrological Surface
madis_data/LDAD/mesonet	DP, RH, Q, DPD, AH, WVMR, P, T, TV, WDIR, WSPD, VIS, ELEV, LAT, LON, PRECIP, SOIL, RAD	U.S.	6/1 – 9/3, 2013	Meteorological Surface Dataset - mesonet
madis_data/LDAD/nepp	WSPD, WDIR, GUST, ELEV, LAT, LON	U.S.	6/1 – 9/3, 2013	Meteorological Surface Dataset – New England Pilot Project
madis_data/LDAD/profiler	WDIR, WSPD, TV, HT, P	U.S.	6/1 – 9/3, 2013	Multi-Agency Profiler Dataset
madis_data/LDAD/WISDOM	WDIR, WSPD, HT, P, LAT,	U.S.	6/1 – 9/3,	WISDOM Balloon Wind

Directory Name	Measurements	Location	Dates	Description
	LON, T, RH		2013	Dataset
madis_data/point/acars	WDIR, WSPD, T, TV, DP, RH, Q, DPD, AH, WVMR, P, LAT, LON	U.S.	6/1 – 9/3, 2013	Aircraft Communications and Reporting System
madis_data/point/acarsProfiles	WDIR, WSPD, T, TV, DP, RH, DPD, AH, WVMR, HT, P, LAT, LON	U.S.	6/1 – 9/3, 2013	Aircraft Communications and Reporting System - Profiles
madis_data/point/HDW	WDIR, WSPD, PHT	U.S.	6/1 – 9/3, 2013	Satellite Wind – GOES retrieval
madis_data/point/HDW1h	WDIR, WSPD, PHT	U.S.	6/1 – 9/3, 2013	Satellite Wind – GOES retrieval, hourly
madis_data/point/maritime	DP, RH, Q, DPD, AH, HT, WVMR, P, T, TV, WDIR, WSPD, VIS, ELEV, LAT, LON, PRECIP, CLOUD, GUST, TWB	U.S.	6/1 – 9/3, 2013	Meteorological Surface Dataset – Maritime – Coastal Marine Automated Network, fixed/drifting buoys, ship reports
madis_data/point/metar	DP, RH, Q, DPD, AH, HT, WVMR, P, T, TV, WDIR, WSPD, VIS, ELEV, LAT, LON, PRECIP, GUST	U.S.	6/1 – 9/3, 2013	Standard METAR (surface observations) from Automated Surface/Weather Observing Systems, and non-automated stations
madis_data/point/POES	RAD	U.S.	6/1 – 9/3, 2013	NOAA Polar Orbital Environmental Satellites
madis_data/point/profiler	WDIR, WSPD, HT, P	U.S.	6/1 – 9/3,	NOAA Profiler Network

Directory Name	Measurements	Location	Dates	Description
			2013	
madis_data/point/radiometer	T, TV, DP, RH, Q, AH, WVMR, P, HT, CLOUD	U.S.	6/1 – 9/3, 2013	Radiometer data
madis_data/point/raob	WDIR, WSPD, T, TV, DP, RH, Q, DPD, AH, WVMR, P, HT	U.S.	6/1 – 9/3, 2013	Radiosonde data
madis_data/point/sao	DP, RH, Q, DPD, AH, HT, WVMR, P, T, TV, WDIR, WSPD, VIS, ELEV, LAT, LON, PRECIP, GUST	U.S.	6/1 – 9/3, 2013	Canadian stations
madis_data/point/satrad	RAD	U.S.	6/1 – 9/3, 2013	Satellite radiance
MODIS/Aqua	CLOUD	U.S.	Summer 2013	Data from AQUA satellite, as a part of MODIS data product.
MODIS/Level2_CloudProduct	CLOUD	U.S.	Summer 2013	Part of MODIS data product.
NASA_LRC/2013-06-24	WSPD, WDIR	MD WEA	6/24, 2013	NASA Overfly data during summer campaign
NASA_LRC/2013-06-26	WSPD, WDIR	MD WEA	6/26, 2013	NASA Overly data during summer campaign
natlDataBuoyCntr	SST, T, WSPD, WDIR, WAVE	Surrounding MD WEA area	6/1 – 8/31, 2013	Buoy data from NDBC. Over 70 buoys of data in surrounding area.
POES	SST	MD WEA	6/20 – 8/30, 2013	One text file of SST from MD WEA throughout the campaign –

Directory Name	Measurements	Location	Dates	Description
				satellite retrieval.
reprocessed_MADIS	All MADIS data	U.S.	6/1 – 9/3, 2013	MADIS files run through the MADIS API and put into text format.
SAR_data	Synthetic Aperture Radar	U.S.	2012 – 2013	Provides data about the Earth's surface, can 'see' through darkness/clouds/rain.

LaCie/sftpusers/campaign_HughSharp2013

Directory Name	Measurements	Location	Dates	Description
level0/fourtec	T	Hugh Sharp campaign	10/18 – 10/28, 2013	Temperature sensor aboard the ship, same one as in MD WEA campaign.
level0/OMCP	T, RH, P	Hugh Sharp campaign	10/18 – 10/28, 2013	Sensor aboard the ship, same as in MD WEA campaign.
level0/RadiometerData	T, WVMR, P	Hugh Sharp campaign	10/30 – 11/5, 2013	Same radiometer as MD WEA campaign.
motion_data	Motion/orientation	Hugh Sharp campaign	10/18 – 10/28, 2013	Motion data from ship.

LaCie/sftpusers/dataAnalysis/scott

Directory Name	Measurements	Location	Dates	Description
nam-218/monthlyForecastPlotsonHeights	WSPD, WDIR, WVMR, P, T (plots)	MD WEA	5/2013 – 1/2014	Color plots showing forecast given by NAM for a variety of forecast times.
nam-218/WindDistributions	WSPD (plots)	MD WEA, Beltsville, Horn Point	2013	Probability Distribution Functions of Wind Speed at Various Heights for different seasons of 2013 at different locations.
profilerPlots	WSPD, WDIR (plots)	Beltsville, Horn Point, Piney Run	2013	Data from wind profilers, 7 day plots showing wind speed and wind direction.
RapNamNarr_modelComparisons	WSPD, WDIR (plots)	Beltsville, Horn Point (comparison)	2013	Comparisons between NAM, RAP, and NARR forecasts with data from Beltsville and Horn Point Profilers. Color plots.
wrfRuns	T, WSPD, WDIR, REFL,	MD WEA and	7/18 – 7/19	WRF run output plots

Directory Name	Measurements	Location	Dates	Description
	WVMR, BVF, HDIV, PV (plots)	surrounding area		showing reflectivity, temperature, wind speed, and wind temperature in MD WEA region during LLJ event. Maps and cross sectional profile plots.

LaCie and LaCie2

Directory Name	Measurements	Location	Dates	Description
model_data/nam	North American Mesoscale Model files (grib2)	U.S.	2013	12km horizontal resolution with 1 hour temporal resolution
nwp_data/hiresw	High-Resolution Window Forecast Model	East U.S.	2014	4km resolution
nwp_data/nam	North American Mesoscale Model	U.S.	2014	Grid 190 – Native at 12km resolution Grid 227 – U.S. at 5km resolution
nwp_data/rap	Rapid Refresh Forecast Model	U.S.	2014	Grid 130 - 13km resolution, 50 vertical levels
nwp_data/rtma	Real-Time Mesoscale Analysis Forecast Model	U.S.	2014	Grid 184 – 2.5km resolution

LaCie/wrf/dom12km_2nest_cfg01/CS_20130718-25

Directory Name	Measurements	Location	Dates	Description
littler_obs	MADIS data	MD WEA	7/18 – 7/25, 2013	MADIS data in littler format for use with WRF.
wrf_cfsrr_6hrly_lev-69_fddaD01All_v1	WRF output files	MD WEA	7/18 – 7/25, 2013	Climate Forecast System Reanalysis with FDDA nudging
wrf_era-pl_6hrly_lev-69_fddaD01All_v1	WRF output files	MD WEA	7/18 – 7/25, 2013	European Center for Medium Range Weather Forecast Reanalysis with FDDA nudging
wrf_nam-all_6hrly_lev-69_fddaD01All_v1	WRF output files	MD WEA	7/18 – 7/25, 2013	North American Mesoscale Model with FDDA nudging
wrf_nam-all_6hrly_lev-69_v1	WRF output files	MD WEA	7/18 – 7/25, 2013	North American Mesoscale Model with no nudging
wrf_narr_3hrly_lev-69_fddaD01All_v1	WRF output files	MD WEA	7/18 – 7/25, 2013	North American Regional Reanalysis with FDDA nudging
wrf_rapHyb+namSoil_1hrly_lev-69_fddaD01All_v1	WRF output files	MD WEA	7/18 – 7/25, 2013	Rapid Refresh Model with

Directory Name	Measurements	Location	Dates	Description
				FDDA nudging
wrf_rapHyb+namSoil_1hrly_lev-69_fddaD01noPBL_v1	WRF output files	MD WEA	7/18 – 7/25, 2013	Rapid Refresh Model with FDDA nudging, no planetary boundary layer
wrf_rapHyb+namSoil_1hrly_lev-69_v1	WRF output files	MD WEA	7/18 – 7/25, 2013	Rapid Refresh Model with no nudging

Key:
AH = Absolute Humidity
BVF = Brunt-Vaisala Frequency
CLOUD = Cloud Level/Type
DP = Dew Point
DPD = Dew Point Depression
ELEV = Elevation
GUST = Wind Gust
HDIV = Horizontal Divergence
HT = Geometric Height
P = Pressure
PHT = Pressure Height
PRECIP = Precipitation
PV = Potential Vorticity
Q = Specific Humidity
RAD = Radiation/Radiance
REFL = Reflectivity
RH = Relative Humidity
SI = Scarlet Isabella
SOIL = Soil
SST = Sea Surface Temperature
T = Air Temperature
TV = Virtual Temperature
TWB = Wet Bulb Temperature
VIS = Visibility
WAVE = Wave Height/Period data
WDIR = Wind Direction
WSPD = Wind Speed
WVMR = Water Vapor Mixing Ratio