FINAL REPORT

EVALUATION OF NEW JERSEY'S OFFSHORE WIND RESOURCES:

Atmospheric/Oceanic Modeling and Analyses to Support the Offshore Wind Energy Development Process as Defined in New Jersey's Offshore Wind Economic Development Act (OWEDA)

NJ Offshore Wind Energy *Phase III* Final Report for the Period 24 Jun 2014-23 Jun 2015

Prepared for:

State of New Jersey
New Jersey Board of Public Utilities (NJBPU),
Division of Economic Development & Energy Policy and the Office of Clean Energy

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SYNOPSIS

Advanced NJ Offshore Wind Resource Assessment and Wind Turbine Array Parameterization

Introduction

The study described in this report is the third (*Phase III*) in a series of modeling and monitoring assessments of New Jersey's offshore wind resource. These studies were conducted by the Rutgers Department of Marine and Coastal Sciences (DMCS), Center for Ocean Observation Leadership (RU-COOL) with funding support provided by the New Jersey Board of Public Utilities (NJBPU), Clean Energy Program (CEP). The innovative oceanic and atmospheric modeling programs described herein are intended to enhance our understanding of New Jersey's offshore wind resource characteristics along with associated wind energy capacity capabilities relative to the BOEM NJ WEA (Wind Energy Area). Therefore, the RU-COOL modeling/monitoring programs were devised with the intent to ensure that New Jersey's coastal and offshore resources are developed in a responsible and cost-effective manner.

Rutgers DMCS, RU-COOL Modeling/Monitoring Program

The Weather Research and Forecasting (WRF) model, which is accepted by most government, agencies, the military, academic institutions, and private industry, is used as the basis for the RU-COOL high-resolution modeling routines (RU-WRF). The RU-WRF model is designed primarily for analyzing and forecasting the specific characteristics of New Jersey's coastal/offshore wind resources. The RU-WRF model, which was utilized throughout all three phases of our offshore wind resource study, incorporates both atmospheric and oceanic parameters that enable us to more fully understand the entire spectrum of phenomena that control New Jersey's offshore wind resource. We have demonstrated that the RU-WRF model provides representative wind resource assessments that are sensitive to the physical processes and geographical configurations unique to New Jersey's coastal/offshore areas. Therefore, our modeling efforts account for the influence of the sea breeze circulation and coastal storms on the offshore wind resource flow properties and subsequent potential power production. The following innovative technologies and procedures were either incorporated into or combined with the RU-WRF model to improve the realism and accuracy of the model results:

- ***"De-Clouded" IR Satellite Detected Sea Surface Temperatures (SSTs)*:** SSTs have been determined to be the most significant variable for determining the degree of energy exchange between the sea/air interface and therefore are considered to be one of the most significant parameters for defining offshore wind resource properties. Therefore, RU-COOL derived the de-clouded algorithm to "detect" SSTs during both clear and cloudy conditions along with resolving area-specific SSTs including upwelling/non-upwelling centers, which are generally not detected by satellite products currently being used by most organizations and institutions. This unique capability enables us to determine the extent and intensity of sea breeze development associated with both the North and South BOEM Lease Zones along with the resultant impact on offshore wind resource characteristics.

- ***"Virtual" Meteorological Tower (VMT) Wind and Temperature Profiles:*** Based on 3D RU-WRF modeling, an array of several simulated ("Virtual") meteorological towers was established for selected sites within and adjacent to the NJ WEA. Model data from the VMT array produces wind and temperature profiles from near the sea surface to atmospheric heights representative of offshore wind turbine dimensions and beyond (>200m). Rather than installing offshore platforms with "tall" (~100m) met towers or remote-sensing instrumentation at a cost that could exceed $7 million, the VMT concept is very cost-effective for determining wind vector profiles, atmospheric stability, and turbulence properties, which are all pertinent parameters used by the wind energy industry for design applications and operating procedures.

- ***High-resolution "nesting" capability:*** The RU-WRF model is configured for various grid resolutions with the highest resolutions "nested" within the primary spatial domain, which allows the model to provide simulations ranging from the mesoscale ($\geq$ 2km) to the microscale (<2km). This nesting capability enables the model to run at grid resolutions that cover the entire Mid-Atlantic offshore areas along with resolving the local flow patterns (e.g., the sea breeze circulation) that affect the wind resource associated with specific offshore areas such as the NJ WEA.

- ***RU-Model "Verification":*** RU-WRF model performance is evaluated on a continuing basis using comparisons with representative validated coastal and offshore monitoring systems, which include both in-situ instrumentation (e.g., met towers; buoys) and remote-sensing technology (e.g., SODAR; LIDAR). The verification procedure conforms to the criteria accepted by the wind energy industry and NREL's National Wind Technology Center (NWTC).

- ***"Integrated" Resource Planning and Implementation:*** The wind resource data and resultant information could also be used to support integrated resource planning and applications associated with the engineering, environmental, and economic issues that are relevant for offshore wind energy development and subsequent operational procedures. For example, wind resource and potential power production data can be provided to the Rutgers Center for Economic, Energy, and Economic Policy (CEEEP). These data sets can then be used as input into CEEEP's DAYZER energy model to determine impacts on the electrical power grid controlled by the PJM Interconnection and resulting energy revenues that potentially could be realized from proposed offshore wind facilities. The Rutgers RECON model could further project the possible economic impacts in the State resulting from offshore wind development including the effects on the supply chain process and job creation. Additionally, the Rutgers Department of Environmental Sciences (DES) air quality modeling program can convert offshore wind energy production data into equivalent pollutant emissions that would be emitted by conventional fossil fuel power plants. The results of this analysis could then demonstrate the environmental benefits offshore wind energy development, including the substantial reduction in adverse effects associated with health, property, and economic issues. Once implemented, the combined efforts of the integrated modeling program would significantly reduce the "uncertainty" that is inherit with offshore wind energy projects. Consequently, the integrated program will provide a "total picture" of the viability of offshore wind energy development and will therefore help to significantly reduce the "risks" associated with offshore wind energy planning, installation, and operations.

Phase III Offshore Wind Study Objectives

The objectives of the *Phase III* Offshore Wind (OSW) study are summarized as follows:

1) Provide realistic and reliable 3D modeling of New Jersey's offshore wind resource including are-specific simulations of the BOEM NJ WEA, which is the offshore area designated for wind energy development.

2) Resolve flow vectors and trajectories produced by the sea breeze circulation, coastal storms, and other possible perturbations that could spatially and temporally affect New Jersey's offshore wind resource and potential power production, especially during periods of "Peak" energy demand.

3) Estimate the "most" efficient and cost-effective offshore wind turbine array arrangement that will negate the detrimental effects of turbulent wakes among the turbines within the array. Also, other loss factors that cause reductions in energy production will be evaluated.

4) Provide CEEEP with the resultant data sets derived from the DMCS offshore wind resource and potential power production studies defined in the preceding three objectives. CEEEP will then use these data sets and associated information for their energy/engineering and economic models to ascertain the viability of New Jersey's proposed offshore wind energy development projects.

Coastal/Offshore Modeling Results and "Key" Findings

Using a "hypothetical" offshore wind energy facility consisting of 6 MW wind turbines with 100m hub-heights and a total installed capacity of 3000 MW, the Rutgers DMCS offshore wind resource modeling results produced the following "Key" findings. These results should prove relevant for Stakeholders interested in New Jersey's offshore wind energy development activities and, especially, the development endeavors related to the BOEM NJ WEA:

- Wind turbine generator (WTG) hub-heights of ~100m above mean sea level (MSL) appear to be "optimum" for most offshore applications. The suggested hub-height should prove to be very effective for minimizing the adverse impacts of turbulence and wind shear while maximizing WTG performance to ensure reliable and efficient energy production.

- A suggested 10D X 12D (D=WTG rotor diameter) WTG array spacing arrangement should prove to be the "best" array design that will account for New Jersey's unique coastal topography, shoreline configuration, and dynamic offshore wind resource characteristics. The suggested WTG array spacing scenario should assist in alleviating most of the adverse effects attributed to turbulent wakes that occur within a large offshore WTG facility consisting of several WTGs.

- The prevailing wind direction for New Jersey's inland and adjacent coastal areas is from the WSW. However, prevailing offshore winds over the BOEM NJ WEA are from the SSW. Therefore, to ensure that energy production is efficient and reliable, the "ideal" WTG array would be oriented from the Southwesterly sector to the Northeasterly sector. Also, there are significant wind energy contributions when winds are blowing from the Northwesterly and Northeasterly sectors. However, the frequency of occurrence for offshore winds from these sectors is significantly less than the stated prevailing wind direction. Although, the predominant wind sectors and resultant potential power production should be included as important design criteria, it should be realized that wind directions over New Jersey's offshore waters are very variable as a result of frequent air mass exchanges, coastal storm events, and sea breeze occurrences.

- "Short-term" (monthly and diurnal) wind speeds exhibit significant variability. For example, our study shows that monthly wind speeds at the 100m level vary from ~ -20% to +30% respectively below and above the *Norma*l wind speed. Therefore, to reduce the "risks" related to the planning and design process for an offshore wind energy facility, "shot-term" variability in wind speeds should be taken into account. This variability also needs to be considered for efficient and cost-effective operations, especially during periods of "Peak" energy demand. Although, New Jersey's offshore wind resource shows significant variability during "short-term" periods, "long-term" (annual and seasonal) average winds appear to be reasonably consistent. The annual average 100m wind speed (8.43m/s) for the BOEM NJ WEA was derived from hourly data compiled for the entire duration of our OSW project (*Phase I* through *Phase III*; Jul 2011-Jun 2015). Although, the indicated average is slightly below the climatological *Normal* (8.76m/s), New Jersey's offshore wind resource can be considered to be more than adequate for achieving efficient and cost-effective energy production.

- To reduce the "uncertainty" involved with the variability in the wind resource, especially when power is needed during critical periods of "Peak" energy demand, "short-term" local perturbations in the overall offshore wind resource should be resolved and incorporated into the design process, planning protocols, and operational procedures. The most prominent perturbations in New Jersey's offshore wind resource are sea breeze occurrences and coastal storms. Our study shows that there is significantly more temporal and spatial variability in the offshore wind resource during sea breeze events when compared to non-sea breeze occurrences. Consequently, as the offshore component of the sea breeze circulation propagates over all or a portion of the NJ WEA, some WTGs will be producing power while other WTGs will be idle. Similar variability in the offshore wind resource can also be attributed to coastal storms.

    - Frequent sea breeze occurrences generally coincide with the summer season "Primary Peak" energy demand period.

    - Less frequent coastal storms (e.g., *Northeasters*) usually coincide with the winter season "Secondary Peak" energy demand period.

    - Both the sea breeze and coastal storm circulations exhibit significant spatial and temporal variability over the term of their existence.

- As previously stated, the variability in wind direction and speed directly affects the offshore wind resource and subsequently will substantially impact the magnitude and duration of wind power generation produced by individual WTGs located within a large wind energy facility. Consequently, a knowledge of the "cause and effect" concept associated with wind resource variability is necessary to reduce the "risks" associated with WTG array design and individual WTG placement and should therefore be applied to each offshore wind energy facility proposed to be installed within the BOEM NJ WEA.

- The offshore wind resource appears to be similar for both the North and South BOEM NJ Lease Zones. However, wind intensities over the North Zone appear to be somewhat greater when compared to the South Zone. Also, the duration along with the spatial extent of the horizontal and vertical dimensions of the sea breeze circulation is more pronounced over the North Lease Zone when compared to the South Lease Zone. This comparison implies there may be more variability in the North Lease Zone wind resource than potentially encountered in the South Lease Zone. Furthermore, both North and South Lease Zone wind intensities tend to increase from the coast to farther offshore, which is the "typical" case for offshore wind speeds. However, during sea breeze occurrences, winds will generally decrease from the coast to offshore areas where the offshore component of the sea breeze circulation terminates. Winds associated with offshore distances greater than areas affected by the sea breeze circulation will then become more intense. Regarding the BOEM NJ WEA, which extends offshore to ~ 20nm, the sea breeze circulation will have a frequently occurring impact on the offshore wind resource and potential power production, especially during the summer season "Primary Peak" energy demand period. To ensure efficient and cost-effective offshore wind energy facility design and operations, it is suggested that the climatology of area-specific (e.g., BOEM NJ South/North Lease Zones) wind resource characteristics associated with the sea breeze circulation be determined to arrive at a realistic conclusion regarding the variability and resultant impact on the offshore wind resource and resultant potential power production.

- Estimated annual average Net Capacity Factors (NCFs) for assumed 6 MW WTGs arranged in a 10D X 12D array with a total installed capacity of 3000 MW were ~32%. NCFs are dependent on the type and amount of power production losses including turbulent wake effects among individual WTGs. Therefore, offshore wind energy facilities using newly designed more efficient WTGs along with "optimizing" the WTG array spacing arrangement could probably achieve NCFs exceeding 40%. Using the preceding criteria (i.e., 6 MW WTGs, 3000 MW capacity, and 10D X 12D array spacing), the estimated annual energy yield for the entire BOEM NJ WEA would be ~6,124 GWhrs.

- An evaluation of recently developed larger capacity 8 MW WTGs compared to smaller WTGs (e.g., 5 and 6 MW machines) currently used for offshore wind energy applications was conducted for the BOEM NJ WEA. Using the same scenario (i.e., 3000 MW capacity with 10D X 12D array spacing), the "hypothetical" 8 MW WTG facility would have an estimated annual energy yield of ~9,370 GWhrs, which is ~3,000 GWhrs greater than the energy produced by the 6 MW WTGs with the same installed capacity). Resultant average annual NCFs were estimated to be ~36%. Additionally, if the newly designed 8 MW WTGs were selected for installation, it appears that the NJ WEA could accommodate a capacity of ~4000 MW, which is an increase of 1000 MW when compared to the current estimated maximum capacity value being used by both NREL and Rutgers. These results imply that the larger more efficient WTGs will be more cost-effective and overall more viable for forthcoming offshore wind energy installations.

Implications

The Rutgers DMCS modeling results suggest that an understanding of the inherit variability encountered with New Jersey's offshore wind resource resulting from such phenomenon as the sea breeze circulation along with annual average 100m winds being >8.4m/s will enable the BOEM NJ WEA to become very conducive for efficient and economically viable wind power production. Additionally, minimal environmental and maritime constraints along with shallow waters and a bathymetry that has a relatively "gentle" sloping smooth sea floor should enhance the capability for cost-effective offshore wind energy development within the NJ WEA. Furthermore, once the designated BOEM NJ WEA, which encompasses >300,000 acers and extends offshore from ~ 7nm to 20nm, is developed with a potential installed capacity of > 3000 MW, New Jersey's offshore wind facilities should be able to significantly supplement conventional generation load requirements. This implication becomes especially relevant during periods of "Peak" energy demand when offshore wind energy could reduce the current burden put on available energy supply and grid transmission/distribution systems.

Basically, the unique modeling/monitoring program developed by Rutgers DMCS, RU-COOL could probably be considered the most representative and cost-effective method for analyzing and predicting the wind resource parameters that are specific to New Jersey's coastal/offshore areas thus reducing the "risks" and "uncertainty" associated with resource planning and enhancement of societal benefits. Also, public funding provided by NJBPU for the studies performed by Rutgers University, which is the State University, will ensure that all interested Stakeholders can take advantage of the resultant information and data sets that are available online by using the following URL:

http://rucool.marine.rutgers.edu/bpu

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ABSTRACT

In addition to establishing the overall viability of an offshore wind energy project, NJ BPU regulations state that proposed wind energy facilities "shall account for the coincidence between time of wind power generation and peak electricity demand." Extensive data analyses concluded that three primary interactive atmospheric/ocean processes-sea breeze evolution, coastal upwelling development, and coastal storm formation-have a significant impact on NJ's offshore wind resource and related potential wind power production. This impact is most prominent during periods of "Peak" energy demand and could be positive or negative depending on the intensity, duration, and spatial dimensions of the named phenomena relative to the location and size of the proposed wind energy facility. To accommodate the intent of the stated BPU regulations, the effect of the indicated processes on the offshore wind resource, especially during concurrent times of wind power generation and "Peak" energy demand, was evaluated using a specialized configuration of the Weather Research and Forecasting (WRF) model that was derived by RU-COOL specifically for coastal/offshore applications (i.e., the RU-WRF model). Pertinent model features include area-specific high-resolution sea surface temperatures (SSTs) with 1km grid spacing coordinates, high-resolution "nested" grid spacing over the model domain ranging from the microscale (e.g., 0.4 to <2km) to the mescoscale (e.g., 3km to 9km), and boundary layer physics that most realistically represent the offshore wind resource. Along with the high-resolution nesting capability, the model was set-up with initial boundary conditions that define the physical properties of the sea breeze circulation and coastal storm characteristics relevant to NJ's offshore areas designated for wind energy development. Also, verification routines were incorporated into the model, which compare model results with remote-sensing and in-situ monitoring systems that are reflective of the coastal/offshore areas being studied. The monitoring sites were selected for their capability of providing valid data from near surface to heights compatible with offshore wind turbine dimensions and overlying atmospheric levels that affect wind turbine performance (i.e., ~10 >200m above the land and sea surfaces).

In conjunction with the analyses used to determine the offshore wind resource impact caused by sea breeze occurrences and coastal storm events, the RU-WRF model was used to evaluate the overall offshore wind resource associated with the BOEM NJ Wind Energy Area (WEA). Hourly data utilized for both model input and verification were derived from a combination of various monitoring and modeling programs. The resultant data sets were compiled for the most recent four-year period of record (i.e., June 2011-May 2015). Additionally, an investigation was conducted to ascertain whether or not the installation of newly designed 8 MW wind turbines would be more beneficial when compared to wind power generators (e.g., 5 or 6 MW machines) currently used for most offshore wind energy installations. The results of the overall offshore wind resource assessment along with the analyses of specific sea breeze occurrences and coastal storm events are being used as input for engineering and economic models run by the Rutgers University Center for Energy, Economic, and Environmental Policy (RU- CEEEP). The results of these model evaluations will be used to estimate the energy and economic impact of offshore wind energy development, subsequent penetration into the PJM electrical power grid, and O&M activities. Therefore, CEEEP's primary focus will be to evaluate the cost-effectiveness of potential offshore wind energy development projects.

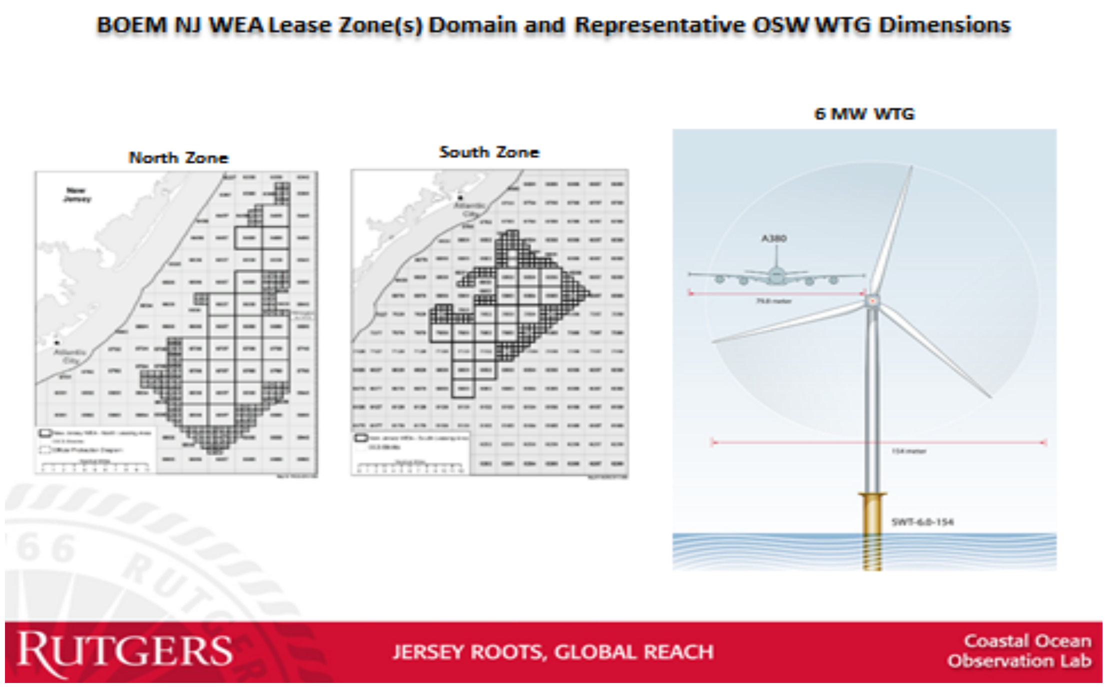
Ongoing and forthcoming studies include the configuration and implementation of a coupled atmosphere/ocean model, which will provide improved capabilities to diagnose the aforementioned coastal/offshore air-sea processes, with the intent of reducing the relevant "risk" inherit with the modeling methodology utilized to support NJ's offshore wind energy initiative. This coupled model could then be "combined" with energy/engineering, environmental, and economic models to more accurately predict the endeavors associated with offshore wind energy facility construction efforts, operational procedures, and maintenance protocols. This proposed innovative "combined" modeling program is unique to NJ and, therefore, NJ can be considered the "leader" in alleviating much of the "uncertainty" associated with determining the technical feasibility and economic viability of offshore wind energy applications.

NJ Offshore Wind Resource Assessment; Wind Power Production Projections

INTRODUTION

The RU Dept. of Marine and Coastal Sciences (DMCS), Center for Ocean Observation Leadership (RU-COOL) has continued their offshore wind (OSW) resource analyses during the period 24 Jun 2014-23 Jun 2015 (*Phase III*). These analyses utilized our high-resolution innovative RU-WRF modeling program. Offshore wind resource modeling simulations for the BOEM NJ WEA along with area-specific simulations of selected sea breeze and coastal storm events were conducted during the *Phase III* period of RU-COOL's OSW studies. Long-term offshore wind resource simulations were modeled at a 3km horizontal grid resolution, the sea breeze occurrences were modeled at 3km (mesoscale) and <2km (microscale) grid resolutions, and a coastal storm event was modeled at a 6km grid resolution. Our modeling experience acquired over the prior OSW studies (i.e., *Phase I* (Glenn and Dunk, 2010) and *Phase II* (Dunk, 2014)) has suggested that the stated resolutions are the most representative for realistically resolving the respective wind flow scenarios. The results of these previous studies along with the current study can be reviewed using the following URL: **http://rucool.marine.rutgers.edu/bpu**

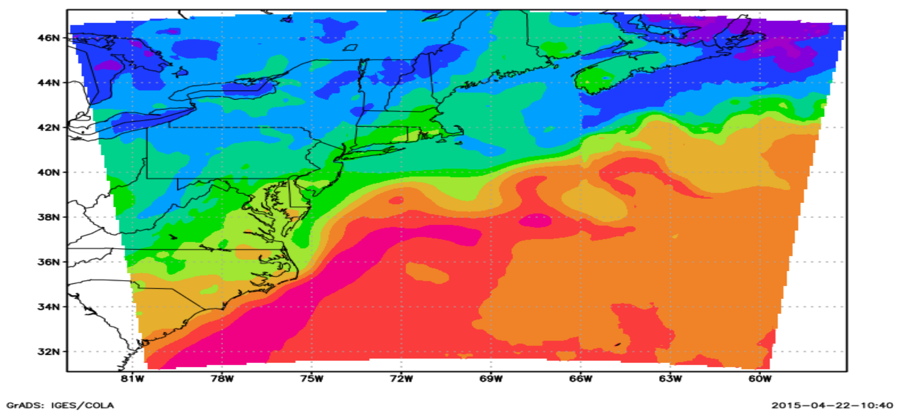
Meteorological parameters used for model input were extracted from the most recent 4-yr period (i.e., June 2011-May 2015) of data compiled from extensive high-resolution daily RU-WRF model runs. These modeling runs incorporated validated monitoring observations obtained from coastal meteorological towers and buoys along with high-resolution sea surface temperatures (SSTs) derived from the unique RU-COOL Infrared (IR) satellite "de-clouded" product. RU-WRF model results for hourly wind resource variables and resultant power production parameters were evaluated for "hypothetical" offshore wind facilities located in both the proposed North and South BOEM NJ WEA Lease Zones. The resultant data sets were provided to the RU Center for Energy, Economic, and Environmental Policy (CEEEP) for input into their energy/engineering and economic models. BOEM NJ WEA lease zone delineations along with representative offshore wind turbine generator (WTG) dimensions used for this study are respectively shown in the following figures:



DISCUSSION

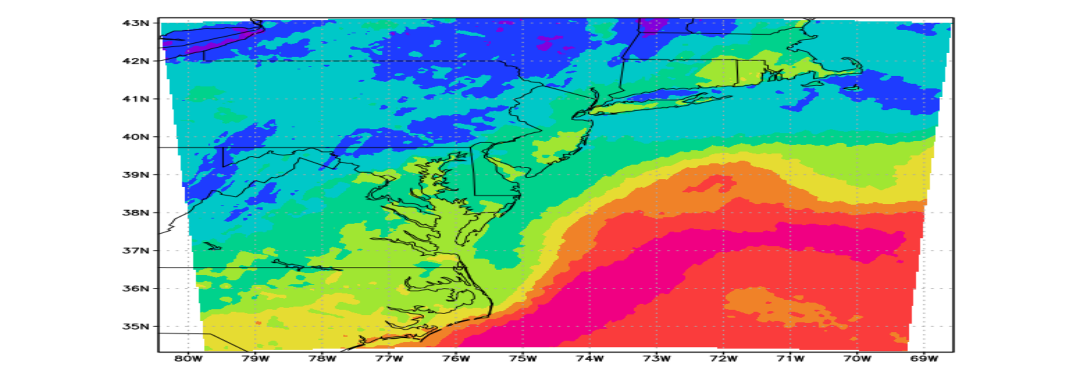
Modeling Methodology

The RU-COOL modeling program is based on the Weather Research and Forecasting (WRF) model Version 3.5.3, which has been configured specifically for offshore applications (i.e., the RU-WRF model). If the latest version of WRF (i.e., Version 3.7) proves to be more applicable for our coastal/offshore studies, we will convert to this new version. Boundary conditions and the physics used to initialize and "drive" the current model were selected to "best" simulate winds along with other relevant meteorological parameters associated with the Marine Atmospheric Boundary Layer (MABL) that extends from sea level upward to ~3km. The RU-WRF model is currently run at 9km, 3km, and 0.4< 2km horizontal grid resolutions. Therefore, the mesoscale (≥2km grid resolutions) model is "nested" to run at microscale (<2km grid resolutions) to resolve the local wind circulations that cause perturbations within the general flow patterns of the offshore wind resource. The area modeled at the 9km resolution is considered the *external* modeling domain, which is used to set initial boundary conditions for the higher resolution model runs. The 9km modeling domain is depicted in the following map:



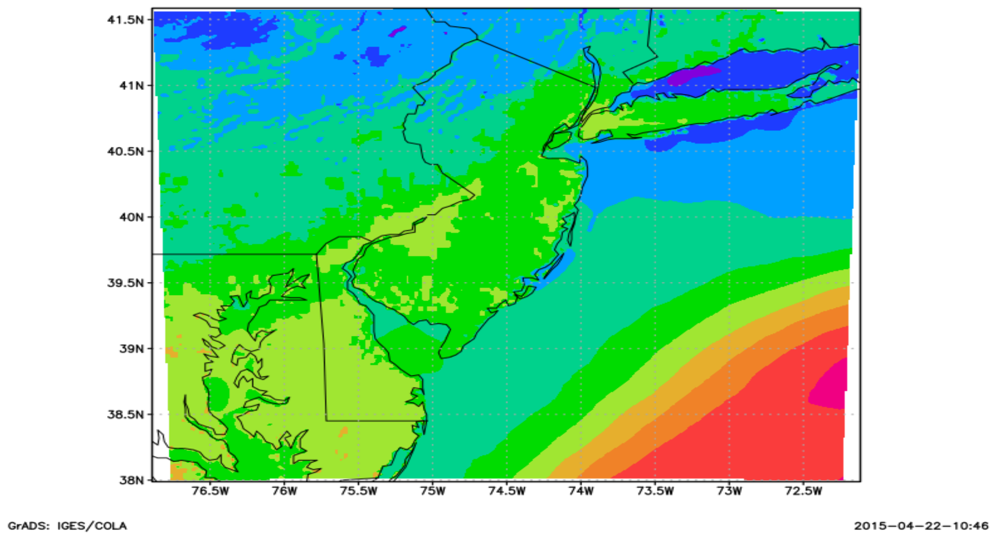
9km grid resolution mesoscale *External* modeling domain

The RU-WRF model is run at a 3km grid resolution for the *internal* modeling domain, which encompasses offshore/inland regions adjacent to and within the BOEM NJ WEA. The *internal* modeling domain extends from Cape Cod, MA southward to Cape Hatteras, NC and eastward to ~100nm offshore. Boundary conditions for the 3km RU-WRF model runs are updated every hour utilizing the NCEP Rapid Refresh (RAP) assimilation/modeling system. The 3km *internal* modeling domain is shown in the below map.



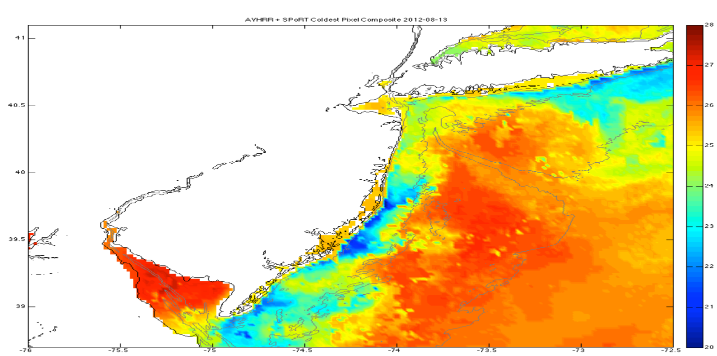
3km grid resolution mesoscale *Internal* modeling domain

The results of the 3km model runs are then used to set boundary conditions for high-resolution (0.4< 2km) model simulations configured specifically for the local offshore areas designated for NJ's wind energy development initiative (i.e., the BOEM NJ WEA). The *local* modeling domain is depicted in the following image:



0.4 < 2km grid resolution microscale *Local* modeling domain

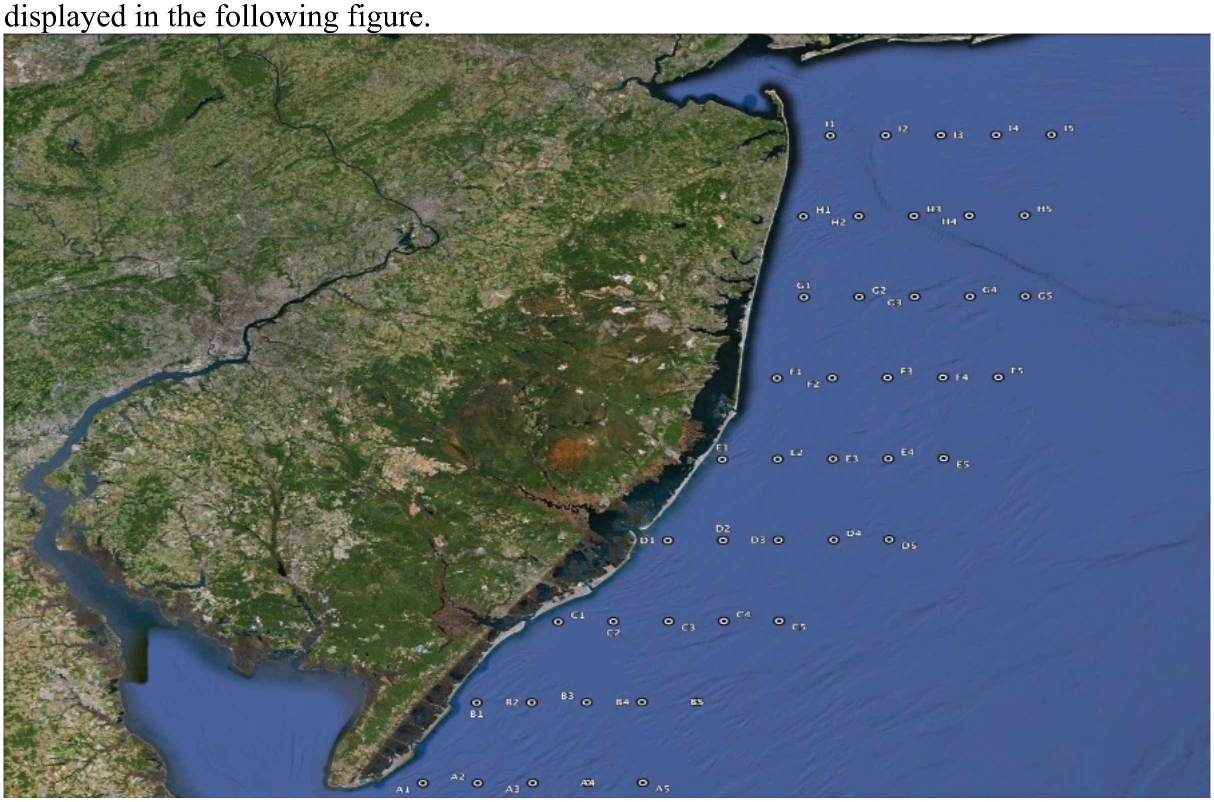
Since sea surface temperature (SST) is the primary parameter that "dictates" the magnitude of energy exchange between the ocean and overlying atmosphere. Temperature differences between the air/sea interface along with adjacent terrestrial temperatures and resultant vertical/horizontal temperature gradients will significantly influence the characteristics of the offshore wind resource. Consequently, representative SSTs are considered to be a critical RU-WRF model input parameter for both diagnostic and predictive applications. Therefore, RU-COOL has developed a new algorithm, which includes visible reflectivity, to differentiate between cloudy and clear conditions associated with IR Satellite detection of SSTs. Therefore, SST can be "detected" during cloudy conditions, which will minimize missing data experienced with conventional low resolution satellite SST detection technology. This high-resolution product, which uses a "dynamic" rather than a "static" ocean commonly used in most mesoscale modeling programs, resolves coastal upwelling centers that are not normally detected with current methods. An example of this unique product is provided in the proceeding image:



Satellite SST imagery derived from the RU-COOL De-Clouded Product/SPoRT Composite showing coastal upwelling (colder temperatures (dark blue) near the central/southern NJ shoreline with warmer temperatures (yellow to red) detected farther offshore.

The new algorithm described on the previous page has been tested and verified using actual SST measurements acquired from monitoring buoys and autonomous underwater vehicle (AUV) instrumentation. This SST detection procedure, which has never been used by any other institution or organization, is unique to our modeling program. Furthermore, the new "de-clouded" product has been automated for RU-WRF model input and appears to enhance model accuracy and overall performance.

RU-WRF modeling simulations for the 3km mesoscale and 0.4<2km microscale domains will focus on the BOEM NJ WEA offshore wind resource. Since meteorological monitoring data is limited for these offshore areas, we utilized the innovative concept of "Virtual" Meteorological Towers (VMTs). Rather than installing one or two offshore meteorological tower(s) at a cost that can exceed $7 million per tower installation and instrumentation, the VMT concept is very cost-effective for analyzing wind vector profiles along with other parameters that are pertinent to the offshore wind energy industry. The VMTs were positioned as a strategic 9X5 monitoring array (i.e., a total of 45 "hypothetical" met towers), which will account for NJ's offshore wind resource characteristics that are relevant for wind energy development. Wind profiles determined from the VMTs were derived for 10m incremental atmospheric heights that extend from 10m above Mean Sea Level (MSL) to 150m. These incremental heights were selected to coincide with the dimensions (i.e., hub and blade tip heights) of offshore WTGs. Atmospheric heights above 150m to >1km are also modeled with larger increments to include any effects that air layers above the WTGs would have on the underlying wind resource. Therefore, the simulated model outputs for the VMTs will provide substantially more representative information at a fraction of the cost associated with physical towers or buoy mounted remote-sensing instrumentation. The VMT array that was used for the RU-WRF modeling program is displayed in the following figure.

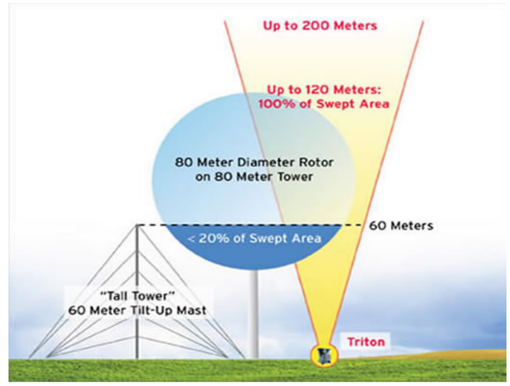


"Virtual" Meteorological Tower array positioned offshore from the coast of NJ

Monitoring Methods

In-situ and remote-sensing monitoring methods were used for RU-WRF model input and also to verify model results. Primary model support was acquired from the Rutgers Tuckerton Atmospheric Monitoring Station. The Tuckerton site includes a fully instrumented 12m meteorological tower and a sound detection and ranging (SODAR) system to monitor winds up to heights of > 200m*.

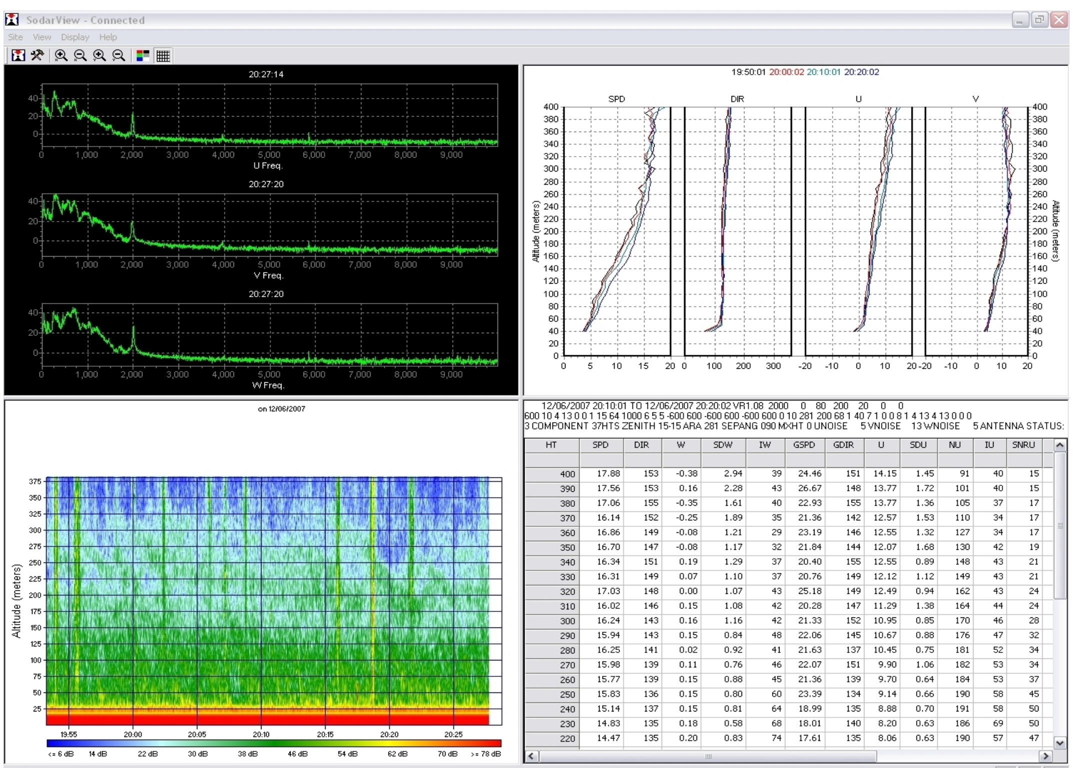
Rutgers Tuckerton Meteorological Tower



Rutgers Tuckerton SODAR System

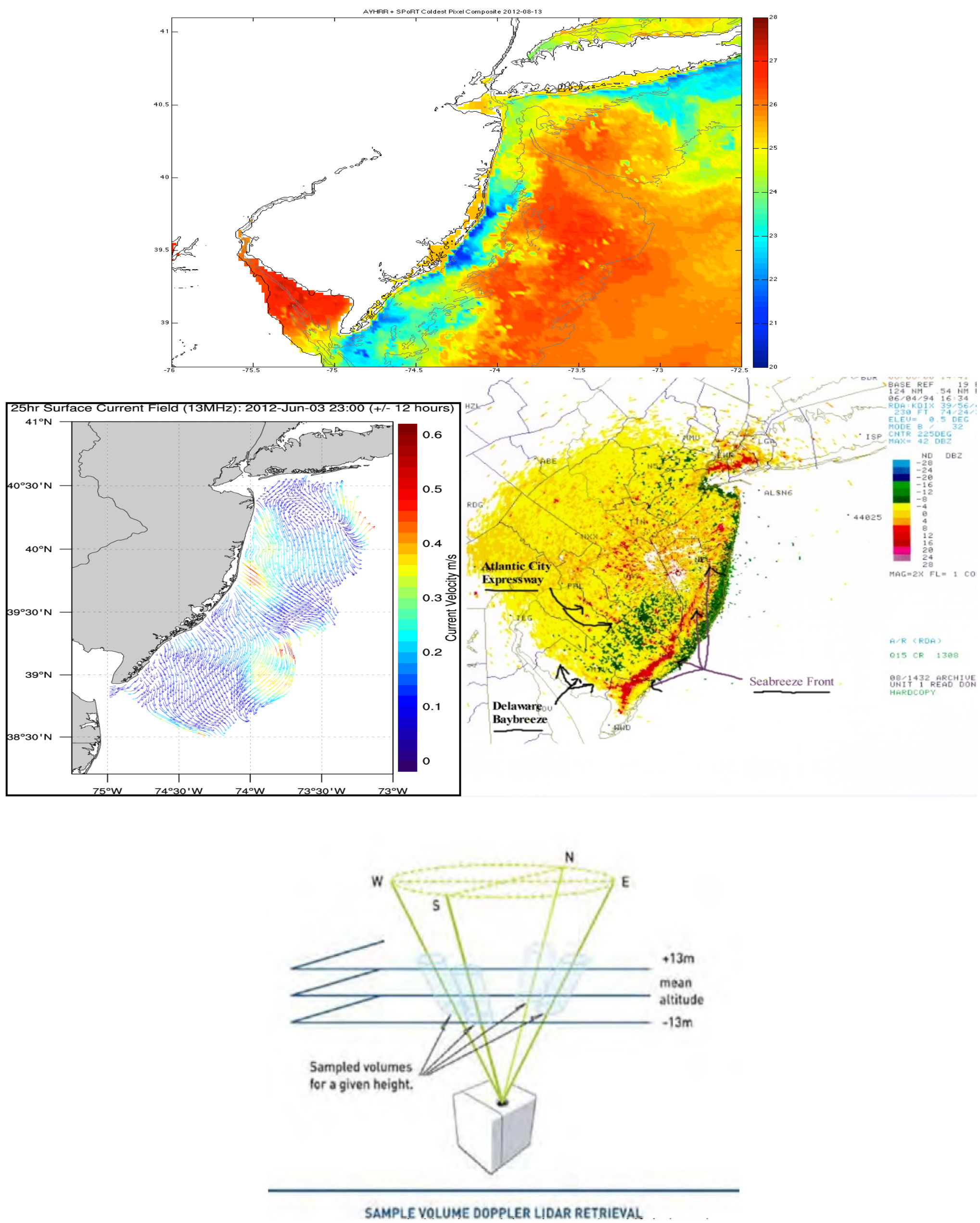
Output from the Tuckerton Station instrumentation was automated to provide real-time data transfer (Tower and SODAR) for model input. The tower and SODAR data are available on the website: **http://rucool.marine.rutgers.edu/bpu-windspeed**

***The 200m height is used as the height that covers the vertical dimensions (hub and blade tip heights) of a typical OSW WTG.**



Example SODAR Data Output Showing Wind Velocity Profiles that extend from ~40m to > 200m

Model support was also obtained from other available monitoring sites, which included coastal meteorological towers and offshore buoys/monitoring platforms. Additionally, IR Satellite, Wx RADAR, CODAR, and LIDAR systems were utilized to enhance model input and verification programs. Furthermore, these data sets were considered to be representative for the offshore wind resource associated with both NJ State Waters and the BOEM NJ WEA. The remote-sensing systems, which have improved the accuracy and reliability of the RU-WRF modeling program, are displayed in the following images:



Respective remote-sensing systems used to support the RU-WRF Modeling Program: IR Satellite (SST Detection), Coastal RADAR (CODAR) (sea surface currents/sfc wind detection), Wx RADAR (sea breeze “front” detection), and LIDAR (wind/turbulence profile monitoring).

RESULTS

Overall Coastal/Offshore Wind Resource Modeling Results

Offshore wind resource characteristics can be attributed to MABL dynamics, which include the effects of turbulence intensity, wind shear, and atmospheric stability. Depending on the convective properties of the air above MSL and resultant atmospheric stability, the MABL can extend to near 3km. Therefore, when considering the dimensions of offshore WTGs, WTG structural integrity, and wind power generation efficiencies, the overall performance of offshore WTG arrays will be affected by the physical characteristics and associated dynamics of the MABL. Wind shear values, which are dimensionless, are calculated using the formula accepted by the wind energy industry. The wind shear formula is defined by the equation:

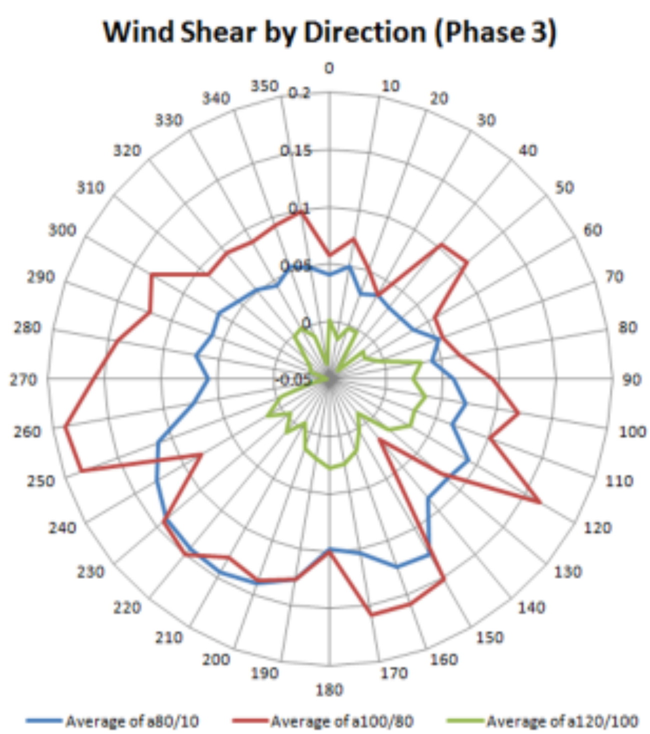
Wind Shear Formula (Power law)

The wind speed at a certain height above ground level is:

$$U=U_{ref}(z/z_{ref})\alpha$$

Where, U and U_{ref} are the mean wind speeds at the heights z and z_{ref}. The assumption of a normal wind profile or the power law relation is a common approach used in the wind energy industry to estimate the wind speed U at a higher elevation (z) using tower measurements (e.g., usually at 10m) or representative modeling of wind speeds (U_{ref}) at a selected reference height (z_{ref}). The shear exponent (α) is defined as the wind shear value.

The following figure graphically depicts the average MABL wind shear at heights between 10m and 80m, between 80m and 100m, and between 100m and 120m:



The data presented in the preceding graphic provide pertinent information regarding offshore wind shear characteristics that are associated with WTG dimensions (i.e., hub and blade tip heights). This information is summarized in the below bullet items:

- Wind shear is dependent on wind direction and height above the sea surface and appears to be bimodal: Wind shear is greatest during southwesterly winds with wind directions ranging from WSW to SSW; Wind shear is also relatively high when winds are from the ESE to SSE. Note that there are also slight peaks in wind shear when winds are from the NNE to NE.

- Wind shear between 80m and 100m is greater than the other two incremental heights that were analyzed during this study with shear values ranging from ~+0.05 to ~+0.15.

- Wind shear above 100m, which is based on data acquired during *Phase III* of the OSW project, is minimal ranging from -0.05 to ~+0.04.

- Most offshore wind shear values (e.g., <<0.2) are significantly less than wind shear values observed over inland areas. Inland wind shear values of >0.2 are considered to be "typical" as being dependent on atmospheric conditions and underlying terrain features that determine surface "roughness" characteristics. Also, it can be assumed that lower wind shear values observed over the ocean indicate that under normal conditions minimal turbulence production will occur within the MABL.

Based on the previous findings related to offshore wind shear and related wind speed profiles estimated to occur over the BOEM NJ WEA, it can be reasonably concluded that the 100m hub height above mean sea level (MSL) is close to "optimum" for offshore applications. Therefore, the 100m WTG hub height was considered to be the most representative for the RU-WRF modeling procedures that produced the results contained in this report. Average hourly, monthly, and annual offshore wind speeds that will "drive" WTGs, which will potentially be installed within the BOEM NJ WEA are summarized in the following table:

Project Average													
HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	AVG
00 - 01	10.16	9.80	9.65	9.91	9.43	8.59	8.87	7.01	6.86	8.29	9.24	9.09	8.90
01 - 02	9.98	9.68	9.49	9.84	9.33	8.23	8.62	6.82	6.86	8.46	9.30	9.06	8.80
02 - 03	9.97	9.56	9.34	9.84	9.23	7.87	8.51	6.70	6.82	8.79	9.47	9.23	8.77
03 - 04	9.89	9.59	9.47	9.78	9.23	7.83	8.41	6.76	6.97	8.98	9.57	9.35	8.82
04 - 05	9.98	9.53	9.55	9.81	9.19	7.77	8.20	6.78	7.01	9.17	9.62	9.40	8.83
05 - 06	10.01	9.44	9.56	9.88	9.20	7.62	7.97	6.75	7.05	9.10	9.59	9.39	8.79
06 - 07	10.10	9.42	9.67	9.85	9.09	7.60	7.78	6.79	7.10	9.16	9.54	9.35	8.78
07 - 08	10.01	9.39	9.73	9.59	9.16	7.54	7.52	6.69	6.99	9.04	9.40	9.31	8.69
08 - 09	10.00	9.50	9.74	9.37	8.94	7.35	7.32	6.64	6.88	8.80	9.23	9.26	8.58
09 - 10	10.02	9.67	9.77	9.31	8.89	7.23	7.12	6.50	6.72	8.54	9.04	9.18	8.49
10 - 11	10.28	9.84	9.85	9.29	8.67	7.08	6.99	6.28	6.54	8.19	9.00	9.04	8.41
11 - 12	10.35	10.07	9.91	9.26	8.32	7.06	6.87	6.28	6.49	8.01	8.91	8.99	8.37
12 - 13	10.26	10.28	9.97	9.27	8.19	6.72	6.80	6.18	6.45	7.88	8.81	8.93	8.30
13 - 14	10.25	10.33	10.07	9.18	8.06	6.44	6.53	6.01	6.41	7.80	8.68	8.97	8.22
14 - 15	10.35	10.29	9.78	9.00	7.80	6.18	6.28	5.90	6.31	7.59	8.72	8.88	8.08
15 - 16	10.26	10.08	9.64	8.77	7.49	5.86	6.10	5.64	6.21	7.34	8.60	8.73	7.88
16 - 17	9.70	9.73	9.51	8.50	7.22	5.72	5.94	5.31	6.04	7.26	8.40	8.73	7.66
17 - 18	9.33	9.48	9.13	8.28	7.52	5.99	6.12	5.32	5.91	7.23	8.32	8.64	7.59
18 - 19	9.14	9.28	9.18	8.40	8.18	6.55	6.53	5.45	5.90	7.29	8.26	8.65	7.73
19 - 20	9.31	9.34	9.23	8.56	8.74	7.31	7.32	5.83	5.99	7.57	8.32	8.69	8.01
20 - 21	9.57	9.37	9.35	9.03	9.24	7.78	8.03	6.24	6.15	7.75	8.44	8.73	8.30
21 - 22	9.77	9.56	9.68	9.47	9.35	8.17	8.40	6.65	6.37	7.96	8.65	8.92	8.57
22 - 23	9.91	9.62	9.83	9.58	9.68	8.41	8.73	6.92	6.59	8.10	8.87	9.04	8.77
23 - 24	10.15	9.62	10.03	9.81	9.82	8.53	8.93	7.09	6.73	8.13	9.14	9.10	8.92
AVG	9.95	9.69	9.63	9.31	8.75	7.31	7.49	6.35	6.56	8.18	8.96	9.03	8.43

Average wind speeds at 100m above MSL for the BOEM NJ WEA (Jun 2011-May 2015).

Using the wind resource data compiled during the *Phase III* study period, an analysis of wind speed provided in the preceding table produced the following statistics:

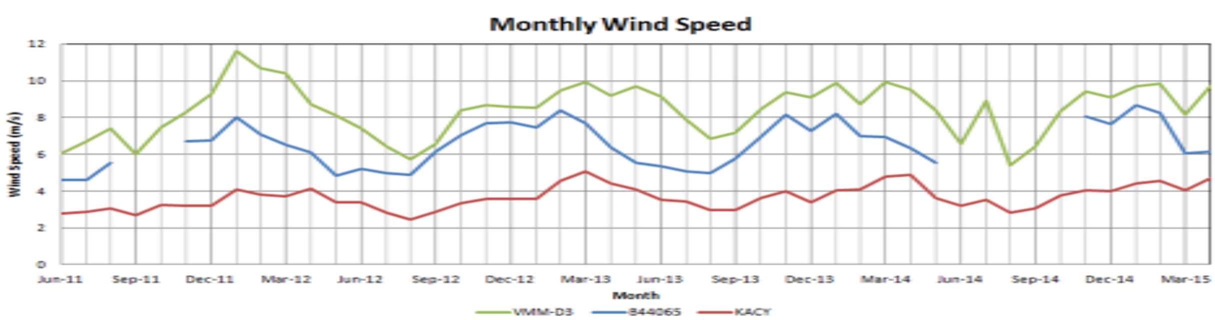
- As expected, average wind speeds (9.56m/s) were higher during the winter "Secondary Peak" energy demand period (Dec-Mar) when compared to the annual average wind speed (8.43m/s) derived during the project period (2011-2015) and were also higher than the annual climatological *Normal** (8.76m/s); average wind speeds (6.93m/s) were lower during the summer "Primary Peak" energy demand period (Jun-Sep) when compared to both the annual average derived for the project period and the annual climatological *Normal*.**

- Average wind speeds (9.03m/s) determined for the spring "Shoulder" months" (Apr-May) were above the annual average wind speed (8.43m/s) derived for the project period (2011-2015) and were above the annual climatological *Normal** (8.76m/s); average wind speeds (8.57m/s) for the fall "Shoulder" months (Oct-Nov) were slightly above the indicated annual average and slightly below the annual climatological *Normal*.**

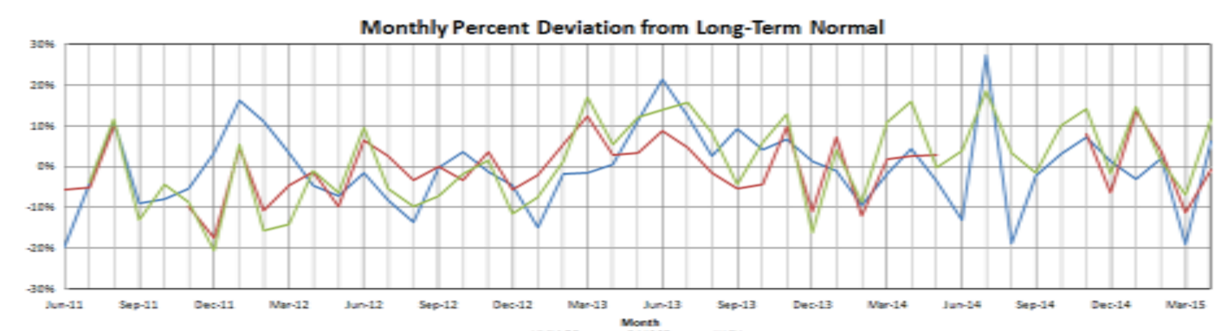
**Climatological Normals for most meteorological parameters used by the utility industry are based on the most recent 20-yr rolling average of complete annual data. Therefore, the current climatological Normal is based on the average for the period Jan 1994-Dec 2014.*

***Minimal changes in wind speed (e.g., >±1.0m/s) can produce significant changes in power production since power production is directly proportional to the cube of the wind speed (m/s^3).*

A "time series" of wind speed and wind speed deviations from the *Normal* were produced for NJ's coastal and offshore areas using monitoring and modeling data from Atlantic City's (ACY) Pomona, NJ 10m tower (green), NOAA's Ambrose Light buoy (red; the anemometer is installed ~5m above MSL), and a RU-WRF model simulated "Virtual" offshore100m meteorological tower (blue) centrally located within the BOEM NJ WEA. This analysis is respectively presented in the following graphs:



Time series (Jun 2011-Apr 2015) of wind speed (m/s) followed by their deviations (%) from *Normal* that are representative of NJ's coastal/offshore areas are presented repectively in the above and below graphs.



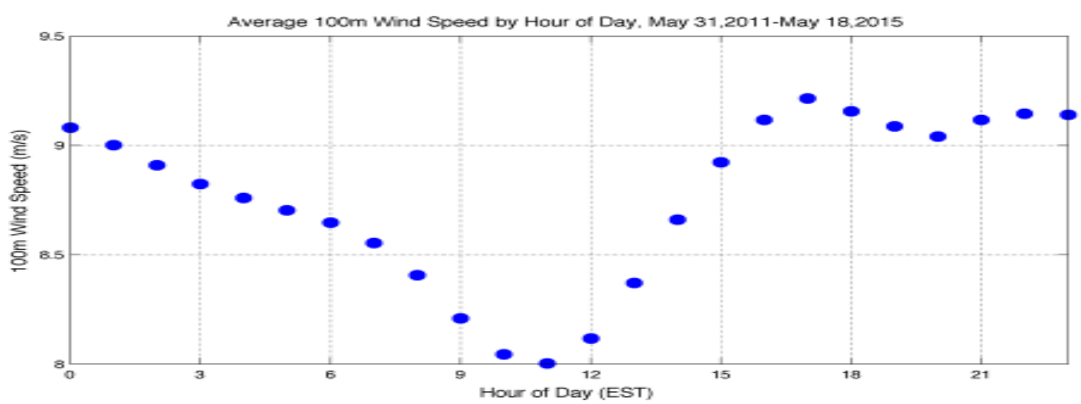
The wind speed time series graphs provide the following pertinent information regarding NJ's coastal/offshore wind resource:

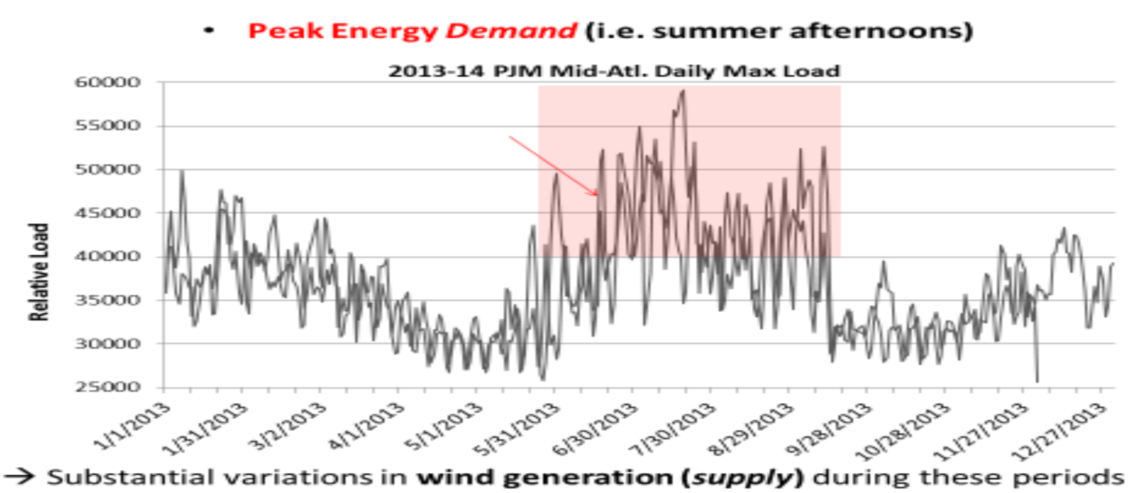
- During most time periods throughout the year, offshore wind speeds are significantly higher (~2.0 to >4.0m/s) than onshore wind speeds at similar heights above the surface.

- Generally, offshore wind speeds increase with height (e.g., during Jan 2011 average offshore wind speeds at 5m and 100m were respectively ~8m/s and 11.5m/s; during Mar 2015 average onshore and offshore wind speeds were respectively~6m/s and 8.5m/s). When analyzing the time series graphs, average offshore wind speed differences are less and more consistent at the 100m height when compared to the 5m height above MSL, which implies that WTG hub heights @100m should be very effective for reliable power production.

- Although, offshore wind speeds appear to be relatively consistent, the preceding time series analysis, which shows wind speed deviations from *Normal* values, indicates that when compared to seasonal and annual averages, monthly average wind speeds exhibit significant variation. This monthly variation is shown to range from ~ -20% to +30% respectively below and above the *Normal* wind speed.

An RU-WRF modeling analysis of the average diurnal variation of offshore wind speeds compiled @100m over the BOEM NJ WEA along with the average daily energy demand are displayed in the respective graphs shown below:





The preceding analysis of average diurnal variation in offshore winds when compared to the variation in energy demand provides the following evidence regarding generation load requirements:

- Adequate offshore wind facility capacity located within the BOEM NJ WEA with the WTGs being driven by substantial winds at the suggested 100m hub height should significantly supplement conventional generation load requirements. This assumption is especially applicable during periods of "Peak" energy demand, and will, therefore, reduce the burden put on the available energy supply and grid transmission/distribution during these critical times. Average hourly wind speeds at 100m above MSL that coincide with the preceding statements are summarized as follows:

    - From May 2011 to May 2015, the average hourly offshore wind speed @100m above MSL was lowest at 11 am (~8.0m/s) and highest at 5 pm (~9.2m/s).

    - Wind speeds remain high from 5 pm to 11pm (9.1m/s), and then slowly drop off to 8.0m/s by 11 am the next day.

- To reduce the "uncertainty" associated with wind variability, local wind perturbations frequently caused by the sea breeze circulation should be accounted for to determine when and where offshore wind power production will be available during the summer season when the "Primary Peak" energy demand period occurs.

- Less frequent coastal storms that impact the offshore wind resource during the winter season "Secondary Peak" energy demand period should be taken into account to determine the availability of offshore wind power production.

The following table shows the average wind speeds and the average max/min wind speeds along with climatological *Normal* wind speeds that were estimated to occur for each *Phase* of the OSW project. The wind speed values presented in the table were derived for the BOEM NJ WEA assuming WTG hub-heights @100m above MSL. The modeled wind speed averages are based on the hourly averages derived for the months defined for the winter (Dec-Mar) and summer (Jun-Sep) "Peak" energy demand periods. The average max/min wind speed values were derived using the maximum and minimum hourly wind speeds that were estimated to occur during each month of the respective "Peak" energy demand periods.

Average Wind Speed (WdSp) @100m:	**Avg Max WdSp.**	**Avg WdSp**	**Energy Demand Period**	***Normal***	**Avg Min WdSp.**	**Avg WdSp**	**Energy Demand Period**	***Normal***
Phase I: May 2011-Jun 2013	11.0 m/s	9.8 m/s	Winter	*10.65 m/s*	5.6m/s	6.9 m/s	Summer	*7.24 m/s*
Phase II: Jul 2013-Jun 2014	10.2 m/s	9.4 m/s	Winter	*10.63 m/s*	5.6 m/s	7.1 m/s	Summer	*7.23 m/s*
Phase III: Jul 2014-Jun 2015	10.3 m/s	9.3 m/s	Winter	*10.62 m/s*	5.8 m/s	7.0 m/s	Summer	*7.22 m/s*

Referring to the preceding table, implications regarding the offshore wind resource over the BOEM NJ WEA @100m above MSL for each *Phase* of our OSW project are summarized below:

- During *Phase I* (Jul 2011-Jun 2013*)*, average maximum and overall average wind speeds, which were estimated to occur during the winter “Secondary Peak” energy demand period, appear to be below *Normal*; also, average minimum wind speeds and overall average wind speeds estimated to occur during the summer “Primary Peak” energy demand period were also below *Normal.*

- During *Phase II* (Jul 2013-Jun 2014*)*, it appears that average maximum wind speeds and overall average estimated wind speeds were *significantly* below *Normal* during the winter “Secondary Peak” energy demand period; average minimum and overall average wind speeds estimated to have occurred during the summer “Primary Peak” energy demand period were below *Normal*.*

- Similar to *Phase II*, *Phase III* (Jul 2014-Jun 2015) estimated average maximum and overall average wind speeds that occurred during the winter “Secondary Peak” energy demand period were *significantly* below *Normal*; average minimum and overall average wind speeds estimated to occur during the summer “Primary Peak” energy demand period were below *Normal*.*

- The annual average wind speed (8.43m/s) for the OSW project, which was derived from the complete hourly data set compiled for all three *Phases* is below the *Normal* annual wind speed (8.76m/s). The below *Normal* average annual wind speed is reflective of the below *Normal* values computed for the seasonal energy demand periods presented in the preceding bullets. Although, seasonal and annual wind speeds were estimated to be below *Normal* during the project period (Jul 2011-Jun 2015), NJ’s offshore wind resource can still be considered to be relatively consistent with wind speeds that would be more than suitable for sufficient power production.

- Wind speeds and diurnal durations of frequent sea breeze occurrences that were observed during each *Phase* of the OSW project were not respectively intense enough or long enough to be accounted for in the “long-term” (i.e., seasonal, annual) averages. This suggest that sea breeze occurrences should be evaluated on a case-by-case basis. Therefore, it is implied that higher modeling resolutions along with representative initial boundary conditions including physics input that are realistic for the offshore environment should resolve the dimensional and flow properties of the sea breeze circulation. Once these characteristics related to the offshore component of the sea breeze cell are identified, their impact on the offshore wind resource can be determined. Furthermore, as previously discussed, “short-term” (i.e., diurnal, monthly) variability should be accounted for in the planning and design process for offshore wind facilities to reduce the “risks” related to power production, especially during periods of “Peak” energy demand. Using the same reasoning associated with sea breeze occurrences can be applied to coastal storm events.**

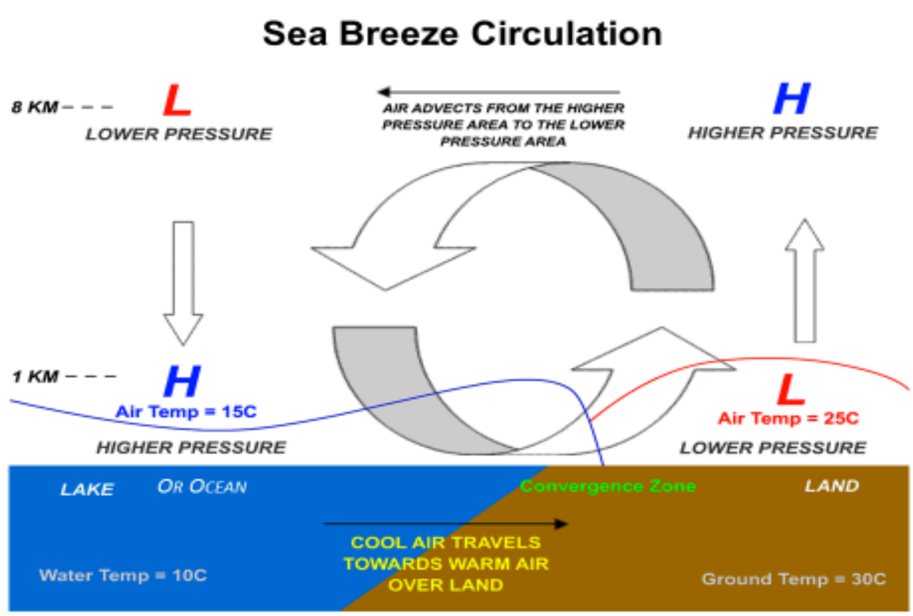
**As previously noted, an increase (decrease) of only ~1.0m/s in WTG hub-height wind speed can be significant for potential power production (i.e., wind power production is proportional to the cube of the wind speed (m/s^3)). **Greater wind speeds associated with certain coastal storm events could be reflected in both monthly and seasonal averages (e.g., wind speeds, durations, and frequencies of the intense Northeasters that occurred during each Phase of the OSW project appear to be abnormally high). Most of these storms occurred during the last part of the winter season through early spring (i.e., the latter part of Feb through early Apr). The Normal wind speed @100m over the BOEM NJ WEA for this period is 9.1m/s. The average wind speed derived during the OSW study for the coinciding period is 9.5m/s with average hourly maximum wind speeds ranging from ~10m/s to 13m/s, which would result in substantial wind power production.*

Coastal/Offshore Local Circulation Modeling Results

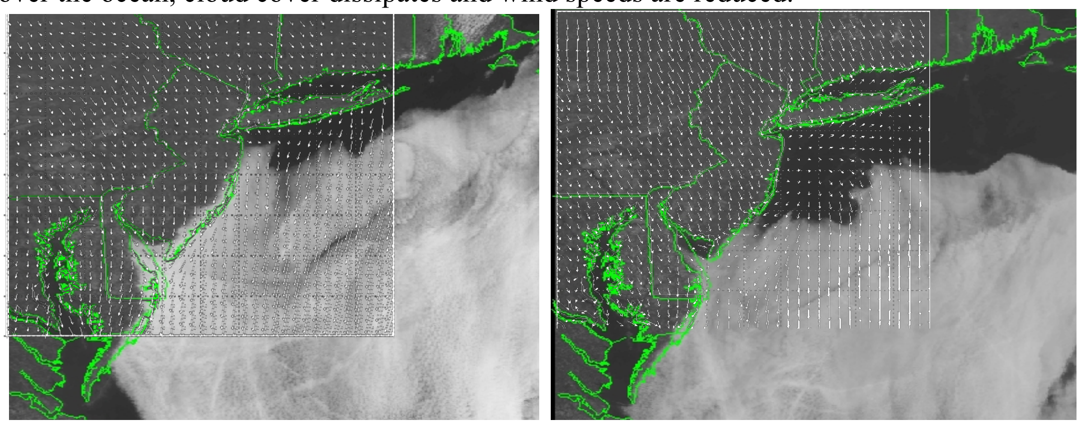
Sea Breeze Analysis

The sea breeze circulation is an area-specific thermodynamic process that will be sustained as being dependent on the intensity of the sea/land temperature gradient and prevailing synoptic conditions. Wind and temperature profiles within and external of each sea breeze occurrence will have different wind vectors along with varying turbulence, wind shear, and stability properties. Consequently, as a result of the significant spatial and temporal variability inherit in sea breeze circulations, these localized wind resource flow perturbations will have a direct impact on offshore WTG operations and subsequent power production performance. Previous and current analyses of various NJ sea breeze occurrences indicate that the sea breeze variability becomes the most prominent over the BOEM NJ WEA during early afternoon through late evening summer season hours, which coincide with the "Primary Peak" energy demand period. The RU-COOL offshore wind modeling study has determined that the frequently occurring sea breeze circulation will have a significant influence on the offshore wind resource and subsequent power production potential. Furthermore, high-resolution RU-WRF modeling results have identified four "types" of sea breeze circulations that occur along the NJ coast. These sea breeze types can be defined according to the following flow characteristics:

1) **Standard (Pure) Sea Breeze:** Standard sea breeze circulations are caused by relatively strong temperature gradients from sea (cool) to land (warm) creating an onshore flow that becomes dominant over a weaker synoptic flow that comes from the westerly sector. The sea breeze will propagate inland until the sea breeze and opposing synoptic flow reach equilibrium. At this location (i.e., the sea breeze "front"), the flow will become vertical as a result of both free and forced convection until the synoptic flow becomes dominant causing a return flow at a higher altitude back toward the sea. At some location from the coast to an area offshore, cooling (reduction in energy) will occur causing the flow to move downward (i.e., subsidence). The flow will then advect near the sea surface toward shore and advance inland creating the "typical" sea breeze cell. The Standard sea breeze circulation (cell) has the largest horizontal and vertical dimensions when compared to the other "types" of NJ sea breeze circulations described in the following discussion. The Standard sea breeze circulation is depicted in the below diagram:

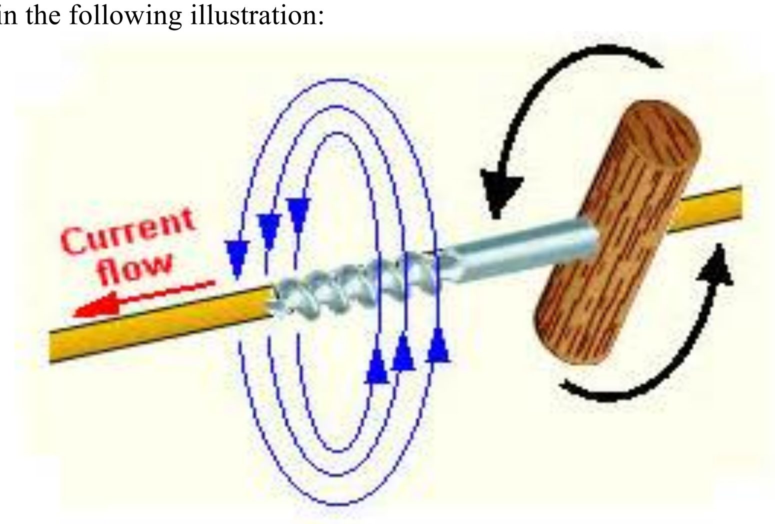


The following Visible Satellite images with overlays of RU-WRF model flow vectors show the progressive subsidence effect on cloud cover and wind intensities, which are occurring over the area that coincides with the offshore component of the sea breeze. As a result of the subsiding air over the ocean, cloud cover dissipates and wind speeds are reduced.



Visible Satellite depiction of cloud cover over NJ and Long Island, NY offshore areas along with an overlay of RU-WRF model wind vectors simulated for a concurrent sea breeze occurrence. The images show that as the sea breeze develops, cloud cover progressively dissipates and wind intensities become reduced over the area effected by the offshore component of the sea breeze.

2) **Side-Door ("Corkscrew") Sea Breeze:** When relatively strong southwesterly synoptic winds are blowing nearly parallel to NJ's coast and occur concurrently with a temperature gradient from the sea (cold/cool) to the land (warm), a sea breeze will generally develop as being dependent on the intensity of the synoptic flow along with the magnitude of the temperature gradient between the sea and land. Consequently, the resulting onshore sea breeze flow will be at an acute angle in relation to the prevailing synoptic flow trajectories creating a "corkscrew" effect in the coastal wind pattern. As the sea breeze intensifies, the angle of the sea breeze wind vectors could approach 90^0 (i.e., the sea breeze wind vectors could become nearly perpendicular to the synoptic flow streamlines). The sea breeze winds will therefore be coming from the *side* of the synoptic flow advecting along the coast and thus the name "Side-Door" is given to this sea breeze type. The Side-Door ("corkscrew effect") can be explained using Maxwell's Corkscrew Rule, which is described in the following illustration:



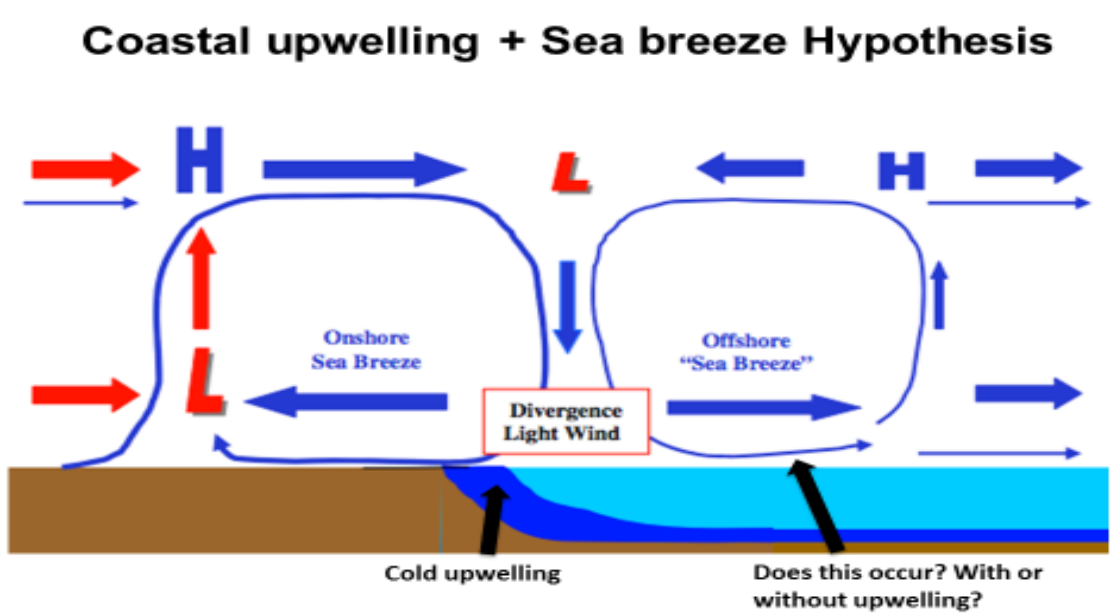
The "Corkscrew Effect": The current flow (red arrow) is analogous to the synoptic flow coming from the southwesterly sector and the blue arrows would represent the Side-Door sea breeze circulation.

Wind flows for Side-Door sea breeze occurrences, primarily those that are associated with coastal upwelling events, are substantially more intense and when compared to the Standard sea breeze circulation. Although, Side-Door sea breeze occurrences associated with coastal upwelling events have intensities that are significantly greater, their durations and both horizontal and vertical extents are dimensionally restricted when compared to the Standard sea breeze circulation. These factors are respectively the result of a large and concentrated sea/land temperature gradient and the "shearing" effect of the synoptic wind trajectories, which can be nearly perpendicular to both the onshore and offshore components of the sea breeze cell. The Side-Door sea breeze type can be subdivided into two classifications:

- ***Upwelling***: when *continuous* coastal upwelling (cold SSTs) occurs along a good portion of the coast creating a large temperature gradient between the sea (cold)/land (warm) interface resulting in a strong sea breeze with consistent intense winds. *Intermediate* coastal upwelling (cold SSTs) occurs as individual "pockets" or centers along the coast producing site-specific intense sea breeze events rather than one larger sea breeze occurrence that develops during the *continuous* upwelling case.

- ***Non-Upwelling***: synoptic winds are not strong enough to produce upwelling or the thermocline in coastal waters is insignificant with little temperature change between the surface and underlying layers. The resultant sea breeze occurrences are substantially less intense when compared to the *upwelling* case.

As a result of strong temperature gradients between cold coastal waters produced by upwelling and warmer offshore waters located adjacent to the upwelling center along with warmer land temperatures, a reasonable hypothesis would be that two sea breeze cells can develop. One cell would develop inland from the coast and the other cell would develop offshore from the coast. This hypothesis is being investigated to see whether or not two cells form and, if they do, what atmospheric/sea conditions are conducive for duel cell development. The concept of the duel cell development process is depicted in the below schematic:

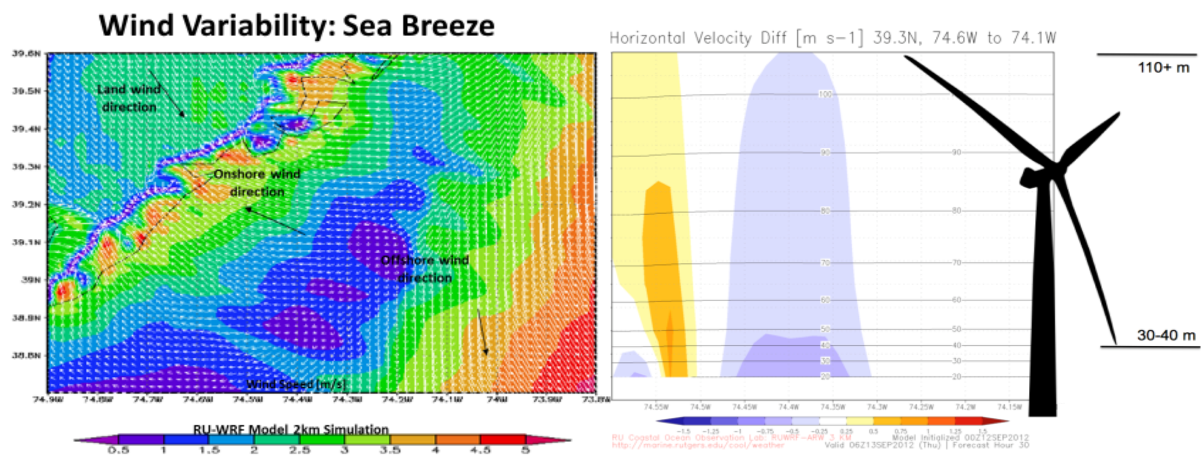


Schematic of the duel sea breeze cells that "theoretically" can develop during coastal upwelling events.

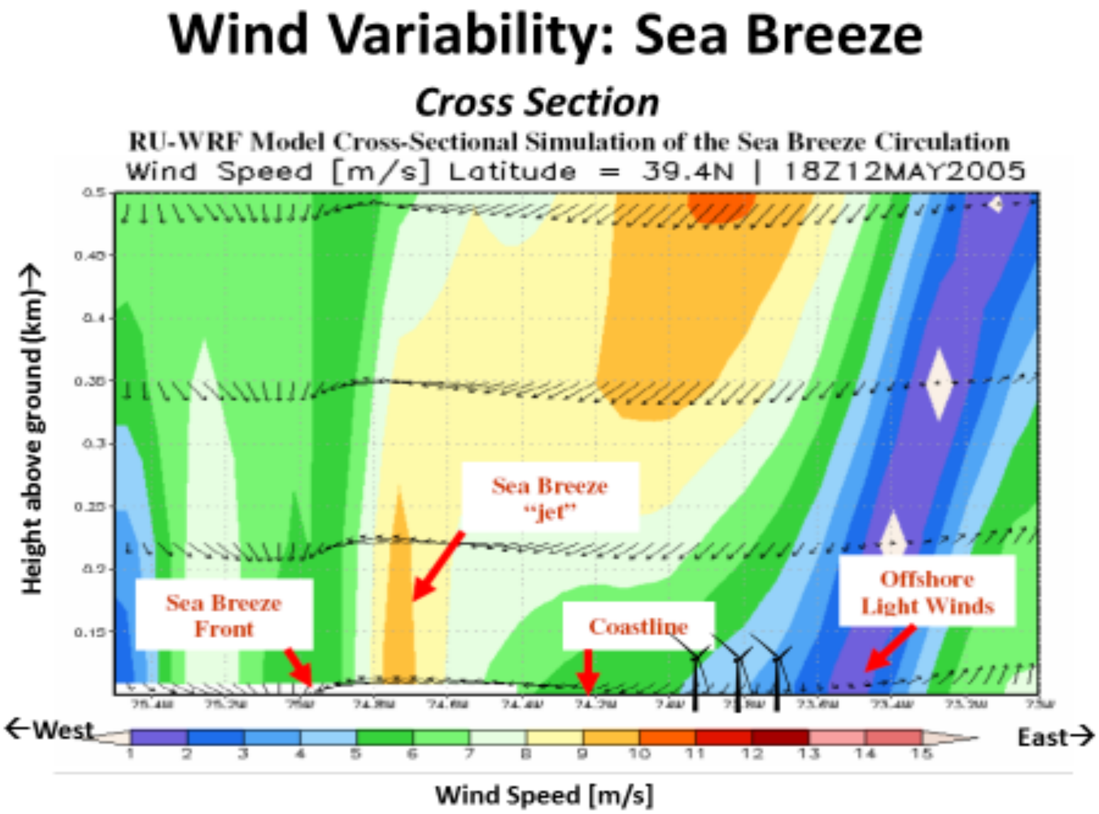
3) **Southeasterly Enhancement**: When synoptic flows are blowing from the southeasterly sector, a "virtual" sea breeze can occur. This type of sea breeze occurrence will be dependent on the magnitude of the temperature gradient across the sea/land interface and the strength of the wind speeds associated with the synoptic flow. If the gradient is strong enough, winds will accelerate across the sea/land interface. Therefore, the onshore flow ("sea breeze") will be "enhanced" resulting in the name SE Enhancement. However, this "type" of sea breeze appears to occur much less frequently than the either the Standard or Side-Door sea breeze circulations. The Southeasterly Enhanced sea breeze will probably have no upper level return flow and, therefore, it is unlikely that a sea breeze "cell" will be identified. Consequently, according to definition this type of sea breeze is not a "true" sea breeze circulation. However, several of the characteristics of this onshore flow are similar to conventional sea breeze circulations. Therefore, we included this as a "sea breeze" type that has a definitive impact on NJ's coastal/offshore wind resource.

4) **Backdoor Sea Breeze**: When synoptic flows are blowing from the northeasterly sector, a "virtual" sea breeze similar to the southeasterly enhancement sea breeze can occur. The climatology of NJ indicates that northeasterly winds occur primarily during colder weather when offshore SSTs are generally warmer than onshore land temperatures. Therefore, the lack of a significant temperature gradient from water to land will result in no acceleration of winds across the coastline. In most cases there will actually be a decrease in wind speeds as winds advect from offshore to inland areas. Consequently, the onshore flow will be considered to be purely synoptic with no indication of any of the characteristics that define the sea breeze circulation. However, there will be "rare" northeasterly wind cases when SSTs are colder than onshore land temperatures producing a gradient that will cause an acceleration of wind speeds from offshore to onshore areas and therefore creating the Backdoor sea breeze. The "corkscrew" effect applies to the Backdoor sea breeze except the coastline is to right of the flow instead of to the left of the flow as is the case for the Southeasterly Enhancement sea breeze.

The following simulations show the horizontal and vertical cross sections of a Standard sea breeze occurrence, which indicate that there is significant variability in both the 3D aspects of sea breeze circulations with substantial impacts on the offshore wind resource.



Standard sea breeze case with minimal wind speeds, wind shear, and turbulence that are associated with NJ's offshore area designated for wind energy development. However, the coastal/onshore component of this specific sea breeze simulations show significant variability in both the horizontal and vertical, especially near the sea breeze "front". On the next page is a cross-section of a different sea breeze case showing the onshore and offshore components of a Standard sea breeze circulation with similar wind pattern characteristics that are displayed in the above simulations.



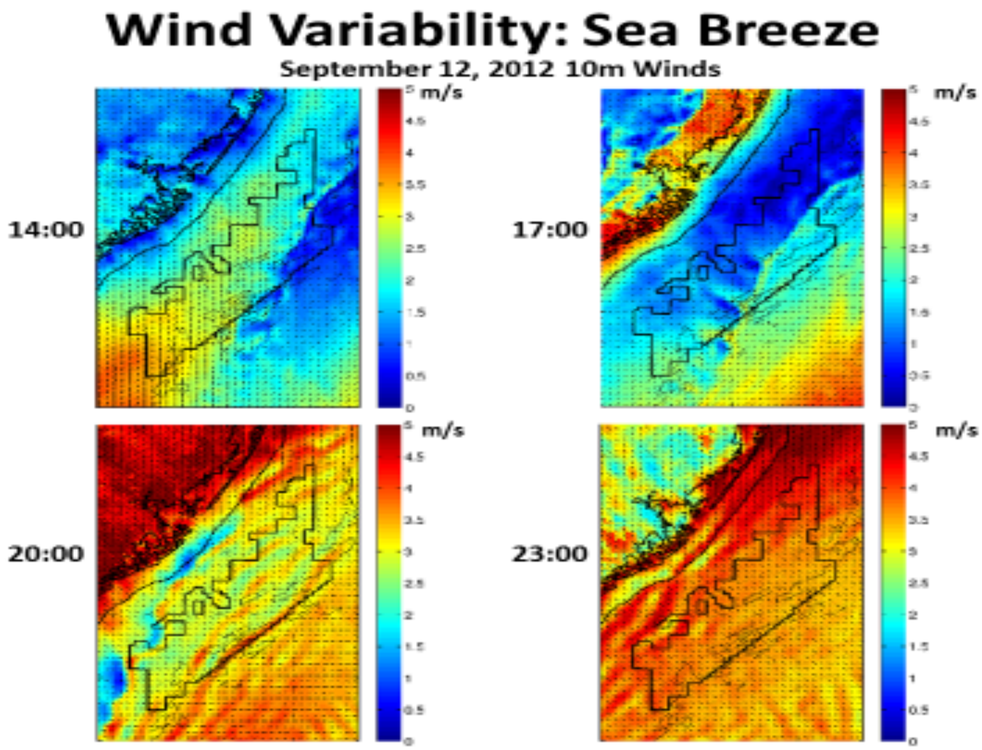
Referring to the preceding horizontal and vertical (cross-sectional) simulations for the two sea breeze cases, the following results are indicative of the Standard sea breeze circulation:

- For the specific sea breeze cases, wind speeds over the BOEM NJ WEA (designated by blue/purple areas) are <4m/s with the same wind speed being nearly constant from near the sea surface and extending upward past offshore WTG hub heights. Consequently, wind power production during this specific time of the sea breeze occurrence would be very minimal.

- Wind speeds (>4 to ~6m/s) and vertical shear become more significant near the sea breeze front that is located onshore in close proximity to the coast. These narrow bands (designated by the red/yellow/orange areas) are located to the left (west) in both the horizontal and vertical images.

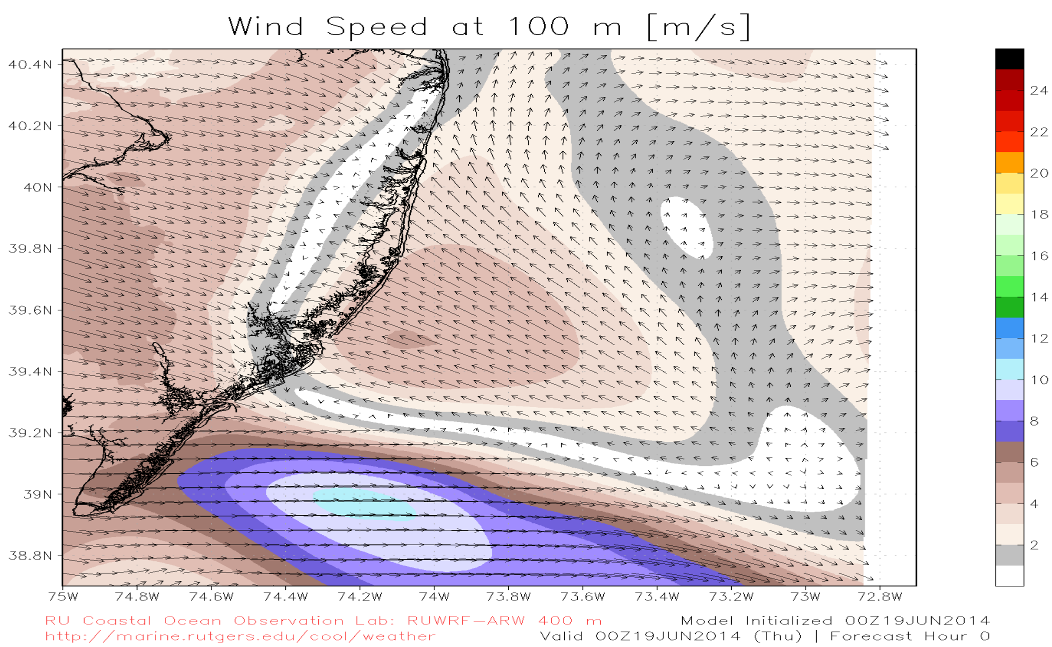
- There is an indication of a low level "jet" with speeds approaching 10m/s and potentially greater that are estimated to occur at heights ranging from ~50m to 200m above MSL. The "jet" is progressing onshore behind the sea breeze "front" as indicated by the gold to red narrow peaks located toward the left of both vertical simulations.

Previous and current analyses of various NJ sea breeze occurrences indicate that the dynamic sea breeze circulation exhibits substantial temporal and spatial variability within the BOEM NJ WEA during early afternoon through late evening hours, which coincide with the summer season "Primary Peak" energy demand period. A progressive time sequence showing the wind speed variability of a selected sea breeze occurrence modeled at 10m over the BOEM NJ WEA is displayed in the images shown on the following page.



Sea breeze occurrence simulated for the BOEM NJ WEA showing both significant temporal and spatial variability in relatively low wind speeds that ranged from <0.5m/s to ~4.5m/s.

The variability encountered by a recent sea breeze event at the 100m height above sea level is shown in the following simulation:



High-resolution (400m horizontal grid-spacing) sea breeze simulation at 100m above MSL showing significant variability in the NJ offshore wind resource with wind speeds ranging from <0.2m/s to ~10m/s.

When analyzing the preceding 100m simulation, the following facts were realized regarding the offshore wind resource:

- Wind speeds over the North BOEM NJ WEA Lease Zone ranged from ~6m/s nearer the coast and decrease to ~2m/s farther offshore as a result of intense sea breeze development. This estimated wind speed gradient is contrary to most offshore wind resource assessments, which assume wind speeds increase from the coast to offshore areas. However, this simulation shows wind speeds do increase from ~6m/s closer to the coast to near 11m/s farther offshore over the South BOEM NJ WEA Lease Zone where the sea breeze did not develop.

- As previously mentioned, the sea breeze circulation is considered a dynamic process with wind flow vectors that constantly change over the diurnal cycle of the circulation. Depending on the individual WTG design, most offshore WTGs will *not* start to produce power until wind speeds exceed ~3.0m/s to 4m/s (i.e., *self-start or cut-in speed*). Therefore, the wind speed gradients descibed in the preceding bullets idicate that WTGs potentially located within certain portions of the North Zone could be producing power while other WTGs would be idle during this sea breeze event. As the sea breeze propagates farther offshore, WTGs that were idle could start to produce power and WTGs that were producing power may become idle.

- Wind speeds over the South BOEM NJ WEA Lease Zone where the sea breeze did not develop, appear to be strong enough to enable most WTGs potentially located in the South Zone to continuiously produce power during the same period when WTGs in the North Zone may or may not be producing power during the simulated sea breeze circulation that only occurred over the North Lease Zone.

- Winds speeds within the potential "buffer" area that would separate the North and South BOEM NJ WEA Lease Zones are indicated to be light and variable (e.g., <1m/s to ~2m/s).

The results of the sea breeze analysis reveal that sea breeze characteristics (e.g., wind vectors, turbulence, shear, and physical dimensions of the circulation system) will change spatially and temporally as the sea breeze intensifies and eventually dissipates during its diurnal cycle. Consequently, along with minimal winds there could be periods during sea breeze occurrences when wind intensities become strong enough for significant power production. Therefore, regarding offshore wind energy development, sea breeze variability and its impact on the wind resource should be identified to reduce the "uncertainty" in offshore WTG array design and operational procedures. Extensive studies related to our sea breeze analysis can be reviewed using the following URLs:

"Sea Breeze, Coastal Upwelling Modeling to Support Offshore Wind Energy Planning and Operations" (**http://rucool.marine.rutgers.edu/media/downloads/Sea_Breeze_Pt1.pdf**)

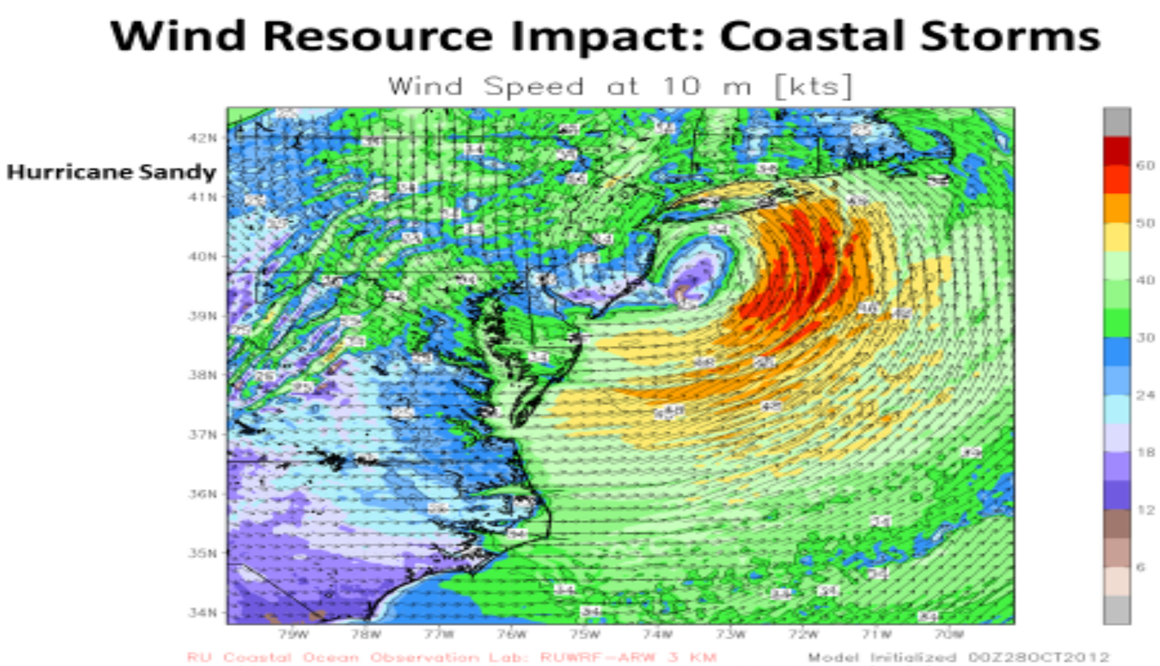
"Sea Breeze Sensitivity to WRF Model Configuration; Sea Breeze Turbulence Analysis" (**http://rucool.marine.rutgers.edu/media/downloads/Sea_Breeze_Pt2.pdf**)

The second "link" provides a detailed sea breeze modeling study consisting of two parts: 1) Modeling parameters were analyzed to determine which parameters are needed to realistically resolve the wind flow patterns and basic structure of the sea breeze circulation. The parameters studied were model resolution and initial physical conditions. The results of this analysis indicate that the correct initial physical conditions are the most critical model input for resolving the sea breeze circulation. Also, the correct model resolution is important for resolving certain sea breeze circulations that are not well defined spatially or contain complex flow patterns. 2)Turbulence properties associated with sea breeze dynamics were analyzed and documented.

Coastal Storm Analysis
NJ's coastal storms (e.g., tropical, extra-tropical, and Northeasters) have a substantial impact on the offshore wind resource and potential power produced by offshore WTGs. Furthermore, these storm systems are associated with wind speeds that are significantly higher than usual, which could result in WTG shutdown and possible structural damage. Sustained wind speeds during these storms could be greater than 25m/s (>56mph), which could be detrimental to the structural integrity of the WTGs. Consequently, most offshore WTGs are designed to *curtail* operations when sustained wind speeds are ≥ 25m/s (i.e., *shut-down or cut-out speeds*). Some newer WTGs are designed to have cut-out speeds of 30m/s, which will reduce some of the power loss due to high wind hysteresis. Therefore, offshore WTG design specifications should coincide with or surpass IEC codes (i.e., design criteria should be compatible with site characteristics):

- The site being evaluated for offshore wind energy development has a > 2% probability of 10-min average maximum sustained wind speeds that are >50m/s (~112mph) and wind gusts averaged for 3-sec can achieve speeds of >70m/s (~157 mph).
    - The average maximum 50-yr wind speed is ~ 50m/s (based on a 10-min average).
    - Extreme 50-yr wind gusts is ~ 70m/s (based on a 3-sec average).
- Based on NJ's climatology, the IEC codes may be sufficient when considering average maximum wind speeds along with extreme wind gusts that will be used for WTG design criteria.

The image shown on the next was derived for Hurricane "Sandy" that occurred during Oct 2012. The RU-WRF model was used for the analysis and prediction of the "super" storm's path and intensity to determine its effect on NJ's offshore wind resource along with other adverse coastal/onshore impacts.



Hurricane Sandy positioned off the coast of NJ with wind speeds showing significant variability ranging from ~12m/s to near 35m/s over the BOEM NJ WEA.

Generally, the adverse impact of NJ's severe coastal storms is caused more from strong wave/current action, storm surge, and flooding than from wind. A comprehensive analysis of NJ's coastal storms and their resultant impact on the BOEM NJ WEA and adjacent offshore waters can be review using the following URL:

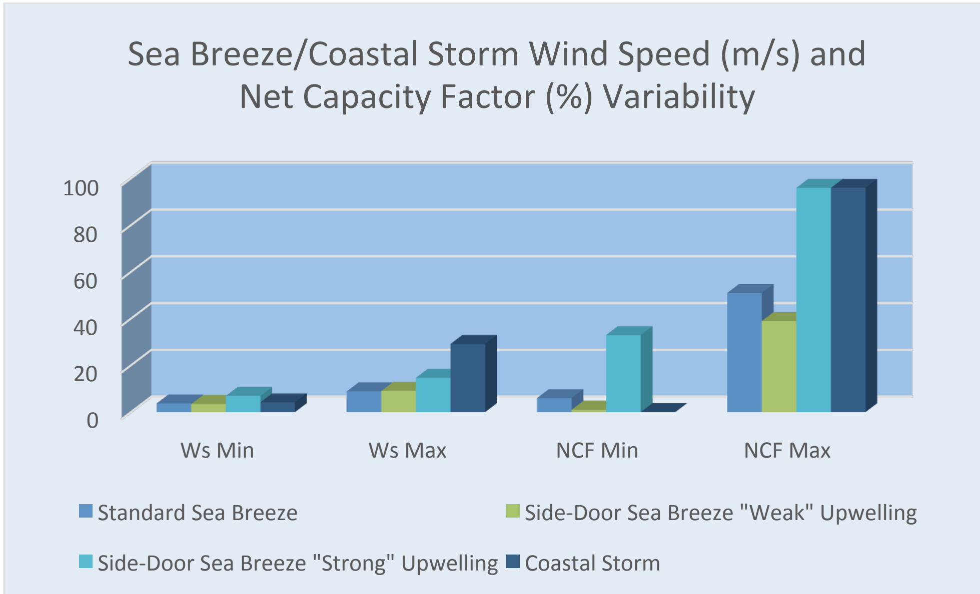
"Hurricane Irene Sensitivity to Ahead-of-Eye Coastal Ocean Cooling using WRF"
(http://rucool.marine.rutgers.edu/media/downloads/Hurricane_Irene.pdf)

Local Circulation Impact on NJ's Offshore Wind Resource
To determine the variability of the sea breeze circulation and coastal storms along with their impact on the BOEM NJ WEA and adjacent coastal/offshore areas, we selected three well defined sea breeze occurrences and one representative coastal storm event as case studies to use for the analyses. The data set and resultant information related to the case studies are included in the attached EXCEL spreadsheet titled: **"BPU DMCS Sea Breeze 3 Coastal Storm Cases".** The sea breeze cases were selected to represent the most common sea breeze "types" that occur along the NJ coast. The coastal storm case was selected on the basis of wind intensities and durations associated with severe storms that typically occur along and offshore NJ's coast. The RU-WRF model was run at 3.0km and 0.6km "nested" grid resolutions to resolve the sea breeze flow and dimensional characteristics. The model was run at a 6.0km grid resolution to realistically simulate the spatial and temporal properties associated with coastal storms. The model runs for each case assumed a 3000 MW maximum capacity for the BOEM NJ WEA using 6 MW WTGs with 100m hub heights. The below table and following chart summarize the RU-WRF model simulation results, which include wind speed, energy production, and Net Capacity Factors (NCFs), for the selected sea breeze and coastal storm case studies. The values presented in the table are based on a diurnal period for the time frame when the major portion of the sea breeze or coastal storm occurred.

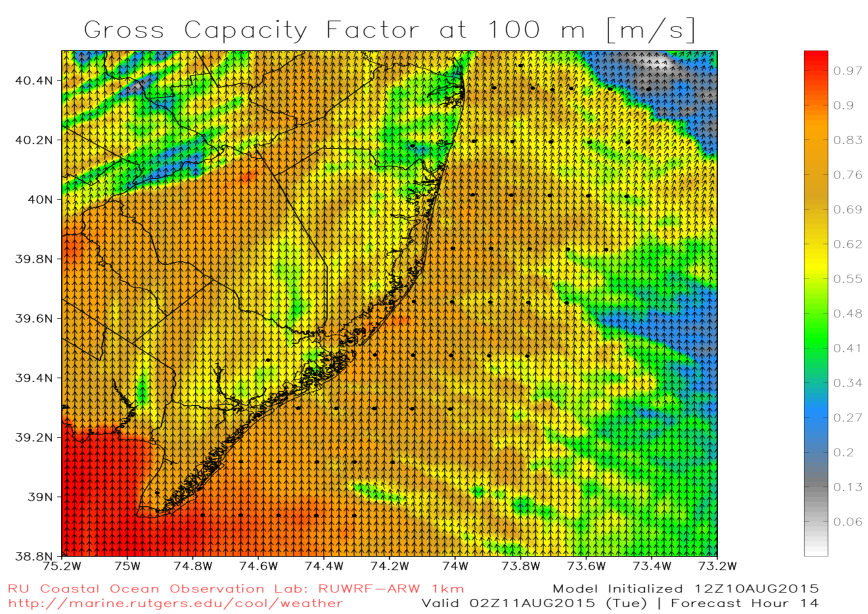
Sea Breeze "Type"	Wind Sp Range	Wind Sp Avg	Energy Range	Energy Avg	NCF Range	NCF Avg
Standard (Case 1)	3.7* to 8.9 m/s	6.1 m/s	163.27* to 1,539.03 MWhr	731.75 MWhr	6* to 51%	25%
Side-Door "Weak" Upwelling **(Case 2)**	3.5* to 9.1 m/s	6.4 m/s	18.28* to 1,166.76 MWhr	574.96 MWhr	1* to 39%	19%
Side-Door "Strong" Upwelling **(Case 3)**	6.9 to 14.7 m/s	10.6 m/s	986.31 to 2,872.14 MWhr	1,927.04 MWhr	33 to 96%	64%
Coastal Storm (Case 4)	4.2 to 29.2 m/s	18.0 m/s	0.00** to 2,872.68 MWhr	1,598.29 MWhr	0** to 96%	53%

Estimated offshore wind energy production parameters simulated for a "hypothetical" WTG array, which contains 6 MW WTGs with hub heights @100m. The model simulations assume a maximum 3000 MW capacity that could be installed within the entire BOEM NJ WEA. **Depending on the WTG design specifications, self-start-up ("cut-in") speeds will occur when wind speeds are ~ 3 to 4m/s. When wind speeds are at or slightly above the start-up speed, power generation and total energy produced along with NCFs will be minimal. **As a result of winds being higher than the WTG automatic shut-down ("cut-out") speed (i.e., ~25 to 30m/s depending on WTG design specifications, the WTGs would terminate operation and therefore power generation and total energy produced along with NCFs would be zero.*

The data provided in the previous table is graphically presented in the following chart:



An additional analysis of the variability of the Gross Capacity Factor (GCF) resulting from the sea breeze circulation was conducted for a recent sea breeze occurrence. This analysis indicates the GCF can range from ~20% to >80%, which is very significant when considering that the cost benefit of offshore wind power production is dependent on the amount of available energy (supply) and consumer requirements, especially during times of “Peak” energy demand. The stated range of GCFs that can be expected to occur during “typical” sea breeze occurrences are shown in the below simulation:



A “snap shot” of offshore WTG Gross Capacity Factors (GCFs) @100m estimated for a sea breeze occurrence over NJ’s coastal/offshore waters, which include the BOEM NJ WEA. The GCFs ranged from ~20 to >80%.

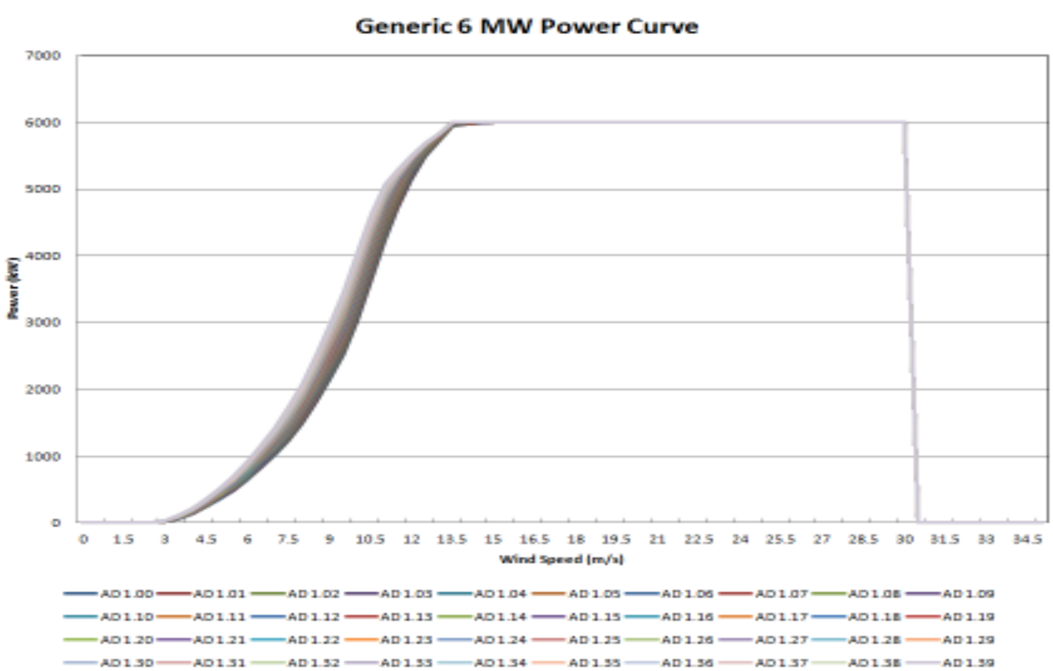
An RU-WRF model "animation" of the sea breeze occurrence referenced on the previous page show the significant temporal and spatial diurnal variability of GCFs that are estimated to occur over the BOEM NJ WEA and adjacent offshore areas. This "animation" can be viewed using the URL: **http://marine.rutgers.edu/cool/weather/RUWRF/animation/3km/gcf.html**

The results presented in the preceding table, graph, and GCF simulation/"animations" along with the data and information provided in the corresponding spreadsheet clearly demonstrate that the diurnal variability of local wind flow perturbations is very substantial. Consequently, sea breeze occurrences and coastal storm events will have a significant impact on the NJ coastal/offshore wind resource and related energy production capabilities.

Offshore Wind Energy Production Projections for the Entire BOEM NJ WEA

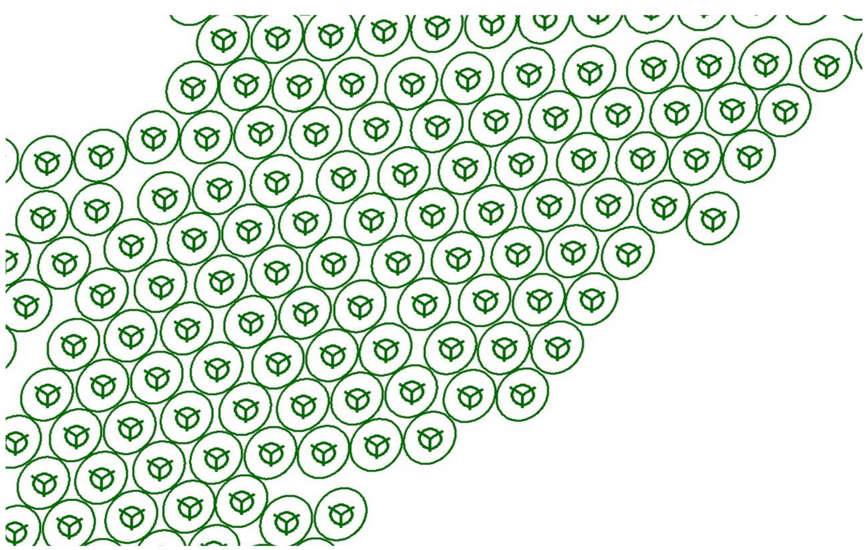
An overall wind resource assessment for NJ's coastal/offshore areas designated for wind energy development was conducted for the most recent 4-yr period of record (June 2011-May 2015). The resultant information was incorporated into an investigation to determine the most realistic potential wind energy production parameters that can be expected for the BOEM NJ WEA. The assessment includes resultant information for capacities ≥1100 MWs referred to in the NJ Energy Master Plan and the NJ OSWEDA. Also, included in the assessment are data for 2000 MW and 3000 MW installed capacities. The complete hourly, monthly, and annual results of the NJ coastal/offshore wind resource assessment are provided in the URL:
http://marine.rutgers.edu/cool/weather/hidden/bpu2015/

The RU-WRF modeling program utilized for our study incorporates a "generic" 6 MW WTG power curve, which was previously developed during *Phase II* of our OSW project. This power curve has been updated during the *Phase III* OSW studies to account for the most current design criteria used for offshore 6 MW machines. This generic 6 MW WTG power curve, which is presented in the following graph, provides the most representative and unbiased information for our modeling programs:



It is anticipated that more efficient WTGs with higher capacity ratings (e.g., 8 MW machines) will be used for offshore wind energy applications. Therefore, our most recent study includes modeling results for both 6 MW and 8 MW offshore WTGs. However, the number of 8 MW WTGs in production and relevant design data is limited when compared to 6 MW machines. Consequently, we had to use the actual power curve and specifications for an 8 MW WTG rather than developing a generic power curve for our analysis. The start-up and cut-out wind speeds indicated by the original 6 MW “generic” power curve are similar to the actual 8 MW power curve; however, the updated power curve shown above has a start-up wind speed of 3m/s rather than 4m/s with cut-out wind speeds up to 30m/s rather than 25m/s. As previously stated, the higher cut-out wind speeds could reduce some of the energy losses resulting from high wind hysteresis.

Although, offshore WTG manufacturers recommend an 8D X 10D (where, D=Rotor Diameter) spacing configuration, our 10D X 12D spacing arrangement previously determined during *Phase II* is based on high-resolution RU-WRF model simulations. These simulations are supplemented with an advanced “deep array” turbulent wake modeling routine, which is representative for large offshore wind facilities. These combined modeling programs include the effects of interactions between the unique characteristics of NJ’s coastal and offshore areas, MABL dynamics, and resultant turbulent wake effects among individual WTGs that are located within an array configuration. Therefore, it can be reasonably assumed that the suggested 10D X 12D spacing scenario is probably the “best” spacing arrangement for the BOEM NJ WEA. The preceding assumption is further confirmed when considering that the 12D spacing will significantly reduce the wake effects that can potentially occur during prevailing WSW-SSW winds. The 10D spacing will account for the remaining less frequent wind directions.
If the 10D X 12D WTG spacing is configured in a “staggered” arrangement, wind power production could possibly become more cost-effective during periods of local wind resource variability caused by perturbations associated with such phenomena as the dynamic sea breeze circulation. An example simulated WTG array spacing configuration is displayed below:



Hypothetical WTG Array showing 10D X12D spacing with a “staggered” configuration to account for prevailing winds along with the effects of local wind flow patterns (e.g., the sea breeze circulation).

The experimental design for our study is based on establishing "hypothetical" offshore wind facilities within the BOEM NJ WEA for 6 MW and 8 MW WTG arrays arranged to accommodate the suggested 10D X 12D spacing scenario between individual WTGs. Therefore, the dimensional boundaries and Lease Zone delineations that were established by BOEM for NJ's offshore wind energy development projects were used for this and the previous studies. During the *Phase II* OSW study, an installed capacity of ~3,000 MW was determined to be the maximum capacity the BOEM NJ WEA could sustain assuming that 6 MW WTGs are selected for installation. Furthermore, an independent NREL study (Musial et. al. (2013)) suggested that the maximum installed capacity for the NJ WEA should be 3,400 MW, which closely coincides with our estimated 3,000 MW capacity value.

The results of the current *Phase III* OSW study suggest that a maximum capacity of ~4,000 MW could be installed within the BOEM NJ WEA if the newer more efficient 8W WTGs were selected as the power generators for a proposed offshore wind energy facility. The results of this portion of the *Phase III* study, which compares wind energy parameters projected for 6 MW WTGs with projected wind energy parameters estimated for 8 MW WTGs, could be used as part of the decision-making process to determine the size (rated MW capacity) and number of WTGs that could be installed to ensure offshore wind energy development within the NJ WEA is efficient and cost-effective.

The complete data set used for the 6 MW vs. 8 MW WTG comparison is provided in the EXCEL spreadsheet titled: **"6 MW vs 8 MW OSW WTGs for the BOEM NJ WEA".** The spreadsheet includes the wind resource and energy production data for other installed capacities (i.e., 1100; 2000 MW) and WTG spacing arrangements (i.e., 8D X 10D; 8D X 12D) in addition to maximum capacity values (i.e., 3000 MW for 6 MW WTGs; ~4000 MW for 8 MW WTGs) that potentially could be installed within the NJ WEA. The results for projected Net Capacity Factors (NCFs) ranged from ~32% to 36%. Although, the difference in NCFs appears to be minimal, total energy produced with a resultant financial benefit could be significant even with a slight increase in NCFs as small as +0.1%. The converse will hold true for a decrease in NCFs. This assumption will be dependent on the amount of installed capacity for an offshore wind facility along with the effectiveness of the wind resource for that specific site. To further clarify the previous statement, an offshore wind energy facility with a greater installed capacity along with an intense and consistent wind resource will realize greater energy production when compared with a smaller facility with the same NCF. This comparison also applies to facilities with the same installed capacity. However, one of the facilities could have a less intense and/or more variable wind resource resulting in less energy production.

The following definitions and explanations are associated with the resultant information regarding projected energy production parameters, which are provided in the spreadsheet referenced in the previous paragraph:

- The Gross Capacity Factor (GCF) is derived using the ratio of estimated annual energy production to the total annual energy produced assuming the selected WTG is operating 100% of the time at its rated capacity. Estimated annual energy production values are derived from the selected WTG power curve and the annual NJ offshore wind frequency distribution. External losses are then determined to derive the NCF.

- External losses will include adverse environmental impacts including site turbulence, wind shear, high wind hysteresis, parasitic (corrosive conditions), and icing; electrical transmission and associated system component resistance; and inherit WTG efficiency reduction attributed to mechanical design characteristics.

- The GCF for a WTG array is derived using the same procedure described for an individual WTG except the total energy production value is the cumulative energy production that can be achieved from the total number of WTGs located within a designated array. Also, the NCF for the WTG array will include the energy reductions stated in the preceding bullet item for individual WTGs plus turbulent wake losses that result from the flow interactions among the individual WTGs located within the array.

➢ WTG arrays were set-up for each scenario to account for the "best" wind resource characteristics estimated to occur within the BOEM NJ WEA and to ensure that the number of WTGs needed to achieve the stated capacity could be sustained within the physical dimensions of the NJ WEA without creating significant "loss" factors.

Although, 8 MW WTGs may have similar hub heights as 6 MW WTGs, their rotor diameters will probably be longer. Therefore, turbulent wake effects between individual 8 MW machines will probably be greater than those encountered by 6 MW machines. Therefore, to achieve a cost-benefit when considering maximum installed capacities there may have to be a "trade-off" between the losses attributed to turbulent wakes and the gains resulting from adding more efficient larger WTGs. Consequently, to allow for a maximum capacity of 4,000 MW for the 8 MW machines, a portion of the WTG array(s) may have to be designed for 8D X 10D and/or 8D X 12D spacing to enable the required number of WTGs to "fit" within the Lease Zone dimensions specified for the BOEM NJ WEA.

As stated previously, when considering the installation of 8 MW WTGs rather than 6 MW WTGs, the maximum capacity of the offshore NJ WEA can be increased from 3000 MW to ~4000 MW. This increased capacity equates to a projected energy production value of ~12 million MWhrs, which results in a substantial (i.e., 100%) increase in generation capability.

The *Phase III* offshore wind modeling scenarios with 10D X 12D WTG spacing arrangements are defined as follows:

➢ Maximum capacity (i.e., 3000 MW) that can be installed within the entire BOEM NJ WEA using 6 MW WTGs.

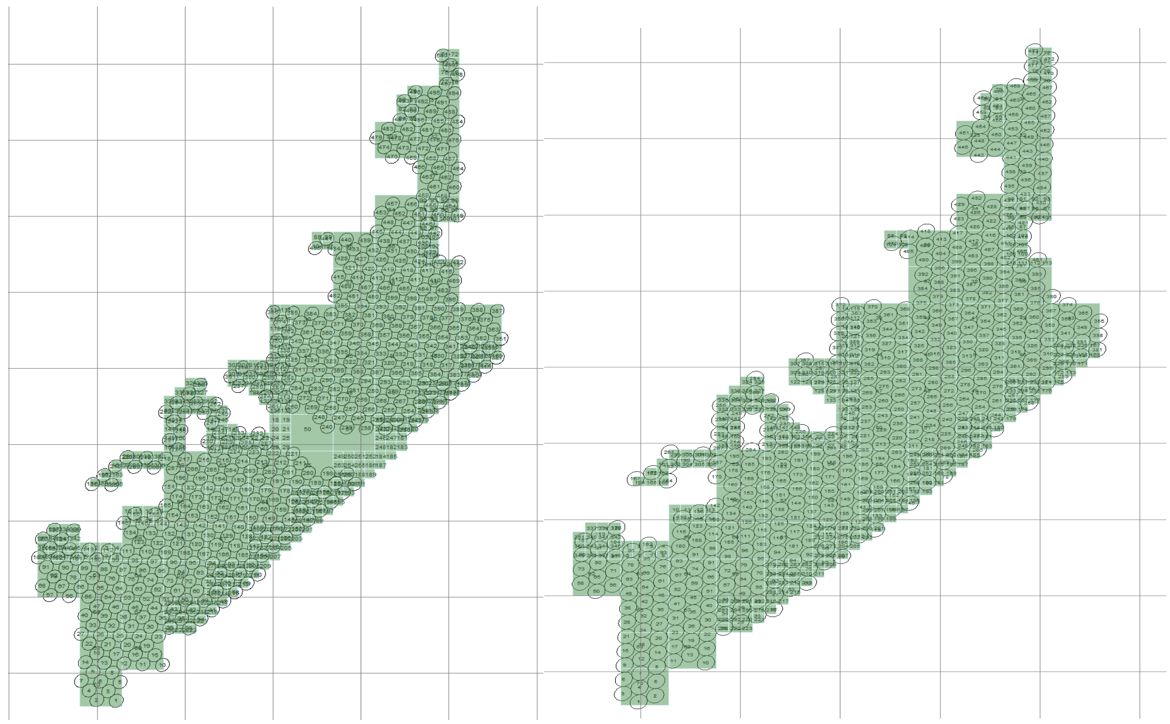
➢ Maximum capacity (i.e., ~4000 MW) for 8 MW WTGs that can be installed within the entire BOEM NJ WEA.

➢ For comparison of the maximum 3000 MW capacity suggested for 6 MW WTG arrays, 8 MW WTG arrays were modeled for two 3000 MW capacity scenarios:

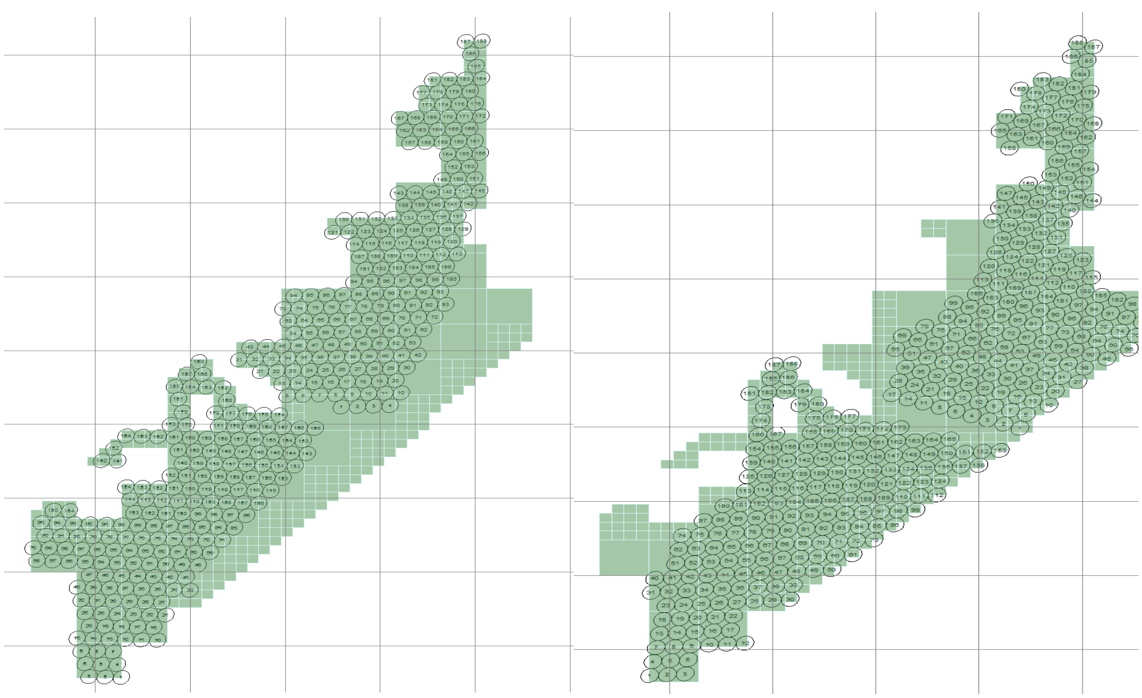
- 3000 MW installed capacity for the entire NJ WEA nearest to the coast.

- 3000 MW installed capacity for the entire NJ WEA farthest offshore from the coast.

Proposed BOEM NJ WEA Lease Zone locations, simulated WTG array configurations, and individual WTG positions within the arrays are shown in the following offshore area layouts:



Maximum BOEM NJ WEA installed Capacity: 3000 MW using 6 MW WTGs; 4000 MW using 8 MW WTGs

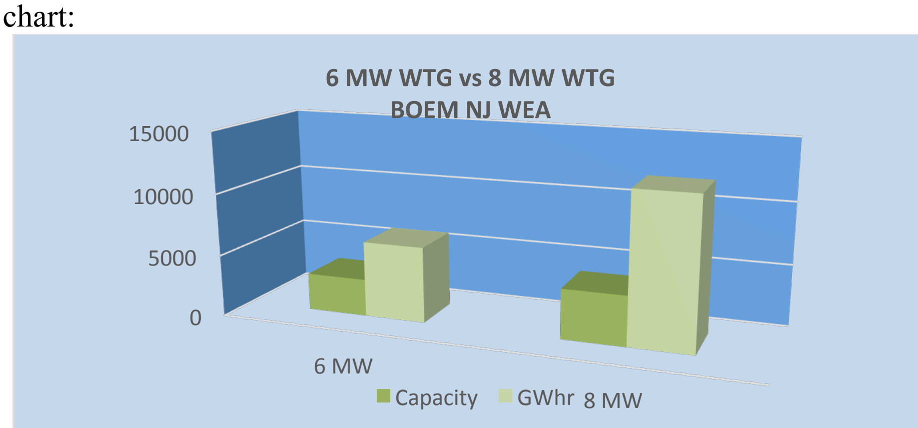


BOEM NJ WEA installed Capacity (~3000 MW using 8MW WTGs) for respectively the near-shore and farthest offshore locations delineated for the BOEM NJ WEA.

The results comparing projected 6 MW and 8 MW OSW WTG energy parameters for the entire BOEM NJ WEA, which includes both the North and South Lease Zones, using an average 8.5m/s wind speed @ 100m hub heights are summarized in the following table:

OSW WTG Rated Capacity	Maximum Installed Capacity	Total # WTGs	NCF	Total Annual Energy Production
6 MW	3,000 MW	500	32.0%	6,123,920 MWhr
8 MW	4,000 MW	500	34.3%	12,038,670 MWhr
OSW WTG Rated Capacity	**Total Installed Capacity**	**Total # WTGs**	**NCF**	**Total Annual Energy Production**
6 MW	3,000 MW	500	32.0%	6,123,920 MWhr
8 MW	3,000 MW	375	35.5%	9,370,385 MWhr

The preceding comparison between 6 MW WTGs and 8 MW WTGs is graphically portrayed in the below chart:



Comparison of maximum installed capacities (MWs) and resultant annual energy production (GWhr) projected for 6 MW and 8 MW WTGs that could be installed within the BOEM NJ WEA.

Based on the results provided for projected wind energy production parameters presented in the previous table and chart, it appears that compared to smaller (e.g., 6 MW WTGs), the “newer” and more efficient larger (e.g., 8 MW machines) would be the more viable option when considering which WTG should be selected for offshore wind energy development within the BOEM NJ WEA.

Individual Lease Zone Energy Production Projections for the BOEM NJ WEA

Model runs using 6MW WTGs with 100m hub heights and a 10D X 12D array spacing arrangement consisting of an assumed capacity of 1,500 MW in the South Zone and 1,500 MW in the North Zone were conducted to estimate potential annual wind energy production for each Zone. For comparison evaluations, a total capacity of 3000 MW was selected to be consistent with prior studies. Model simulations indicate wind intensities are greater farther offshore over both Zones. Also, there appears to be a slightly more intense wind resource over the North Zone with greater WTG wake losses when compared to the South Zone. Additionally, there are no physical divisions in the atmosphere or the ocean relevant to the Lease Zones. Therefore, there is much overlapping of wind resource characteristics associated with the entire BOEM NJ WEA along with the individual North and South Zones. Consequently, overall energy production for both Zones is very similar. Furthermore, it should be noted that the preceding statements will probably not be applicable during sea breeze occurrences or coastal storm events.

Annual net capacity factors and annual wind energy production estimates for the offshore WTG arrays evaluated for each BOEM NJ Lease Zone are presented in the following table:

BOEM NJ WEA/Installed Energy Capacity (MW)	**Avg Annual Net Capacity Factor (%)**	**Total Annual Wind Energy production (MWhrs)**
North Zone/1000 MW	34.92	3,065,065
South Zone/1000 MW	32.78	2,877,264
NW Sector/500 MW	33.98	1,482,358
NE Sector/500 MW	36.82	1,606,198
SW Sector/500 MW	33.04	1,441,377
SE Sector/500 MW	34.06	1,485,837

BOEM NJ WEA Energy Capacity (MW)	**Estimated Annual Wind Energy Production (MWhrs)**
North Zone: 3000 MW	**4,609,343 MWhrs**
South Zone: 3000 MW	**4,340,871 MWhrs**

Wind energy production estimates provided in the preceding table account for loss factors attributed to MABL dynamics (e.g., effects of turbulence intensity and wind shear) and mechanical efficiencies of the WTG components. Depending on the convective properties of the air above the sea surface and resultant atmospheric stability, the MABL can extend approximately 100 m above the sea surface to near 3 km. Therefore, when considering the dimensions of offshore WTGs, WTG performance will be affected by the physical characteristics of the MABL.

CONCLUSION

*Summary Comments, Clarification, and Suggestions**

Offshore wind resource and energy production values resulting from recent RU-WRF model simulations are similar to previous modeling results, which indicate wind speeds over the North BOEM NJ WEA Lease Zone are slightly higher when compared to wind speeds over the South Lease Zone. Also, as a result of a more intense wind resource that is averaged over an annual period, an increase in wind energy production will probably occur over areas farther offshore in both the North and South Lease Zones. However, annual average *Normal* wind speeds (~8.8m/s may not be indicative for certain local wind resource perturbations (e.g., the sea breeze circulation) that can affect wind power production during critical periods of "Peak" energy demand. Depending on the location of the WTG array and time of occurrence, these wind resource perturbations could result in either a negative or positive impact on electrical power generation. Regardless of the variability in diurnal, monthly, and seasonal winds, offshore wind speeds that occur over the BOEM NJ WEA should result in NCFs (e.g., ~34 to ≥36%), which are considered cost-effective for most offshore wind energy operations.

The continuing RU-WRF modeling improvements indicate that the results are becoming more consistent along with good agreement with validated monitoring systems. Therefore, our modeling program is probably becoming the most cost-effective method for simulating the actual physical properties of NJ's coastal/offshore wind resource. Based on RU-WRF modeling results, the following suggestions could potentially help to "optimize" offshore wind energy facility design and productivity:

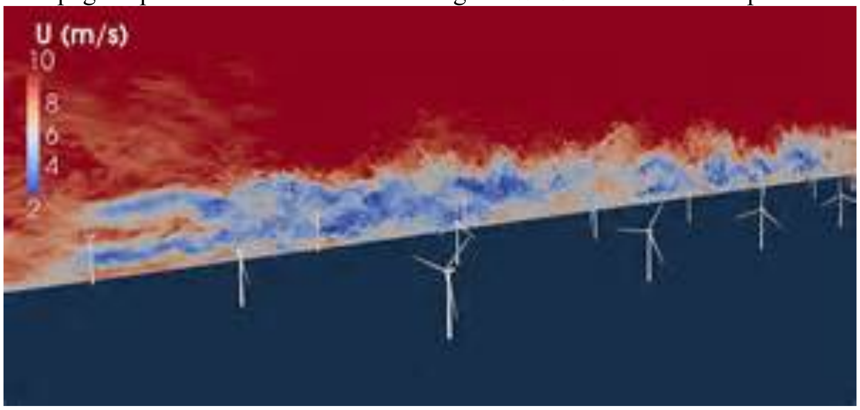
- Select WTGs with hub heights near 100m above MSL. 100m hub heights should be the most effective for minimizing the adverse effects of turbulence and wind shear while maximizing WTG performance, which is dependent on the wind speed profile that shows that winds within the MABL do not significantly increase above the 100m level.

- Utilize a 10D X 12D WTG spacing arrangement. The 10D X12D WTG array configuration should be the "best" spacing scenario that will account for the following features associated with NJ's coastal/offshore wind resource:

    - NJ's unique coastal topography and shoreline configuration that influence both onshore and offshore wind flow properties.

    - NJ's dynamic offshore wind characteristics, which include prevailing wind trajectories along with local circulation patterns (e.g., the sea breeze).

    - When considering the preceding two "bullets", the suggested 10D X12D WTG spacing arrangement should assist in alleviating most of the adverse turbulent "wake" effects and relevant performance reductions, which are inherit with a large WTG array. The image on the next page depicts turbulent wakes resulting for WTG structures and operations.



Simulation of turbulent wake effects among several WTGs located within a large OSW facility.

- Select 8 MW WTGs for offshore wind energy applications. Considering the current state-of-technology for WTG design, the recently developed 8 MW WTGs appear to be more efficient and economically viable when compared to other WTGs used for offshore applications (e.g., 6 MW machines).

When evaluating the extensive data sets produced by the RU-WRF modeling program, the magnitude of the wind speed deviations from the *Normal* values at the100m height above MSL are relatively consistent over the BOEM NJ WEA. Furthermore, average 100m wind speeds are within the power curve range of most offshore WTGs, which implies that NJ's offshore wind resource is more than adequate for efficient and economically viable wind energy production. Basically, with an offshore wind resource that consistently has average wind speeds >8.4 m/s along with a relatively large area (>300,000 acres) that is compatible with construction requirements, the marine environment, and most maritime issues, the BOEM NJ WEA should be very conducive for wind energy development.

***NOTE:** *The results and subsequent suggestions provided in the concluding comments along with the stated findings documented in the main report are based on the RU-WRF modeling program and supporting monitoring systems used by Rutgers DMCS. Although, similar results should probably be achieved if other modeling methods and monitoring technologies are utilized, a more concentrated analysis using specific WTG data along with site-specific wind and turbulence characteristics, could potentially produce somewhat different results that may not totally agree with the results and conclusions provided in this report. Therefore, any discrepancies associated with the alternative modeling/monitoring program should be resolved prior to proceeding with an offshore wind energy development project.*

Implications for Forthcoming Model Implementation

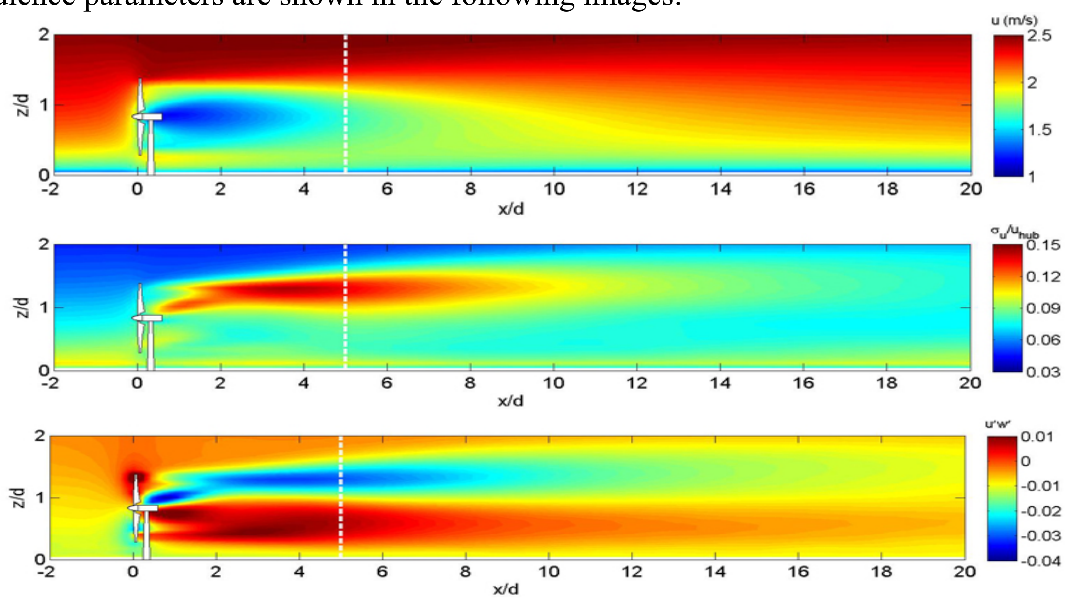
Sea Breeze and Coastal Storm Climatology

The RU-WRF modeling results provide evidence that the short-term (diurnal) temporal and spatial variability of the sea breeze circulation will cause significant effects on the dynamics of NJ's coastal/offshore wind resource, which includes the BOEM NJ WEA. Generally, the greatest spatial extent and intensity of the developing sea breeze circulation occurs during mid-afternoon through early evening hours, which coincide with the summer season "Primary Peak" energy demand period. Therefore, utilization of the RU-WRF modeling system for analyzing the climatology of the sea breeze circulation along with the frequency-of-occurrence (or probability) of each sea breeze "type" (i.e., Standard, Side-Door, SE Enhancement, and Backdoor) should be implemented.

The implementation of the RU-WRF model for determining NJ's sea breeze climatology and the probability-of-occurrence for each sea breeze type should be conducted by configuring the model to run "hindcasts" using re-analysis data and/or supplemental representative historical data sets. Additionally, the extensive data sets used to determine sea breeze climatology along with current monitoring/modeling data could be used to verify or reject the hypothesis that a "duel" sea breeze cell develops during upwelling events. The results of the complete climatological analysis could then be used to account for the sea breeze circulation variability when designing an offshore WTG array and for effective planning to ensure efficient individual WTG operations along with overall facility performance. Similar procedures for determining NJ's coastal storm climatology and frequency-of-occurrence could be implemented.

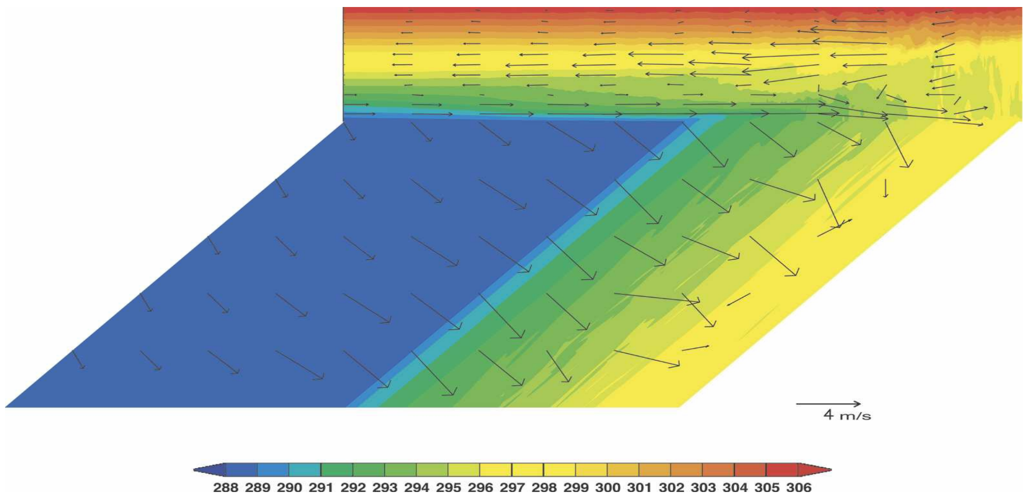
Large Eddy Simulation (LES) Modeling and WTG Parameterization

The RU-WRF model LES subroutine along with the WTG parameterization scheme could be implemented to analyze and predict turbulent wake effects resulting from large offshore wind facilities that are affected by perturbations to the coastal/offshore wind resource. These local flow perturbations, which can be caused by the sea breeze circulation and coastal storms will create complex wind patterns within and external to an offshore WTG array. To account for the variability and controlling physics of the aforementioned complex flow occurrences and their impact on the WTG array in addition to individual WTGs, LES modeling appears to be the most realistic and representative method for qualifying and quantifying the adverse impact of turbulent wakes on WTG performance. For comparison, LES modeling along with WTG parameterization could also be used for assessing turbulent wake impact for periods when no local flow perturbations are affecting the offshore wind resource. Although, "usual" turbulence intensity is less when compared to the turbulence properties produced during local flow perturbations, there will still be resultant reductions in WTG performance caused by turbulent wake effects. The variable and at times intense turbulent wake issue should be taken into account when determining the efficiency of offshore WTG performance in addition to cost-effective planning and design of an offshore wind energy facility. Simulations of WTG turbulent wakes and related turbulence parameters are shown in the following images:



Simulation results for turbulence parameters obtained using LES with a Lagrangian scale-dependent dynamic model: average velocity (top), turbulence intensity (middle), kinematic shear stress (bottom).

In addition to analyzing WTG turbulent wake effects, RU-WRF-LES modeling can be used to provide a detailed area-specific assessment of the turbulence properties, point-specific wind vectors, wind shear, and flow trajectories that potentially could be encountered during each NJ sea breeze type and coastal storm event. The below LES simulation shows the 3D wind circulation for a sea breeze occurrence:

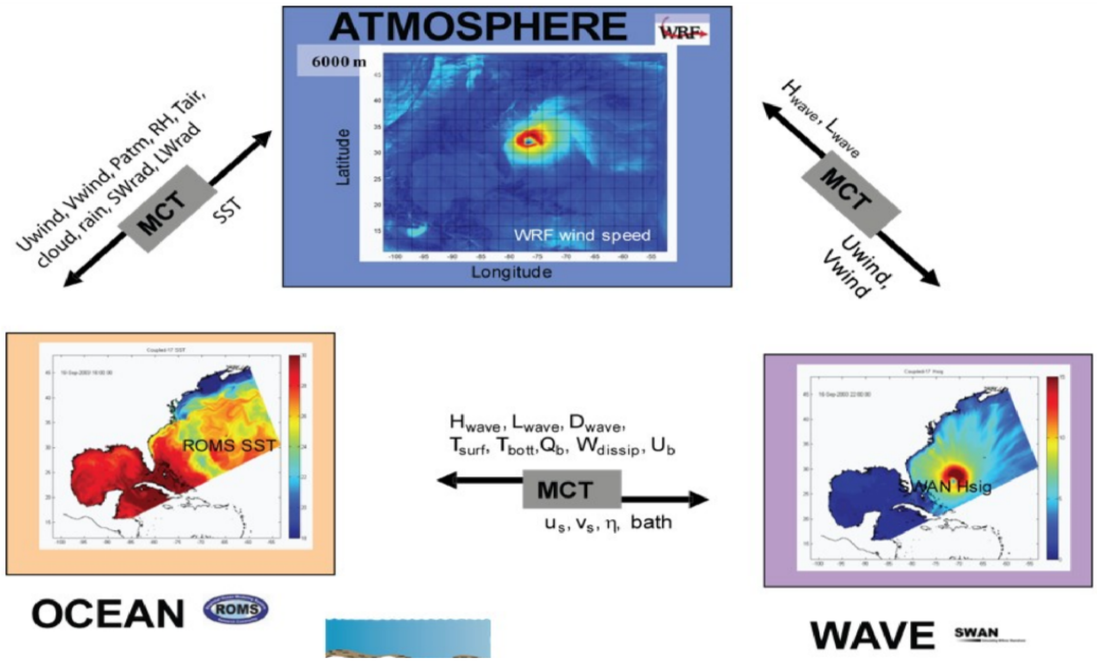


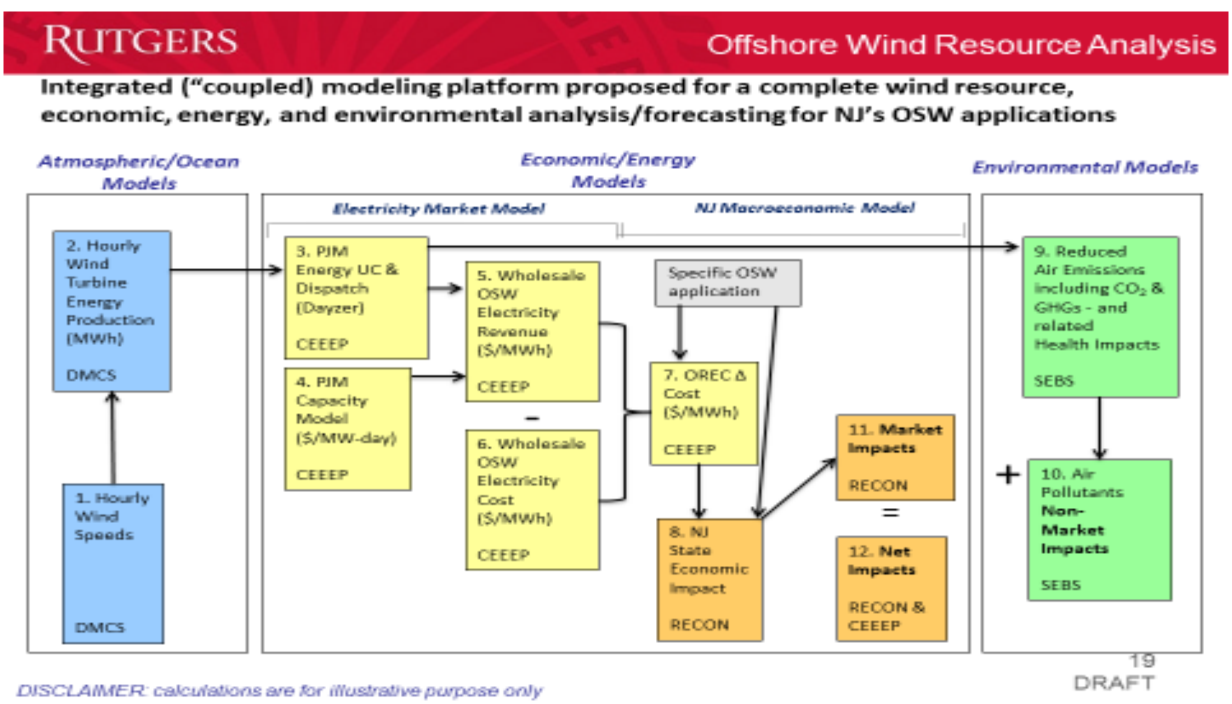
Perspective view of a LES model simulated sea breeze wind vectors near-surface to ~100m above MSL.

Combined Modeling System to Support OSW Projects and Other Utility Activities
A "coupled" ocean/atmospheric model can be developed and implemented. The Coupled-Ocean-Atmosphere-Wave-Sediment Transport (COAWST) system framework provided by USGS will be set-up and used as the basis for the proposed coupled model. If implemented, the atmospheric model component in this system will be the most current version of the RU-WRF model, which is consistent with prior and current atmospheric modeling efforts conducted for the OSW project. The ocean model component that will be used is the Regional Ocean Modeling System (ROMS), which was developed by and is currently being used by the RU DMCS for their several oceanography projects with a focus on the Mid-Atlantic coastal/offshore waters. ROMS uses a "dynamic" rather than a "static" ocean for SSTs, which enhances the realism and accuracy of the model input for the RU-WRF model. Using a static ocean, which is commonly used by most modeling programs, usually produces satisfactory results since SSTs do not significantly change from day to day. However, when analyzing specific local coastal/offshore areas (e.g., NJ) affected by upwelling and/or ocean current changes, there is a high probability that SSTs can significantly change during a diurnal period. Consequently, when considering area-specific offshore endeavors (e.g., wind energy development and operations) the ocean model (e.g., ROMS) will process dynamic SSTs for input to the atmospheric model (e.g., the RU-WRF model) to ensure the accuracy and reliability of the "coupled" model. Furthermore, since the wave component of the coupled model requires extensive computer capabilities, the wave component can be "turned" on or off as needed.

The coupled model can be implemented for both diagnostic and predictive applications (e.g., offshore wind resource assessments, sea breeze analyses/predictions, and coastal storm forecasts). Additionally, the coupled model results could be incorporated into RU CEEEP's Energy/Engineering, Economic, and Environmental model(s) to provide a more automated, efficient, and reliable data exchange procedure.

Schematics associated with the “combined” modeling system are provided in the following figures:





Combined modeling system that can be implemented to support OSW development and operations along with other utility activities.

Based on the previous discussion, in addition to offshore wind energy functions, it is implied that the Rutgers DMCS/CEEEP combined modeling system could be utilized as a “multi-use” program to support the utility industry.

Assessments and atmospheric/ocean forecasting could be provided for the following activities associated with offshore wind energy projects and the utility industry:

- Severe and general area-specific weather forecasting to support OSW construction efforts, O&M protocols, and energy trading (selling)/procurement procedures.

- Severe storm forecasting to support utility storm management and restoration efforts.

Severe weather impacting an offshore wind energy facility.

- PJM grid management including the efficient ingestion of renewable energy facilities (e.g., offshore wind) into the conventional generation "mix" to supplement energy supply requirements, especially during periods of "Peak" energy demand. The addition of renewable energy into the available energy supply could potentially assist in the mitigation of the following problematic issues currently being encountered during both the "Primary" and "Secondary Peak" energy demand periods, which respectively occur during the summer and winter seasons:

    - Available energy supply vs. the exceptionally high demand that is affiliated with the densely populated area serviced by PJM.

    - Grid congested where demand exceeds supply.

    - Efficient transmission and distribution of energy in a timely and cost-effective manner to the consumer.

The Rutgers DMCS coupled atmospheric/ocean model when combined with the Rutgers CEEEP energy/engineering, economic, and environmental models should reduce much of the "risks" and "uncertainty" involved in the decision making process for offshore wind energy projects that potentially will be installed within the BOEM NJ WEA. Therefore, using these unbiased modeling programs to evaluate proposed projects can help to ensure the project is technologically feasible and economically viable. Furthermore, this comprehensive modeling system, which is continually being developed and improved, could be expanded to help resolve the resiliency and reliability issues that are of primary concern for the utility industry, regulatory agencies (e.g., NJBPU), and consumers.

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Dunk, R (2014): *Phase II*: *Atmospheric/Oceanic Analyses and Predictions to Support the Wind Energy Development Application Process Defined in NJBPU's Offshore Wind (OSW) Renewable Energy Rules (N.J.A.C. 14:8-6) and the Offshore Wind Energy Development Criteria Presented in the NJ Energy Master Plan.*

Along with the *Phase III* OSW project, the *Phase I* and *Phase II* OSW studies including supporting documentation, data sets, and resultant NJ offshore wind resource "maps" can be reviewed using the URL: **http://rucool.marine.rutgers.edu/BPU**