1. Sea breeze sensitivity to WRF model configuration

a. *June 18-19, 2014: Sensitivity to RUWRF model resolution and initial conditions*

In the evening of June 18, 2014, a weak sea breeze front penetrated slightly onshore along northern coastal New Jersey (NJ), from northern Long Beach Island up to Sandy Hook. Coastal weather observations along this NJ strip showed moderate winds from the west to west-northwest during the day on June 18, with a sudden shift in wind direction—within minutes and directly the result of the sea breeze—to winds out of the east-southeast. A similar shift in wind direction was not observed south of Long Beach Island to Cape May. Because of the absence of observations offshore, including over the NJ Wind Energy Area (WEA), it is unknown how winds evolved where offshore wind (OSW) energy development is planned.

The validated Rutgers University version of the Weather Research and Forecasting (RUWRF) model was running in real-time during this time period, providing a modeled depiction of winds over the WEA as well as across NJ. Three different spatial resolutions of RUWRF—9 km, 3 km, and 400 m—provided different representations of the coastal/offshore winds during this sea breeze circulation. First, the 9 km resolution RUWRF is shown below in **Figure 1**, at 00 UTC on June 19, 2014 (8pm EDT on June 18), which was at initialization for the daily real-time forecast. This RUWRF model resolution shows general winds from the west/west-northwest, and an area of stronger winds across the southern half of NJ. Second, the 3 km resolution RUWRF is shown in **Figure 2** at the same time as **Figure 1**, and again at model initialization. RUWRF 3km shows the same general pattern of large-scale winds from the west-northwest with the strongest winds in the southern half of NJ and well offshore. However, there is striking difference along the northern half of the NJ coastline, where winds are oriented out of the southeast, associated with the sea breeze circulation. The area of southeasterly winds covers the northern half of the NJ WEA as well. Third, RUWRF 400m is displayed in **Figure 3** again at model initialization, showing a similar story as RUWRF 3km.

For initial and boundary conditions, RUWRF 9km uses the Global Forecast System (GFS) 0.5 degree (~55 km) resolution operational weather model. Winds at 80m from GFS 0.5 degree (100m were unavailable) are shown in **Figure 4** at the same time as **Figures 1-3**; moderate winds out of the west over the southern half of NJ are shown, similar to RUWRF 9km. In contrast to RUWRF 9km, the 3km and 400m nests of RUWRF both use the North American Mesoscale (NAM) 4km model (**Figure 5**) for initial conditions. Weak westerly winds over the central and southern NJ are shown in NAM 4km—a stark difference to GFS.

Finally, **Figure 6** shows verification of RUWRF against observations of wind at Barnegat Inlet, a coastal meteorological station owned and operated by WeatherFlow, Inc. and whose location is depicted in white in **Figures 1-3**. Observed 10m winds show a sharp and sudden shift in wind direction from about 300 degrees to about 125 degrees around 00 UTC. RUWRF 9km does not show this shift in wind direction, whereas RUWRF 3km and RUWRF 400m both do. RUWRF 9km keeps the wind blowing at around 250 degrees for the next several hours, while RUWRF 3km maintains wind direction at around 100-150 degrees and a lighter wind at around 3 m/s.

For this sea breeze case, it appears that the initial conditions used are just as important as model resolution. RUWRF 9km used GFS 0.5 degree for initial conditions, which had a much lower resolution than the NAM 4km used for RUWRF 3km and 400m initial conditions. The spatial and temporal variability of each sea breeze event, including across coastal/offshore regions, can be effectively modeled with the right choice of initial conditions and sufficient model resolution. The next section describes a sea breeze case in 2013 where only model resolution—not initial or boundary conditions—was tested.

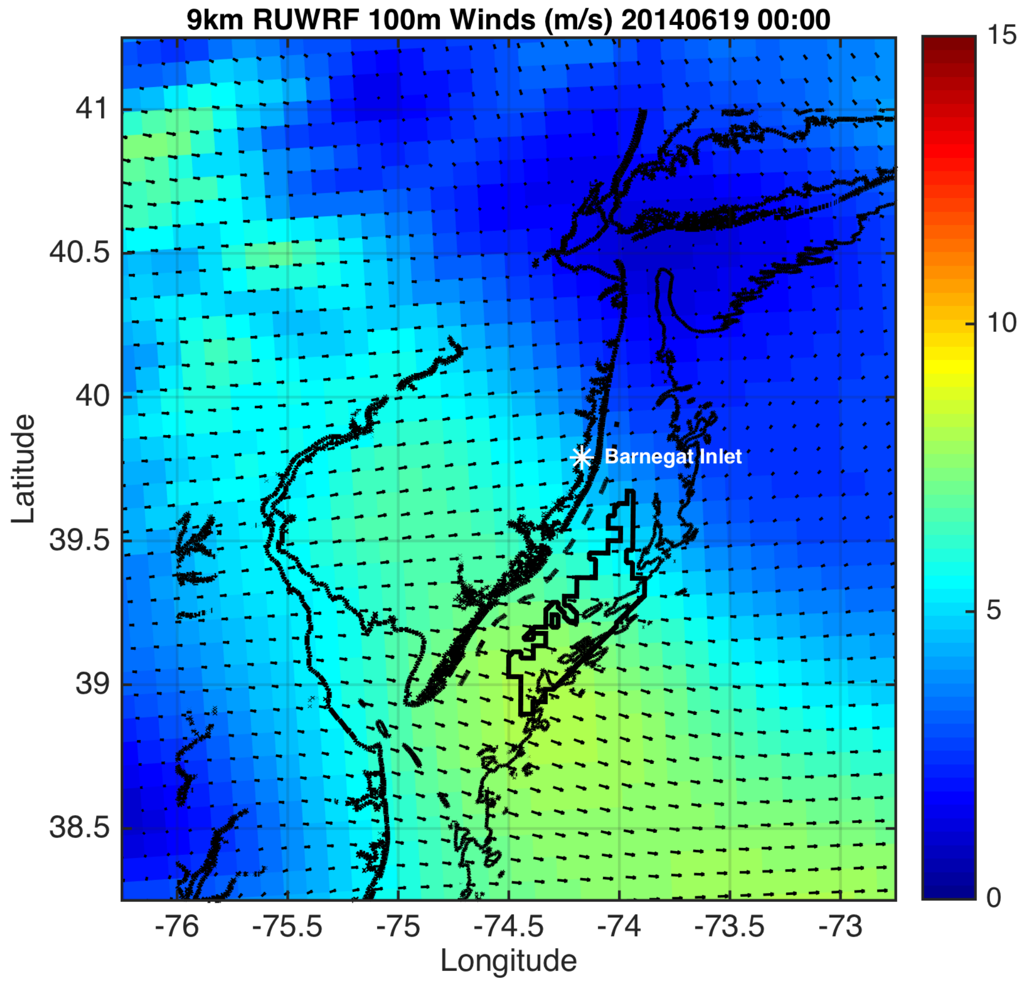

Figure 1. RUWRF 9km, showing 100m winds (m/s) at 00 UTC on June 19, 2014. Barnegat Inlet (white) is shown for model verification later. NJ WEA (black), 30 meter isobath (water depth, black), and federal/state water boundary (dashed black) are also shown.

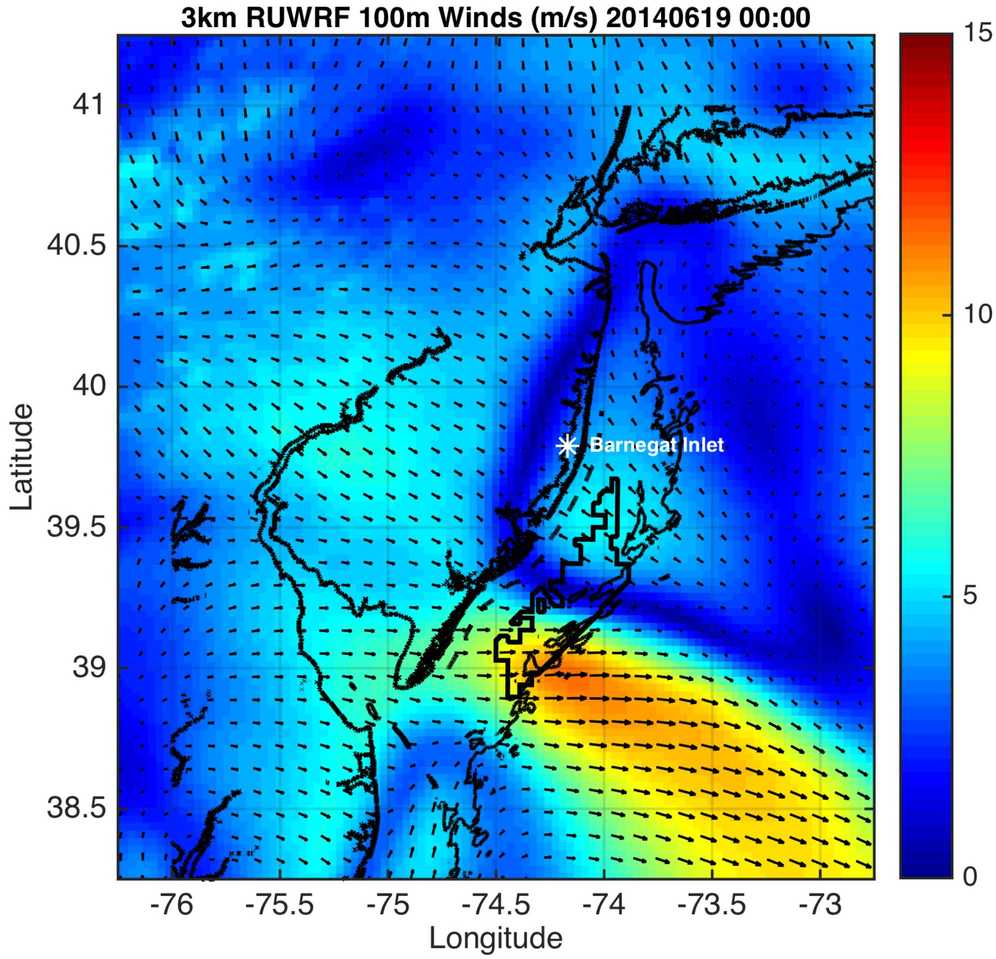

Figure 2. Same as Figure 1 but for RUWRF 3km.

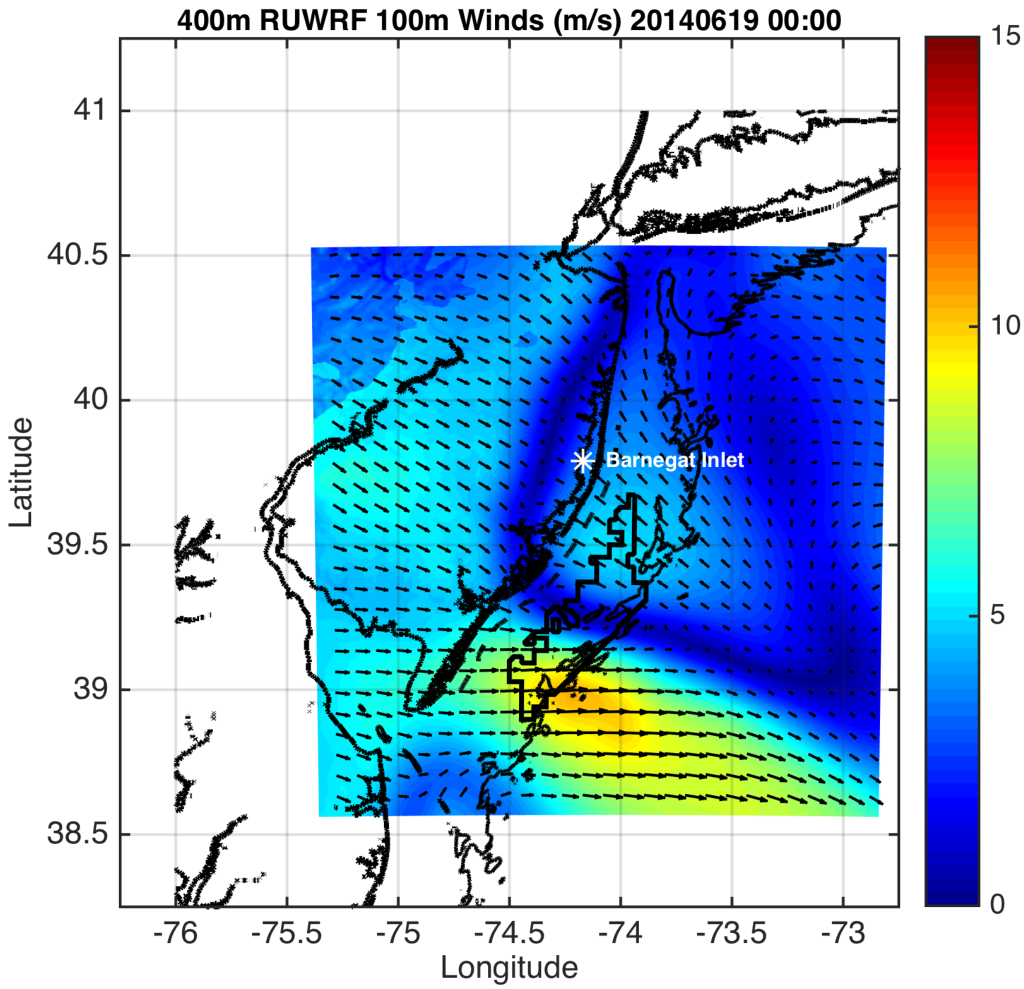

Figure 3. Same as Figure 1, but for RUWRF 400m.

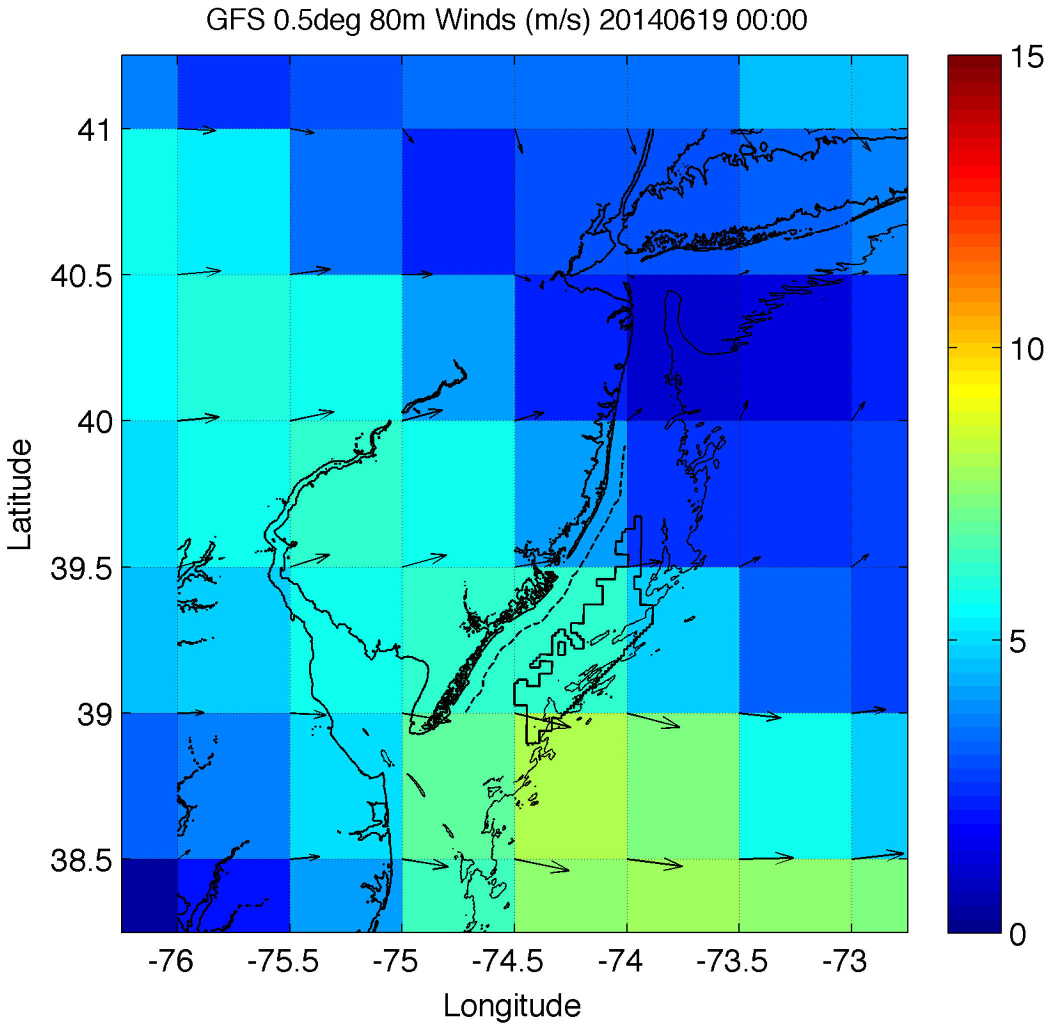

Figure 4. GFS 0.5 degree 80m winds (m/s) at the same time as Figures 1-3.

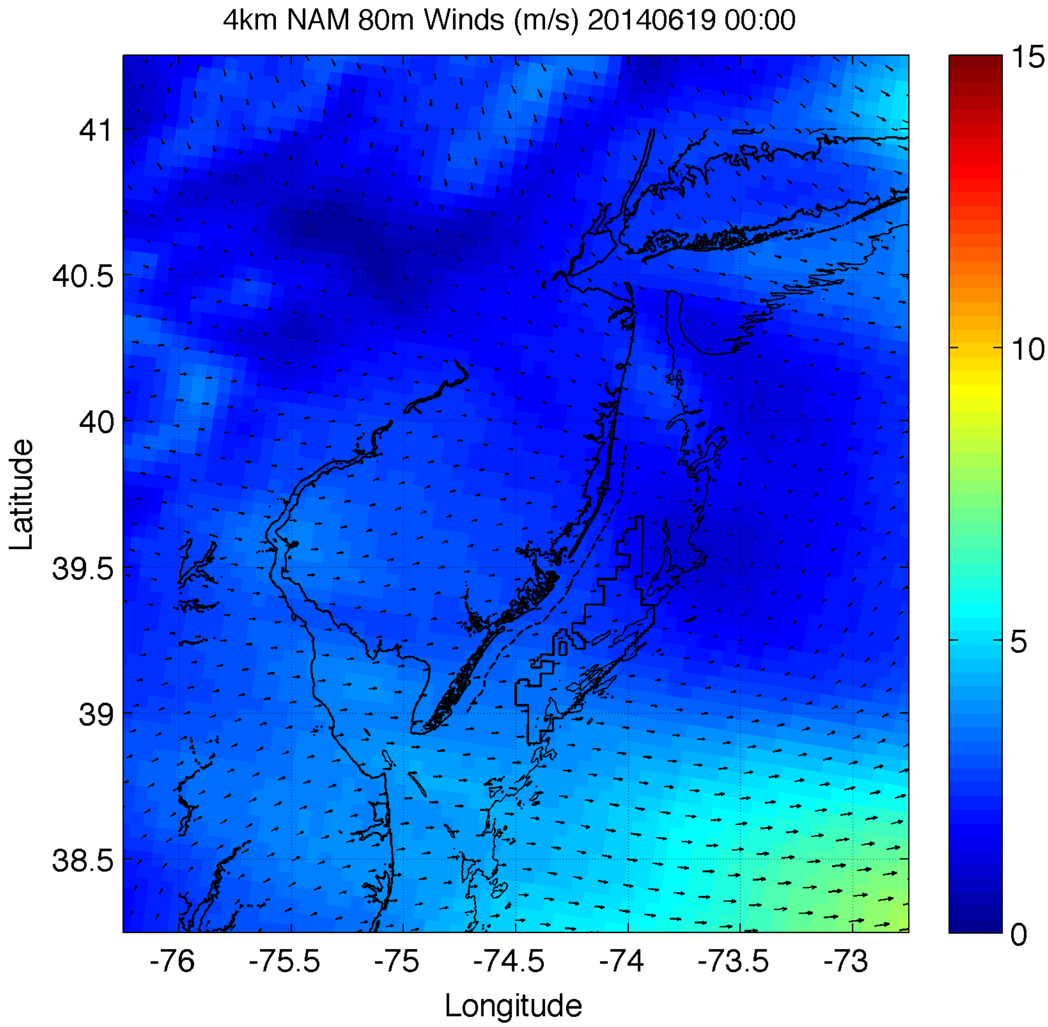

Figure 5. Same as Figure 4 but for NAM 4km.

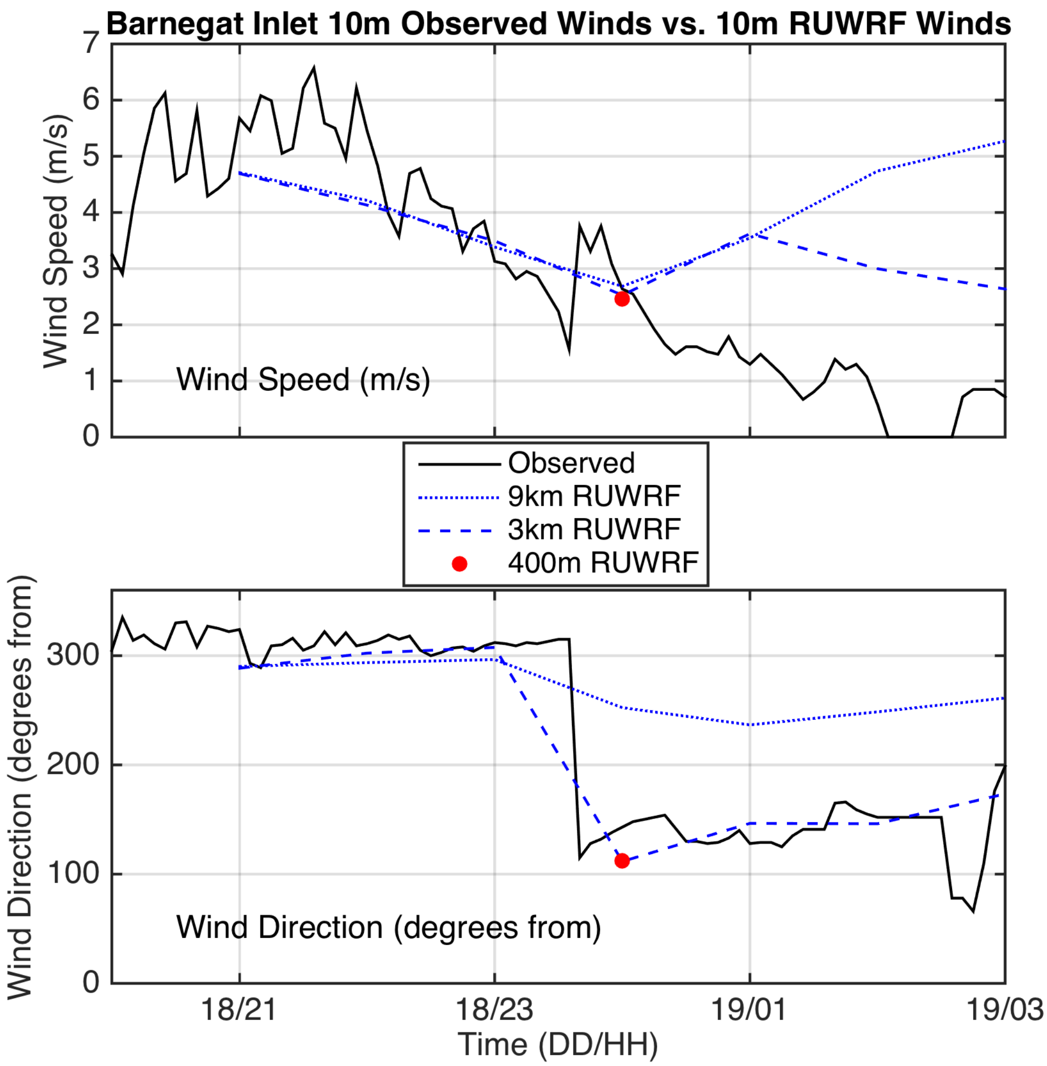

Figure 6. Barnegat Inlet WeatherFlow station 10m wind speed and direction vs. RUWRF modeled 10m wind speed and direction for 9km, 3km, and 400m. Times shown are UTC.

b. April 27-28, 2013: Sensitivity only to model resolution

On April 27, 2013, a spring sea breeze occurred in New Jersey, beginning at around 16:00 UTC, or noon local time, and lasting through about 01:00 UTC on April 28, 2013. Stronger winds out of the northeast (5-14 m/s) occurred in the early morning hours prior to the sea breeze, with synoptic winds diminishing to very light 0-5 m/s toward the later morning hours. Three WRF simulations—15km, 3km and 600m resolution—were conducted over this sea breeze case to test the sensitivity of the model's handle on capturing the sea breeze to model resolution. All three resolutions used the same exact boundary and initial conditions (NAM 12km), and the same exact model configuration, i.e. physics, microphysics, planetary boundary layer scheme, etc. Thus, in contrast to the prior section which tested model resolution and initial conditions, this sensitivity only tested model resolution.

Figure 7 displays a snapshot of 100m hub height winds at 21:00 UTC from the 15km simulation, and **Figures 8 and 9** display the same hourly snapshot from the 3km and 600m simulations, respectively. Note that the sea breeze front extends from extreme southern NJ near the Delaware Bay up to Sandy Hook, with stronger 5-7 m/s winds out of the southeast behind the front, and very light and variable 0-2 m/s winds in front. All three simulations capture the overall wind pattern, but the 15km simulation seems like it is slower to propagate the sea breeze front inland. Offshore in the NJ WEA, winds are weakest in the 600m simulation and strongest in the 3km simulation at this hour.

Finally, simulated winds are verified against observed winds from the WeatherFlow Tuckerton 10m meteorological tower (**Figure 10**). Vertical black dashed lines indicate the start and end time of the sea breeze circulation for this case, while observed winds (solid black), 15km WRF winds (dotted blue), 3km WRF winds (dashed blue), and 600m WRF winds (solid red) are plotted for both speed (top) and direction (bottom). No abrupt wind direction shift as in the previous case was either observed or modeled, but a gradual shift from about 100 degrees (from the ESE) to 200 degrees (from the SSW) was observed. This gradual shift in wind direction was captured well by all three resolution simulations. Also, wind speeds were captured fairly well by all three simulations. While a gradual decrease in wind speed from about 6 m/s to about 3 m/s was observed, all simulations generally kept wind speeds in the 2-4 m/s range throughout the sea breeze circulation. At least for this one sea breeze case—a pure sea breeze with light synoptic conditions, model resolution did not significantly affect the model's ability to capture the sea breeze.

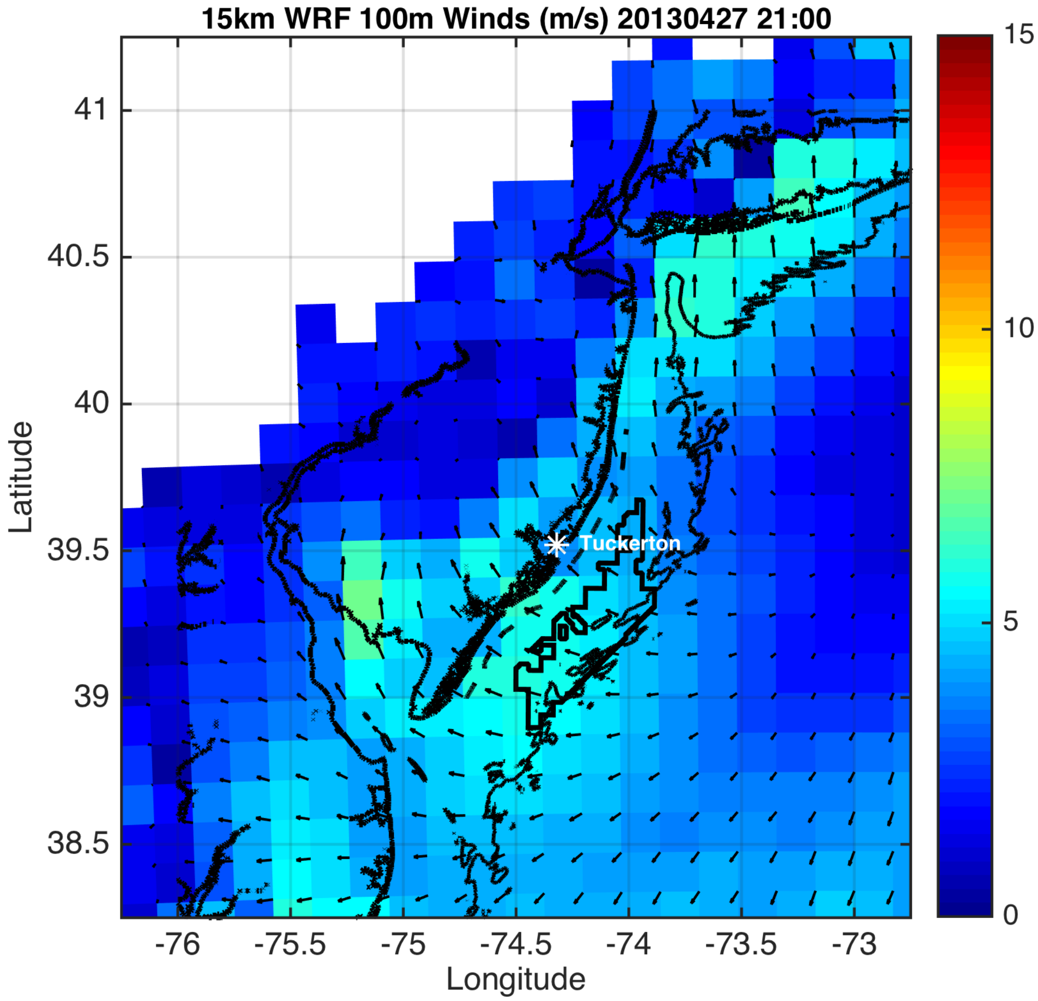

Figure 7. WRF 15km, showing 100m winds (m/s) at 21 UTC on April 27, 2013. Tuckerton (white) is shown for model verification later. NJ WEA (black), 30 meter isobath (water depth, black), and federal/state water boundary (dashed black) are also shown.

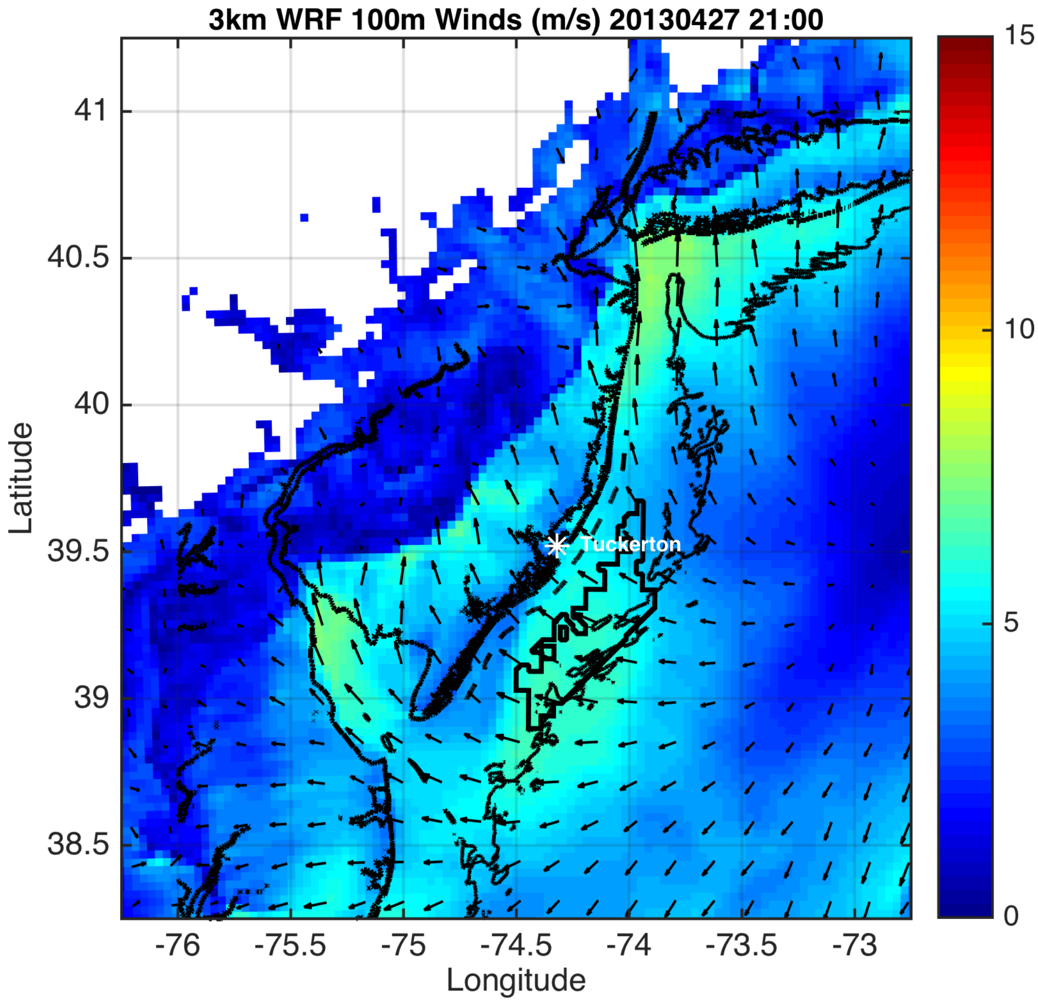

Figure 8. Same as Figure 7, but for WRF 3km.

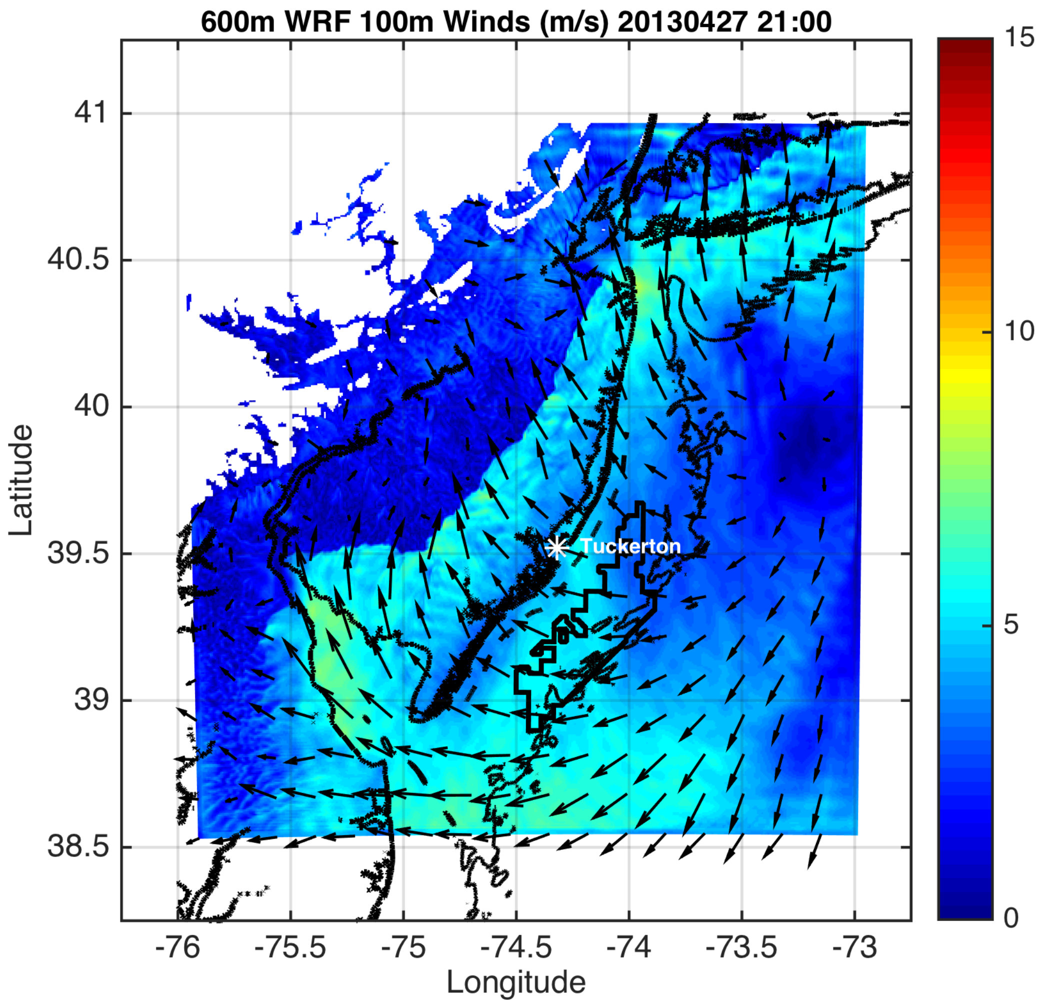

Figure 9. Same as Figure 7, but for WRF 600m.

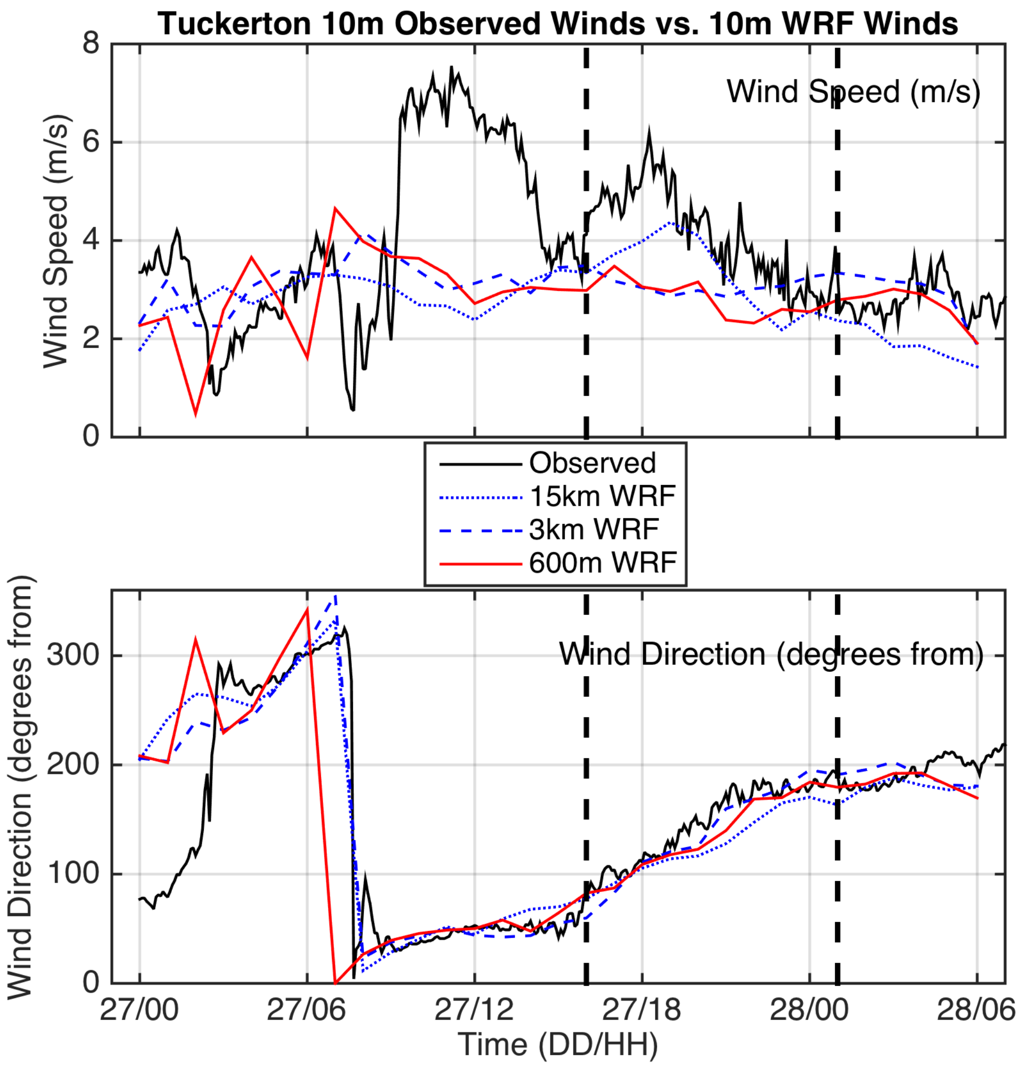

Figure 10. Tuckerton WeatherFlow station 10m wind speed and direction vs. WRF modeled 10m wind speed and direction for 15km, 3km, and 600m. Vertical black dashed lines indicate the start and end time of the sea breeze circulation. Times shown are UTC.

2. Sea breeze turbulence analysis

Atmospheric turbulence can have a significant impact on both wind turbine power generation engineering considerations for wind turbines. First, higher levels of turbulence result in a quick change in wind direction or wind speed, and can thus lead to localized "stalling" of rotor blades and a lower energy output by the turbine. Second, greater turbulence can lead to higher fatigue loads, and thus wind turbines designed for higher turbulence environments cost more and yield less energy.

General wind resource assessments try to quantify the amount of turbulence a site will receive over a long period of time, i.e. 1-5 years. However, turbulence can vary greatly—similar to wind speed—at a given site between every month to every day to every hour. Quantifying this variability is critical to lowering risks associated with investing and constructing these wind farms.

In this section, we aim to quantify the variability in turbulence for coastal/offshore New Jersey for different atmospheric conditions. Specifically, we use data from a WindCube LIDAR, which was deployed by Fishermen's Energy at the Atlantic City Central Pier for a 2-month period from March 13 to May 13, 2013. During this period, the data from WindCube were used to validate the collocated buoy-mounted Axys Wind Sentinel vertical LIDAR.

A visual inspection of NEXRAD weather radar data revealed that during this 2-month period, 20 sea breeze days occurred out of the total 62 days. An example sea breeze case occurred on April 27-28, 2013 (as analyzed in section 1b above). Wind speed at 52m from the WindCube is compared to modeled 3km resolution and 600m resolution WRF simulated wind speed at 50m for this sea breeze case (**Figure 11**). Besides some differences at the start of the day before the sea breeze occurred (start and end times of sea breeze indicated by vertical dashed lines), WRF overall does a decent job at resolving the general wind speed during this sea breeze case.

How do hub height wind speed, wind power density, turbulence intensity (TI), and wind shear within the 20 sea breeze days compare to the entire 62-day period? The WindCube provides data from 52m to 119m in the atmosphere, which are the approximately offshore wind turbine rotor blade height dimensions. To answer this question, we take the median wind speed (m/s) at 52m and 119m for the entire 62-day period, and then take the median 52m and 119m wind speed for just the 20 sea breeze days, and compare. We do the same for 52m and 119m wind power density (W/m^2), 52m and 119m TI, and 119m-52m wind shear (m/s). The resulting medians are shown in **Table 1**. Wind speed, wind power density, and TI at both heights are lower on the 20 sea breeze days as compared to the overall 62-day period. 119m-52m wind shear is actually higher for the sea breeze days as compared to the overall 62-day period.

To determine if the difference in medians is statistically significant, we perform the Kruskal-Wallis Test, which makes no assumptions about the distributions of the data, including normality. This test works well for the data here because the distributions may not be Gaussian—they are most likely Weibull distributions. **Table 1** again shows the results of the Kruskal Wallis Test. For wind speed, wind power density, and TI at both heights, the difference between the median for the sea breeze days and the median for the overall period is statistically significant. For 119m-52m wind shear, the difference between the median for the sea breeze days and the median for the overall period is NOT statistically significant. A larger sample size may be required in order to determine whether wind shear during sea breeze is higher or lower than the overall period.

The results of this analysis make sense: wind speed is lower at a coastal location during a sea breeze day as compared to the average day, and the resulting wind power density, which is based on the wind speed cubed, is also lower. Turbulence intensity is lower during the sea breeze days as well, likely directly due to the lower wind speeds which inherently have lower turbulence values, all else being equal. However, the cause of the lower wind speeds, wind power densities, and TI during the sea breeze days is not known. Is it because the sea breeze is more likely to form during lower synoptic wind conditions? Or is it rather because the sea breeze circulation itself causes lower wind speeds at the coast? Further research will be needed to determine which causes which, and a longer record will be needed to determine whether wind shear across wind turbine blade heights is higher or lower during a sea breeze day as compared to a non-sea breeze day.

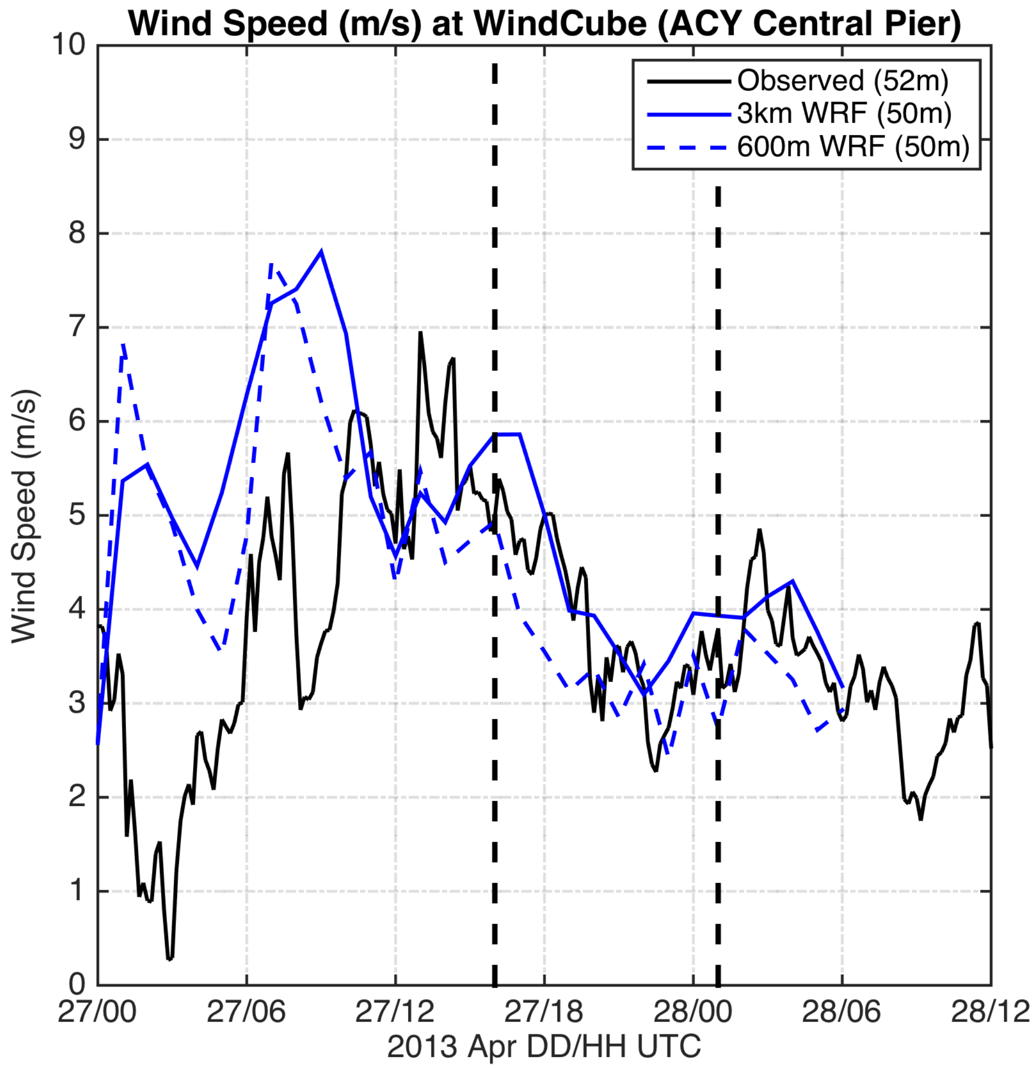

Figure 11. Wind speed (m/s) at WindCube (ACY Central Pier). Observed winds at 52m (black), 3km WRF winds at 50m (solid blue), and 600m WRF winds at 50m (dashed blue) are shown. Vertical dashed lines indicate start and end times of sea breeze circulation.

Table 1: Wind speed, wind power density, TI, and 119m-52m Wind Shear, differences between medians, and p-values computed from Kruskal-Wallis Test.

Wind Speed (m/s) (n = 10,634)						
	52m			**119m**		
	Median	Dif	p-value	Median	Dif	p-value
All Days	6.25			8.27		
		0.44	<0.0001		0.47	<0.0001
Sea Breeze Days	5.81			7.8		

Wind Power Density (W/m^2) (n = 10,634)						
	52m			**119m**		
	Median	Dif	p-value	Median	Dif	p-value
All Days	148.1			343		
		29.1	<0.0001		55.2	<0.0001
Sea Breeze Days	119			287.8		

Turbulence Intensity (n = 10,634)						
	52m			**119m**		
	Median	Dif	p-value	Median	Dif	p-value
All Days	0.159			0.105		
		0.029	<0.0001		0.02	<0.0001
Sea Breeze Days	0.13			0.085		

119m-52m Wind Shear (m/s) (n = 10,634)			
	Median	Dif	p-value
All Days	1.92		
		-0.15	0.893
Sea Breeze Days	2.07		