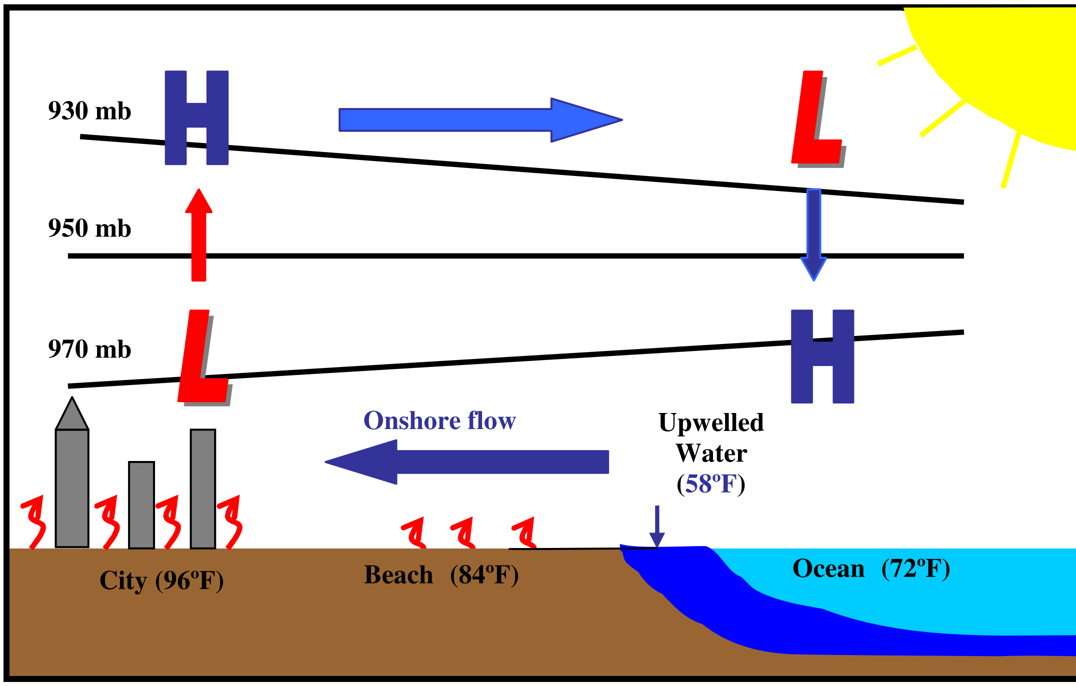
# The NJ Sea Breeze, Coastal Wind Shear, and Wind Power Potential

## *Sea Breeze Description*

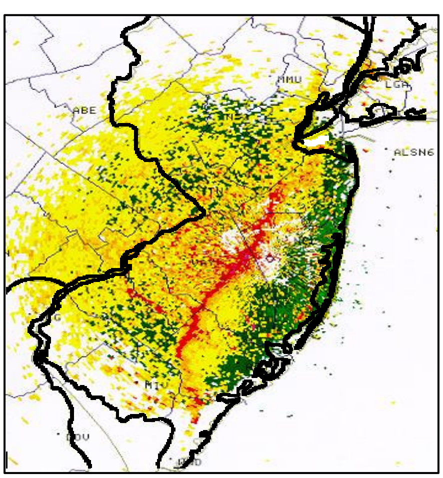
The NJ sea breeze occurs as a result of differential heating between relatively dry warm air over land and moist cool air over water. This thermodynamic process produces a strong temperature gradient with a resultant intense onshore airflow that will cause sea breeze advection to extend from the coast to several kilometers inland. The following diagram depicts the sea breeze circulation.

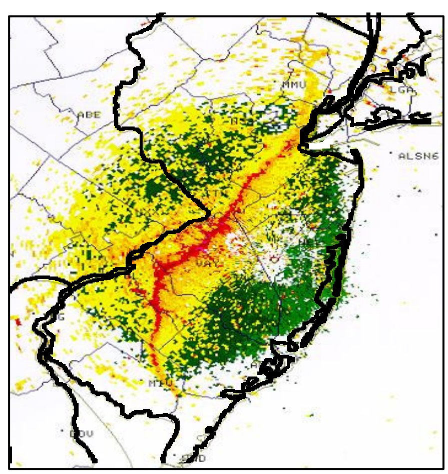



**Sea Breeze Circulation**

As the Atlantic Sea Breeze propagates inland, the onshore flow will be opposed by the prevailing synoptic flow causing the speed of inland penetration to lessen and eventually be curtailed. At this transition location, which is defined as the sea breeze front, winds converge with a significant vertical velocity component. At some upper level, winds above the "front" will travel toward the sea completing the circulation creating the sea breeze cell. The following Doppler radar images show the propagation of the sea breeze as defined by the concentrated red backscatter that delineates the sea breeze front.

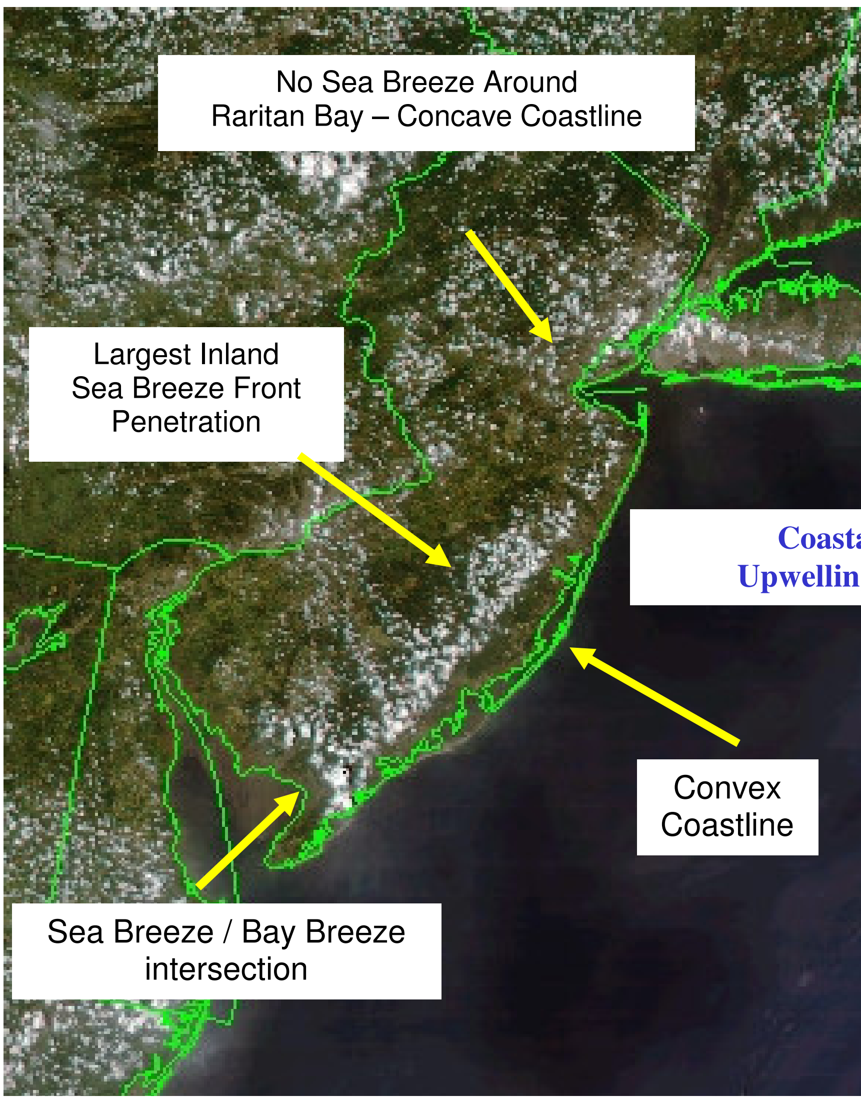
**Doppler Radar showing the Sea Breeze Front**



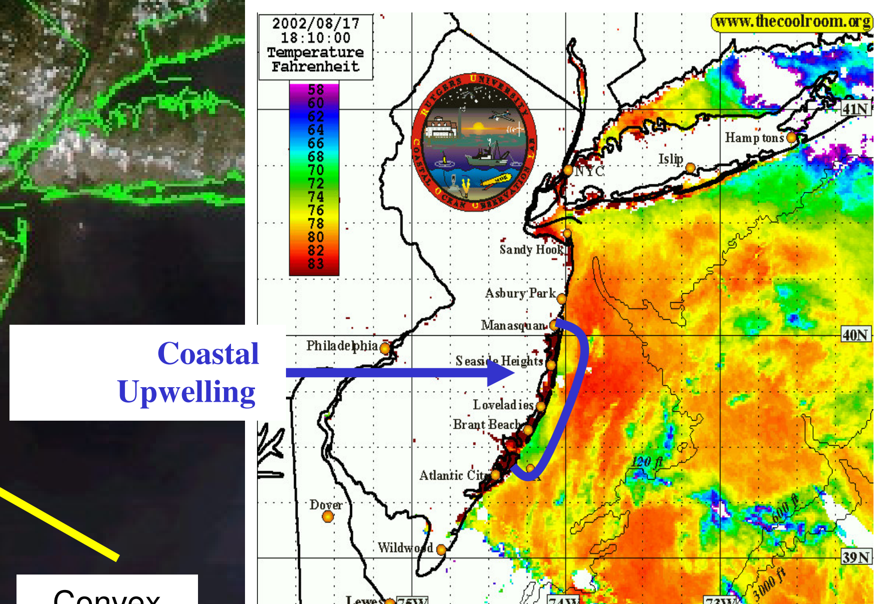



Sea breeze structure and dynamics are dependent on the following physical properties:

- Thermodynamics of the terrestrial and adjacent marine boundary layers.
    - Temperature gradient between the land and water interface.
    - The occurrence or non-occurrence of coastal upwelling (colder water near the bottom of the ocean is brought to the surface along the coast).
- Coastline configurations and inland terrain features.
- The images shown below illustrate the cause and effect relationships associated with sea breeze development:




**MODIS Visible Satellite Image**



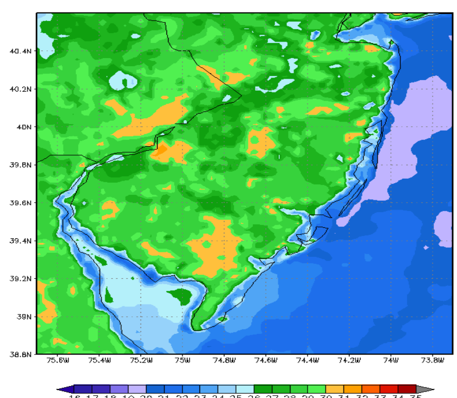

Infrared Satellite Image

Referring to the preceding visible satellite image, convex coastlines (e.g., central and south Jersey coastlines) will strengthened sea breeze development and concave coastlines (e.g., the Raritan Bay area) will tend to weaken sea breeze development. Inland surface features will also affect sea breeze development. Airflow over the forest canopy associated with the extensive Pinelands area located in central and south Jersey is relatively undisturbed allowing the sea breeze to intensify and propagate well inland. Urban features along with a prominent concave shoreline relevant to the Raritan Bay area will not only weaken sea breeze development but could also negate the existence of the sea breeze.

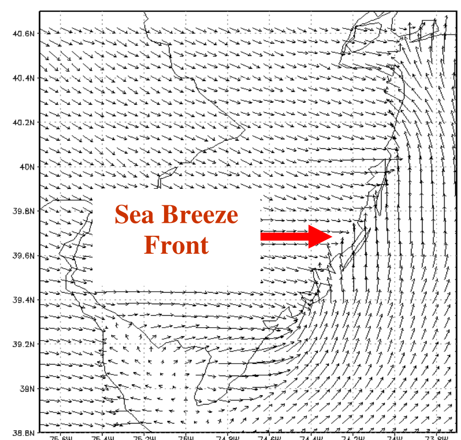
Coastal upwelling will tend to intensify the sea breeze circulation. However, sea breeze depth and penetration inland will not be as great when compared to a well-developed sea breeze not affected by upwelling. Upwelling cases tend to be associated with relatively strong south to southwesterly synoptic flow, which will dampen inland sea breeze propagation. The following sea breeze simulations illustrate the influence of upwelling on sea breeze development: The upwelling case shows limited inland sea breeze penetration with strong winds along the coast and immediately offshore ( 8 to 12m/s). The non-upwelling case shows that the sea breeze has moved farther inland with lesser wind intensities along the coast (7 to 9 m/s).

Upwelling Case

Surface Temperature

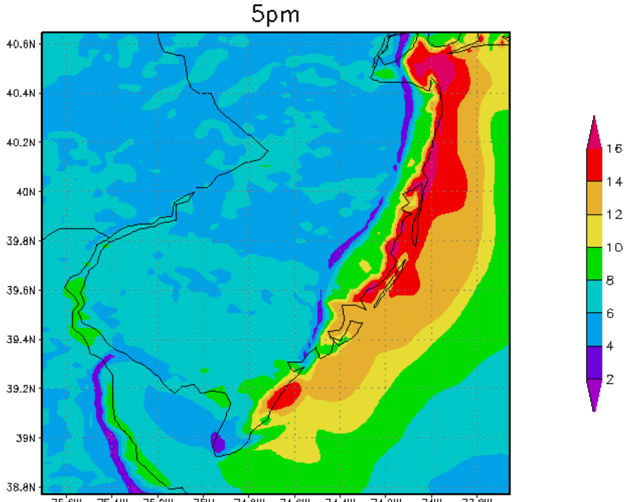


10m Wind

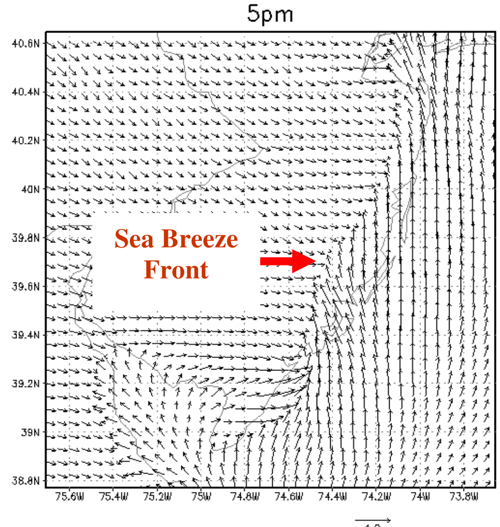



10m Wind Speed (knts) **Non-Upwelling Case** 10m Wind Speed (m/s)

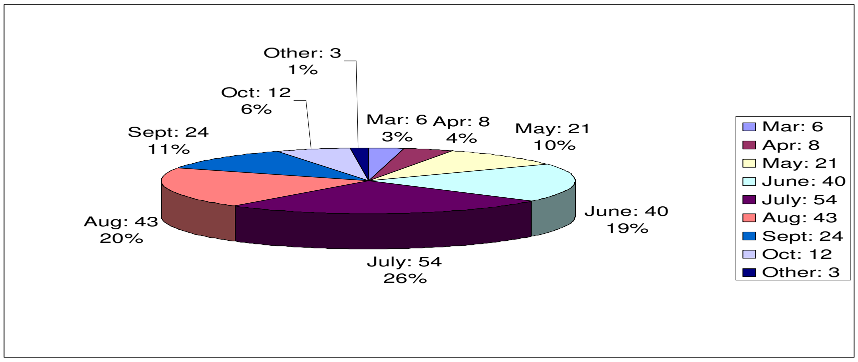
5pm



5pm



Local sea breeze circulations can occur during any month of the year when the thermal characteristics of the marine air and adjacent terrestrial air provide the conditions necessary for sea breeze development. As stated previously, these conditions include significant temperature gradients from colder coastal waters to warmer inland locations and minimal wind intensities associated with the prevailing synoptic flow. Although, sea breezes can occur throughout the year, well-developed sea breezes occur most frequently during the spring and summer seasons. Sea breeze frequencies are displayed in the following chart:

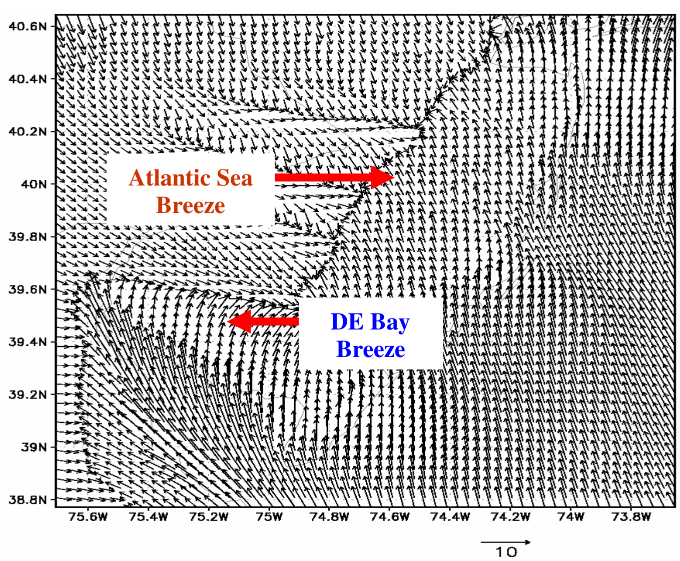



**NJ Sea Breeze Frequency of Occurrence**

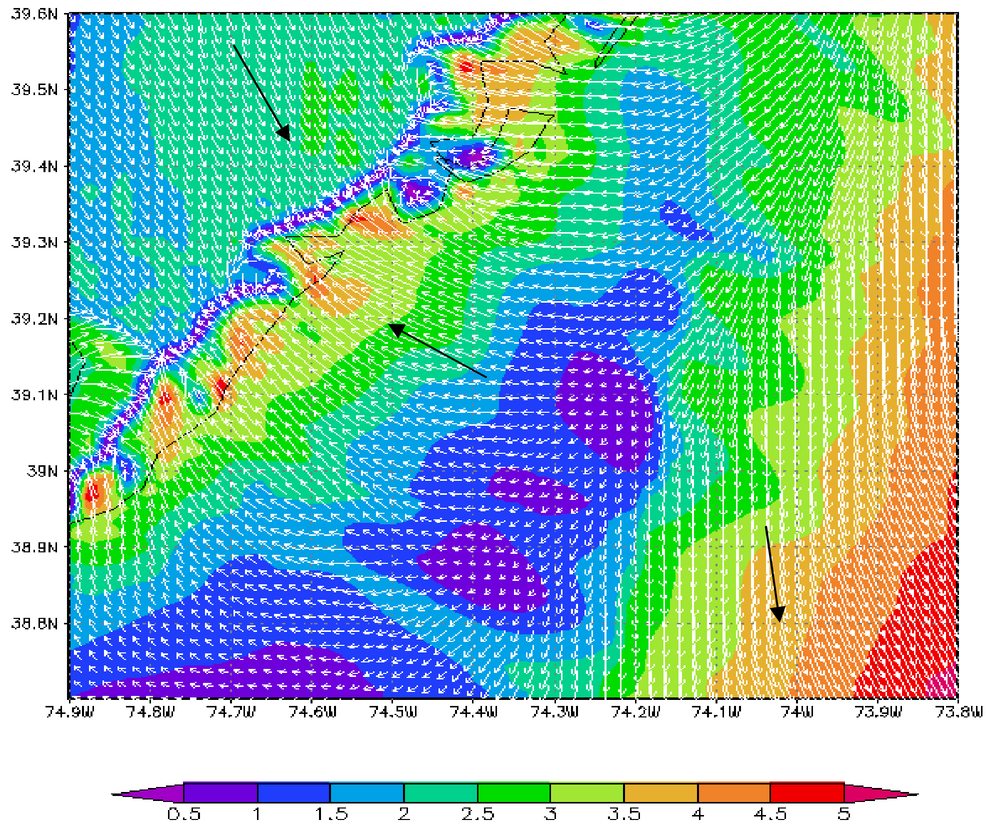
## *Sea Breeze Simulation Modeling*

Coastal meteorological monitoring data, ocean wave, surface current, and wind data derived from CODAR remote sensing along with actual sea surface temperatures (SSTs) were incorporated into the Weather Research Forecast (WRF) model to develop representative high-resolution 3-D wind field simulations. The Rutgers IMCS Coastal Laboratory for Applied Meteorology (CLAM) configured WRF to produce both synoptic (macro) scale and regional (meso) scale simulations that enabled the model to resolve local wind fields. These local wind fields (e.g., the sea breeze and/or DE Bay breeze circulations) can then be embedded in the larger scale wind flow pattern to produce a representative simulation of the actual wind resource. This "nesting" feature with grid resolutions ranging from 500 m to 1 km and from 2 km to 4 km enabled us to provide accurate and precise offshore/coastal wind resource analyses. The resultant model, RU-WRF, can be utilized for both diagnostic and predictive applications necessary for cost-effective policy and decision-making protocols associated with offshore/coastal wind energy development.

**RU-WRF Model Atlantic Sea Breeze and DE Bay Breeze Simulation**



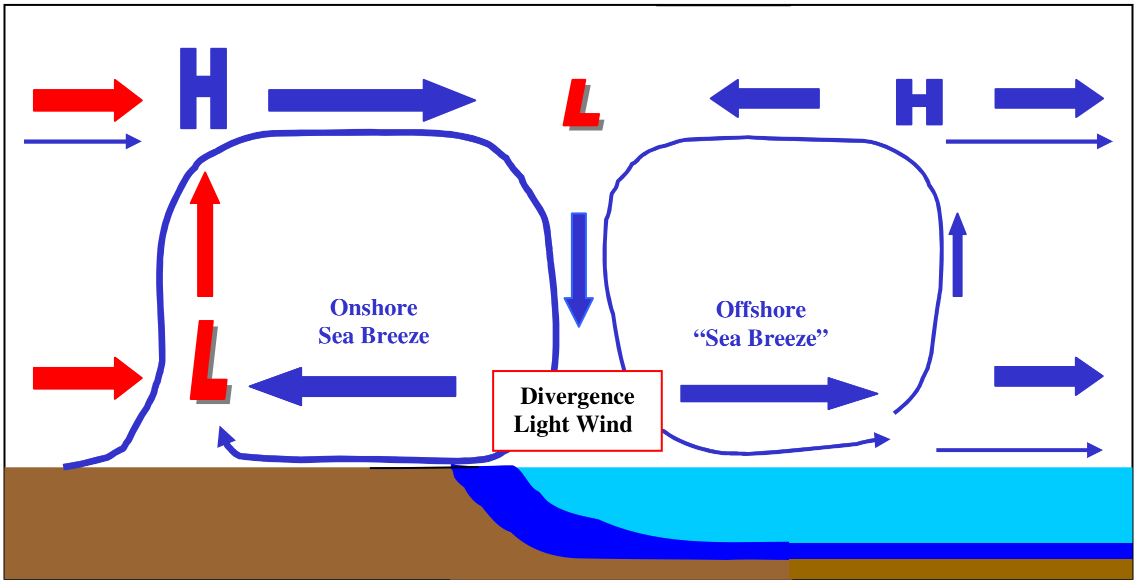
The following wind map displays a composite RU-WRF model simulation of a "typical" Atlantic sea breeze during its initial development. The simulation, which is centered on Central and Southern NJ coastal regions, indicates that wind intensities decrease from the coast to offshore areas out to ~30nm and then increase farther offshore from ~35nm to ≥50nm. Wind intensities decrease from the coast to the sea breeze front, which is located ~5 miles inland from the coastal shoreline. Maximum wind intensities occur near the coast behind the sea breeze front and ~50nm to 65nm offshore (orange to red areas). Minimum wind intensities occur inland at the sea breeze front delineated by the dark blue line running nearly parallel to the coast. Minimum wind intensities also occur offshore defined by the dark blue area between 15nm and 30nm offshore (Central Region); 10nm and 40nm offshore (Southern Region). The black arrows indicate the general wind directions for respectively the prevailing synoptic flow, the onshore sea breeze, and the "offshore" sea breeze.



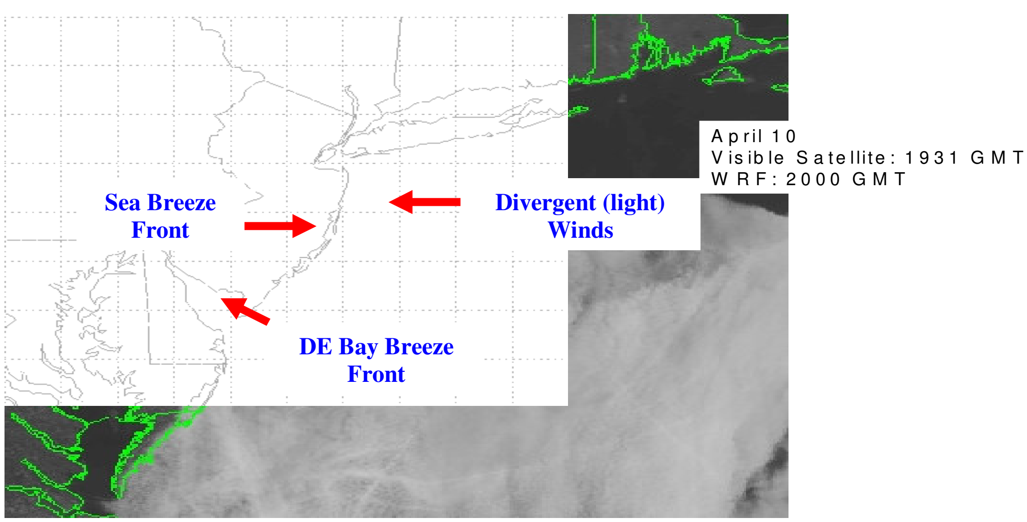

**RU-WRF model Simulation of Both Onshore and Offshore Sea Breeze Components**

Light winds will occur over a relatively large area offshore as a result of divergent winds that occur between the onshore and offshore sea breeze circulations (refer to the above figure). The same physical processes occur during DE Bay breeze development except the DE Bay breeze is not as intense and the offshore component is usually undetectable. As the sea breeze intensifies during the day, onshore wind speeds will increase by nearly a factor of two. Also, as the sea breeze intensifies, the ratio of the distances form the coast to the greatest extent of inland penetration and to the greatest extent of offshore development will vary from 1/10 to 1/2. Since the spatial and temporal dynamics of the sea breeze circulation varies for any given day, coastal and offshore wind resource parameters will be somewhat different over the area of interest for each sea breeze event.

A diagram of the onshore and offshore sea breeze components depicting flow vectors and thermal properties (red: warm, blue: cool) is presented in the following figure:



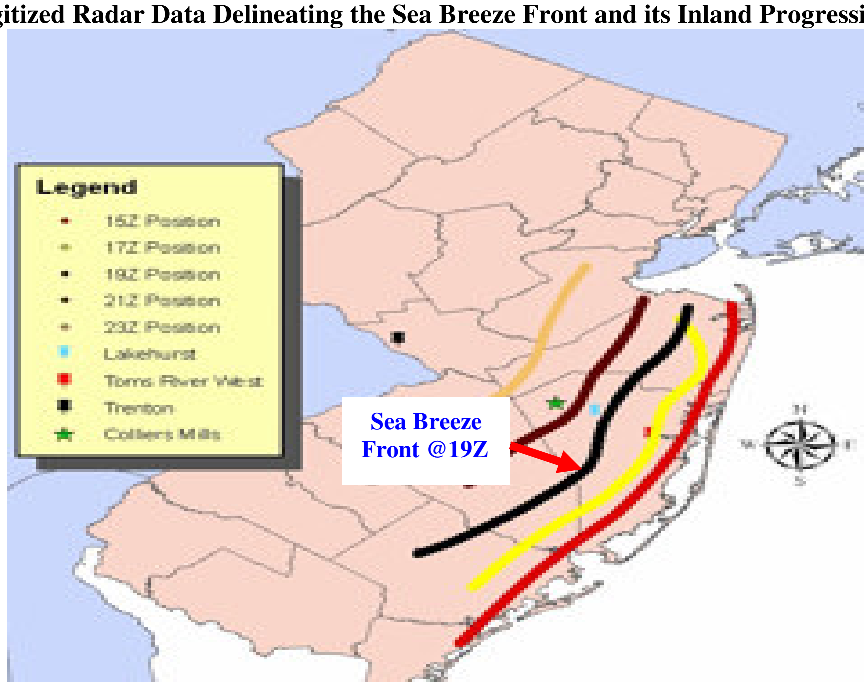

Recent RU-WRF model simulations indicate that the spatial extent of the offshore component of the sea breeze is far greater than originally expected. Model runs along with visible satellite imagery show that the offshore component of the sea breeze circulation exceeds the inland component by a factor of two to possibly an order of magnitude or greater. This finding has significant implications when analyzing the offshore wind resource to determine the "best" locations for offshore wind energy development. The following figure is a visible satellite image with an overlay of a RU-WRF model wind field simulation that shows a developing sea breeze off Long Island and the northern/central NJ coasts. The sea breeze forms along the coast with minimal inland penetration. However, the offshore sea breeze component extends several miles (~5 to 50nm) from the coast as indicated by the black areas where divergent winds result in low wind intensities (light winds <5m/s). Consequently, on the basis of these observations, it can be assumed that the offshore wind resource past 5nm becomes ineffective for wind power production during certain well-developed sea breeze events. These observations validate the previous RU-WRF model simulation and resultant assumptions presented on page 5.



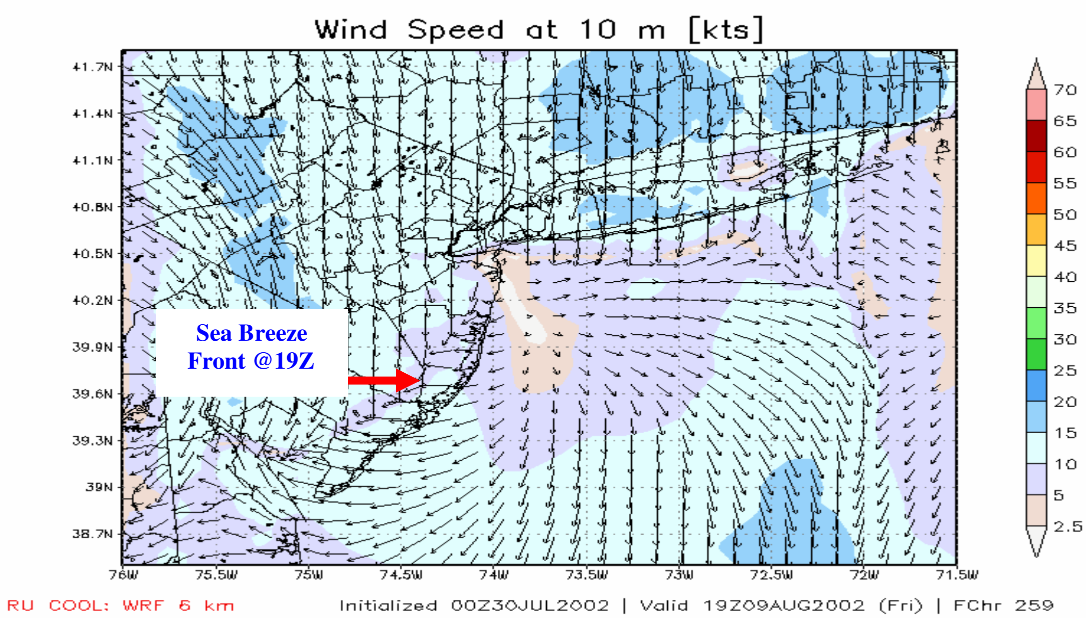
***Sea Breeze Model Verification***

RU-WRF model simulations of representative sea breeze occurrences show that the sea breeze front location and orientation coincide very closely with the actual sea breeze front displayed in concurrent Radar images. A representaive sea breeze event is used to illustrate the close comparison between observed sea breeze front locations and model simulations. The first (top) map depicts digitized Radar data showing the position and progression of the sea breeze front. The second (bottom) map is the corresponding RU-WRF model simulation.

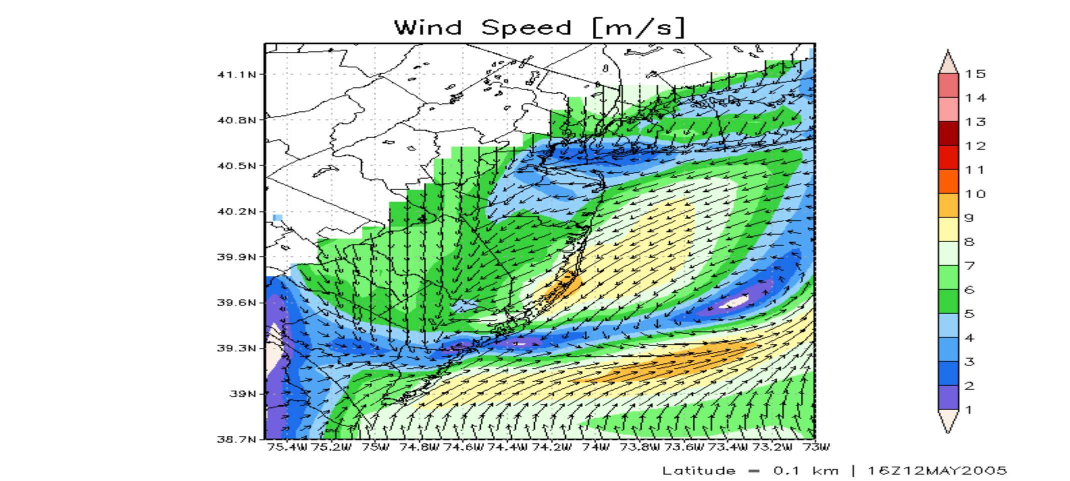
**Digitized Radar Data Delineating the Sea Breeze Front and its Inland Progression**

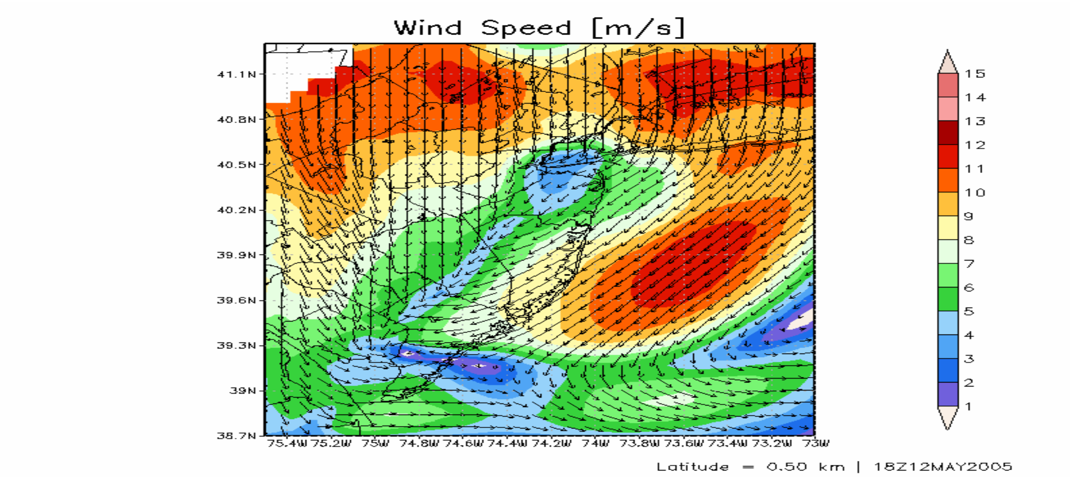


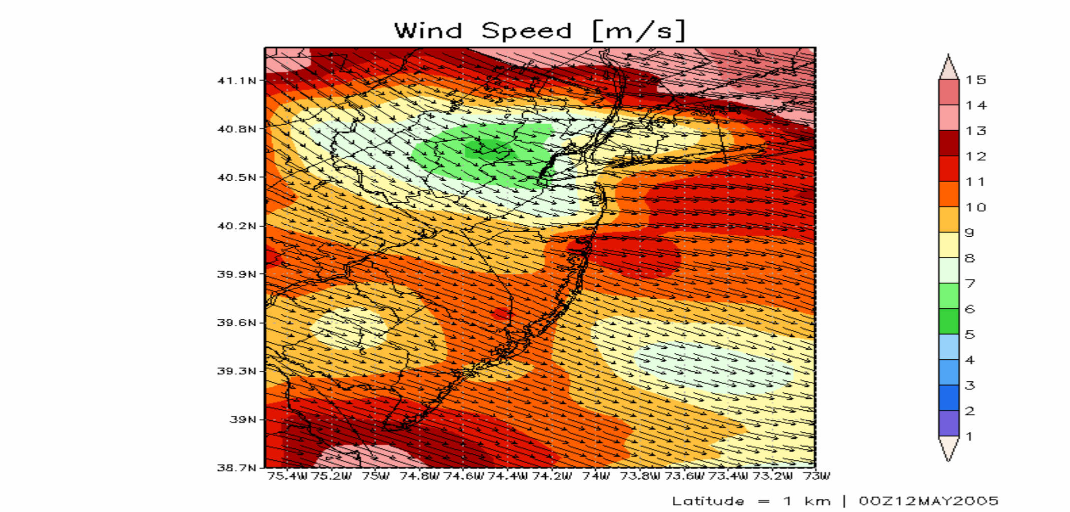

**RU-WRF Sea Breeze Simulation**



RU-WRF simulations verified by Radar and meteorological tower data were selected to represent a "typical" sea breeze circulation with onshore winds that occur within the surface boundary layer (sfc to ~100m), 500m winds (winds from the northeasterly sector) that occur above the TIBL, and the prevailing offshore (westerly) synoptic flow occurring at the upper boundary (1000m) of the sea breeze cell. Sea breeze wind vectors at 100m, 500m, and 1000m above mean sea level are shown respectively in the following simulations:



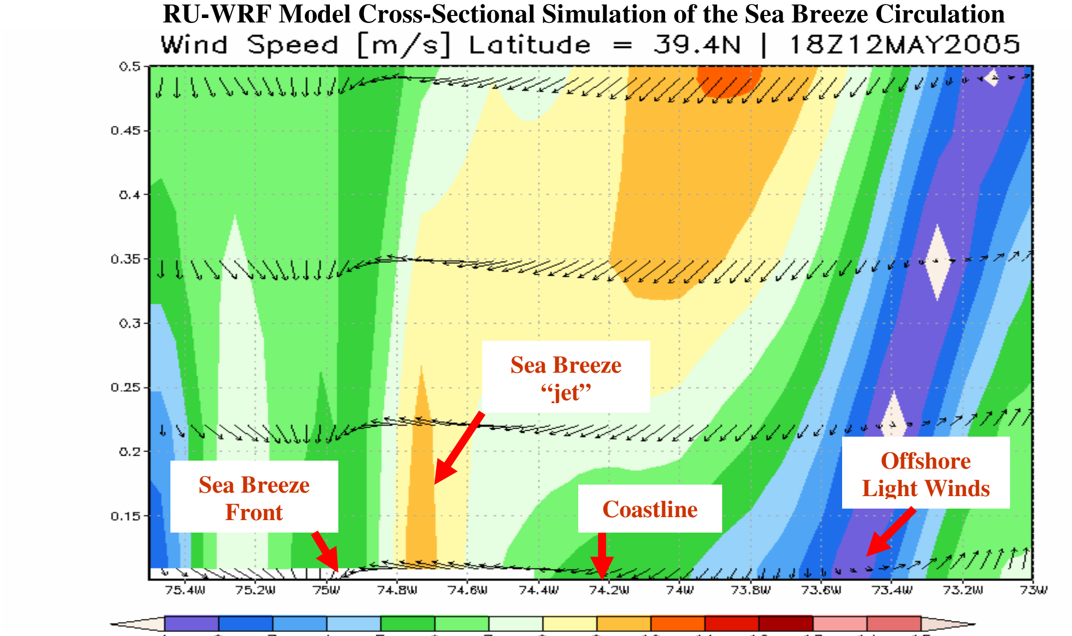



***The Sea Breeze and Coastal Wind Shear***

The preceding RU-WRF model simulations (Page 8) suggest that there is strong vertical wind shear within the sea breeze circulation with winds backing from easterly (onshore) sectors to the northerly and then to the westerly (offshore) sectors respectively from lower to upper levels of the sea breeze cell. The simulations also give indications that over an area following the sea breeze front and extending vertically to a level immediately above the TIBL, higher wind speeds occur producing a low level sea breeze "jet". For example, wind speeds indicated in the simulations over coastal areas from Forked River south to Atlantic City range from 8 to 10m/s at 100m, 7 to 9m/s at 500m, and 9 to 11m/s at 1000m. Therefore, wind speeds increase with height up to levels associated with TIBL heights along the coast and over adjacent inland areas (respectively, ~20m to ≥200m). Winds then decrease above the TIBL to midlevels of the sea breeze cell (~500m). From the mid-level, wind speeds will increase with height to near the upper boundary of the sea breeze cell (~1000m). Winds will then have a tendency to decrease during the transition from the sea breeze circulation to the prevailing upper airflow.

After analyzing several refined RU-WRF modeling runs and synthesizing the results, the following graphic is the resultant simulation of a vertical cross section of a representative NJ sea breeze. The sea breeze front is positioned inland at approximately 75W Longitude with the coastline located at about 74.2W Longitude. Maximum winds (~9 to 10 m/s) within the TIBL occur inland from the coast near 74.75W Longitude. This area of maximum wind speeds (i.e., the low level sea breeze "jet") occurs at a height of ~50m and extends to near 250m. The TIBL heights over the sea breeze "jet" and near the coastline are estimated to be respectively 225m and <50m. Wind speeds at the coastline and near offshore to approximately 74W Longitude are ~5 to 7 m/s at heights ranging from < 50m to ~150m. Winds offshore from 74W Longitude eastward to approximately 73.5w Longitude decrease from 7 m/s to < 2 m/s at heights ranging from <50m to > 150m. Wind directions within the onshore component of the sea breeze cell are ESE to SE with winds being from the northeasterly section within the offshore componet of the sea breeze circulation. Wind directions ahead of the sea breeze front are NW to N with offshore winds east of the sea breeze cell being from the southwesterly sector. The preceding discussion suggests that there is pronounced vectorial wind shear associated with the sea breeze circulation.

**RU-WRF Model Cross-Sectional Simulation of the Sea Breeze Circulation**



The previous RU-WRF model simulation and resulting assumptions (Page 9) regarding sea breeze wind shear are given more validity by comparing them with monitoring data compiled during sea breeze events. Additional monitoring data obtained from the Oyster Creek Nuclear Plant meteorological tower along with a more in-depth analysis confirm most of our initial findings presented in Phase 2 of the project. However, our refined analysis suggests that the physical processes that produce the sea breeze "jet" and its resulting location are different than were originally stated. Wind data from the 10m, 46m, and 116m tower levels were acquired predominately during sea breeze events. This data along with model simulations revealed that wind shear within the sea breeze circulation is significantly different when compared to wind shear over land areas not affected by the coastal environment. Our findings are summarized as follows:

- As the sea breeze penetrates inland, the energy "driving" the inland advection will be countered by the opposing synoptic flow causing sea breeze advancement to be curtailed. At this area of transition (i.e., the sea breeze front) there will be relatively strong vertical motion setting up the return portion of the sea breeze circulation. This return flow back to sea will occur at the upper boundary of the sea breeze cell.

- As a result of strong thermal gradients produced by the flow from the cooler more dense marine air to warmer less dense terrestrial air, onshore flow within the TIBL will be accelerated from the coast toward inland areas.

- As the onshore flow approaches the sea breeze front, wind speeds will reach a "critical" or maximum value. Airflow ahead of this area of maximum wind speeds will tend to become compressed as a result of the influence of the opposing synoptic flow. This will cause vertical energy transfer (heat and momentum flux) from the lowest level of maximum wind speeds to the top of the TIBL. If there is enough vertical energy, the heat and momentum prosperities below the TIBL could penetrate the TIBL causing wind speeds immediately above the TIBL to be similar to those below the TIBL. Consequently, wind speed distributions affiliated with this area of maximum winds will be relatively uniform extending from near surface (e.g., ~20m) to a height immediately above the TIBL. Winds within the area of maximum wind speed can be considered a low level jet (i.e., the sea breeze "jet").

    - Observed higher wind speeds at the Oyster Creek 46m tower level compared to calculated data were the result of the sea breeze "jet".

    - Wind shear effects at the upper boundary of the sea breeze cell will result in a retardation of wind intensities at this level. The upper sea breeze cell boundary height at the tower location, which is adjacent to the Barnegat Bay, will generally range form ~100 to 200m. This height interval coincides with the 116-meter sensor location. Wind speeds will increase in the free airflow above this transition layer (upper bounds of the sea breeze cell). The upper boundary of the sea breeze cell generally occurs at a height of approximately 1000m. This height could be substantially greater during the most intense sea breezes or could be less depending on atmospheric and oceanic conditions.

    - Since wind speeds are greater at the 46m level when compared to the 116m level, it can be assumed that the sea breeze "jet" at the Oyster Creek tower site occurs at heights ranging from ~40m to 100m which coincide with the 46m sensor height and heights within and immediately above the TIBL.

To determine the wind intensities at heights associated with wind turbines (hub and blade heights) the power law using 1/7 (0.143) as the wind shear exponent is generally used as the "standard" for calculating wind speeds at altitudes above sensor heights:

$\mathbf{v_2 = v_1\ [z_2/z_1]^{\alpha}}$
where,
$\mathbf{v_2}$ = the calculated wind speed.
$\mathbf{z_2}$ = the height of the calculated wind speed.
$\mathbf{v_1}$ = the observed speed
$\mathbf{z_1}$ = the wind sensor height
$\alpha$ = the wind shear exponent.

To test the $1/7^{th}$ power law for coastal applications, the meteorological tower at Oyster Creek (Forked River, NJ; adjacent to the Barnegat Bay) was utilized. Wind sensors on the tower are located at multiple levels (10m, 46m, and 116m), which enabled us to obtain wind profiles that are needed to compare calculated with observed data. When comparing actual data from 46m to the calculated data obtained when applying the $1/7^{th}$ power law to the 10m data, the formula provides results that are generally biased too low. Raising the exponent to a value closer to 0.3 as compared to 0.143 more accurately estimates actual wind speeds. This suggests that free airflow may be approached at lower heights over coastal and offshore areas when compared to inland areas with similar surface roughness values. However, when comparing the observed 116m tower data to the calculated data, most cases exhibited higher formula values. Similar results were obtained from the 90m PSEG tower located in Lower Alloway Twp, NJ near the DE Bay and the 60m B.L. England tower located in Beesleys Point, NJ near Ocean City, NJ.

Based on the profile data acquired from the three referenced meteorological towers, a representative yet conservative coastal wind shear exponent would fit closely the $1/5^{th}$ (0.2) power law. However, during Atlantic sea breeze or DE Bay breeze events, a wind shear exponent that equates to the $1/3^{rd}$ (0.34) power law appears to be realistic for heights within the coastal surface boundary layer (sfc to ~100m $\pm$ 50m). Coastal TIBL heights range from ~20m to 100m and from ~40m to 200m over adjacent inland areas. TIBL heights will depend on coastal topography and thermodynamics of the lower atmospheric marine and adjacent terrestrial boundary layers. Considering offshore and coastal wind turbine design and associated hub heights along with typical coastal TIBL heights, the $1/3^{rd}$ power law would apply to sea breeze events at heights of 80m $\pm$ 40m. Since onshore wind distributions above ~ 40m to TIBL heights are relatively uniform, wind speeds at heights ranging from 40m to 120m would be derived as follows:

$\mathbf{v_2 = v_1\ [z_2/z_1]^{\alpha}}$
where,
$\mathbf{v_2}$ is the calculated wind speed at **80m**.
$\mathbf{z_2}$ is the focal height (**80m**) for wind speed calculations for heights ranging from 40m to 120m..
$\mathbf{v_1}$ is the observed speed.
$\mathbf{z_1}$ is the wind sensor height
$\alpha$ is the sea breeze wind shear exponent **(0.34).**

**To determine wind speeds at heights below 80m to 40m, subtract 0.1m/s from the 80m wind speed for each 5m height increment. To determine wind speeds at heights above 80m to 120m, add 0.1m/s to the 80m wind speed for each 5m height increment. Since data was not available for levels >120m, coastal wind speed calculations for heights above 120m would be skeptical. The coastal wind shear algorithm applies only to NJ and DE near shore, coastal, and immediately adjacent inland locations (<10km from the coastline) influenced by the Atlantic sea breeze or DE Bay breeze.**

Base on the fact that TIBL heights generally increases with increasing distances inland, a different wind shear algorithm would probably have to be developed as function of distance from the coast, associated thermodynamic characteristics, and topography. TIBL heights can be estimated using the following algorithm:

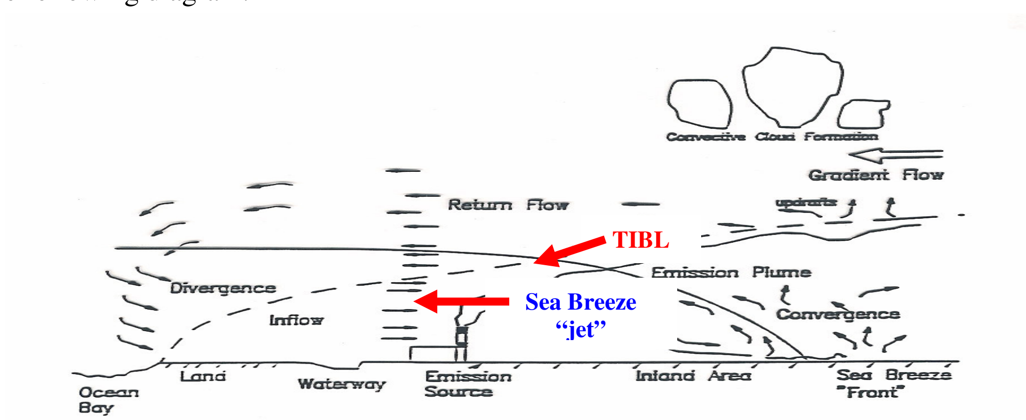
$$\mathbf{h_t = \frac{[z^n{}_{ref} z_3{}^p(1+2B)(n+1)(n+p+1)g(x)H_o x+h_{t,o}{}^{n+p+1}]^{1/n+p+1}}{p(T_3-T_o)c_p \rho_a U_{ref}}}$$

where,

**$h_t$ =** TIBL height.
**$h_{t,o}$ =** initial TIBL height.
**$H_o$ =** sfc heat flux.
**$z_{ref}$ =** height of monitored wind speed within the TIBL.
**n=** wind power-law exponent.
**$Z_3$=**height of estimated wind speed and temp. at the upper TIBL boundary.
**B=**ratio of heat flux at the top of the TIBL.
**p=**temperature lapse rate power-law exponent.
**$T_o$ =** observed sfc temperature
**$T_3$ =** temp. at top of TIBL.
**$c_p$**=specific heat of air.
**$\rho a$** = air density.
**$U_{ref}$** = monitored wind speed within the TIBL.

The suggested coastal wind shear algorithm using the 1/3$^{rd}$ power law (0.34 wind shear exponent) is based on three specific but similar sites and does not cover the entire NJ coast or DE Bay shoreline. Coastal locations, such as Atlantic City, with large high-rise buildings and locations with other irregular surface features will affect both onshore and offshore flow characteristics. Therefore, the resultant coastal wind shear algoritm may be significantly different than the one derived in this study. To verify and possibly adjust the suggested coastal wind shear shear algorithm, additional wind profile observations using current and new in-situ (meteorological towers) and remote (SODAR or RASS) monitoring systems located at selected sites along the coast should be employed. This enhanced monitoring capability could also be designed to develop site-specific coastal wind shear algorithms for areas designated as being favorable for wind energy development.

The pronounced spatial and temporal changes in wind shear, atmospheric stability, turbulence, and resultant airflow associated with the sea breeze circulation have important implications for wind energy development. Additionally, the sea breeze characteristics that influence the offshore, coastal, and adjacent inland wind resources will affect material transport and dispersion with implications that can be applied for effective environmental management. Sea breeze wind flow vectors, the sea breeze "jet", the sea breeze front, and TIBL (dashed curve) are depicted in the following diagram:



### *The Sea Breeze and Wind Power Potential*

The most intense sea breeze development occurs during the spring and summer seasons. Well-developed sea breezes occur when there is a weak synoptic flow along with a large temperature gradient between the marine air and air over adjacent land areas. These conditions generally result in above normal temperatures with high humidity over inland areas during afternoon and early evening hours. Therefore, sea breeze development during the summer season has a high probability of occurring concurrently with peak energy demand.

When analyzing the offshore and coastal wind resource during a "typical" sea breeze event, maximum wind intensities occur along the coast and decrease with increasing distance offshore until the influence of the sea breeze becomes minimal. This generally occurs at an offshore distance $\geq$25nm. Consequently, wind generators located between 5nm and 30nm offshore may not have adequate wind speeds needed to produce the supplemental power required during peak demand periods. Therefore, wind turbines located along the coast or far offshore may prove to be the most efficient for producing power when sea breeze events coincide with peak energy demand. Possibly, turbines could be strategically located along the coast (i.e., preferably inland along the coastline or as an alternative, at the coast or within 3 nm offshore) to take advantage of the wind resource that ranges from Good to Outstanding during sea breeze occurrences. These "coastal" turbines could then be operated as "peaking" units and could also provide power throughout the year as needed. Other issues, such as regulatory policy and public perception, would have to be evaluated prior to making a decision to locate wind turbines at or adjacent to the coast.

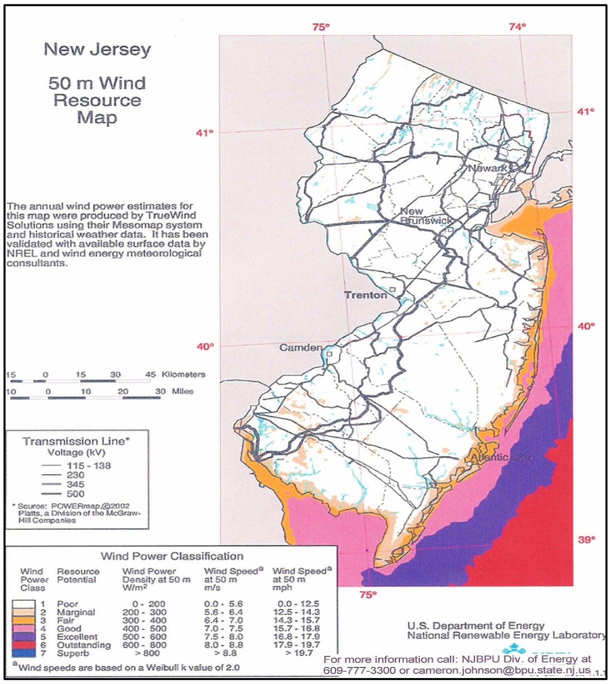
To ensure efficient power production, very specific placement of the wind turbines within the area where the optimum wind resource occurs needs to be accomplished since the power generated by the wind is directly proportional to the wind speed cubed. Therefore, relatively small fluctuations in wind speed could translate into large power production variations. Based on this premise, wind turbines should be located in an area with an adequate wind resource with minimal variability during both sea breeze occurrences and non-occurrences when power production may be critical for meeting energy demand. A portion of the study domain including the Brigantine Shoals/Little Egg Inlet/Great Bay area and adjacent near offshore areas < 5nm or far offshore >25nm defined in of our wind energy analysis satisfies these criteria.

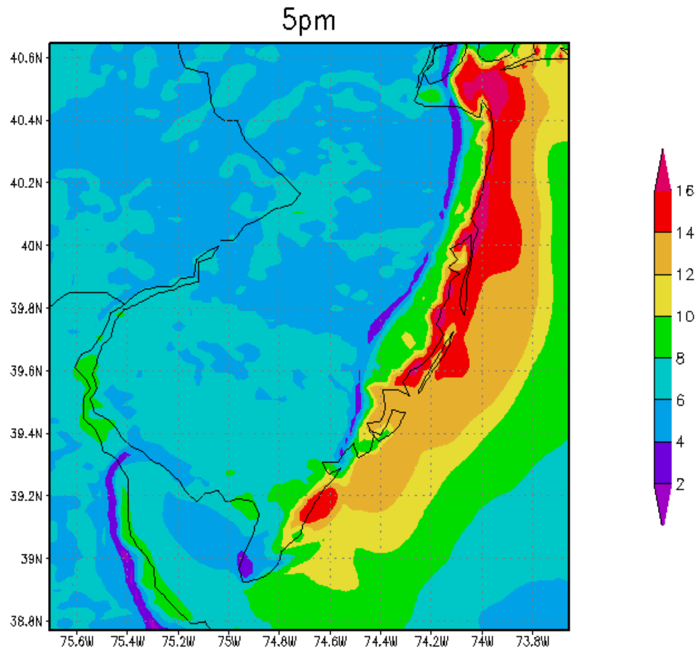
The wind power equation is expressed as follows:

$$\textbf{\textit{Power}} = (\pi / 2) * \rho * E * R^2 * M^3$$

where,
**ρ** = air density.
**E =** turbine efficiency.
**R** = the turbine-blade radius.
**M** = the wind speed.

Although, the NREL NJ wind map and RU-WRF model simulation for the annual average wind resource are in relatively close agreement, the preceding discussion regarding local sea breeze events suggests the wind resource associated with the sea breeze circulation is in direct contrast to the wind resource portrayed by both the NREL's NJ Wind Map and the Rutgers annual wind resource simulation. The contrasting NREL annual wind resource analysis and RU-WRF model sea breeze simulation are respectively presented in the following wind resource maps:




**Wind Speed Units (m/s; mph)** **Wind Speed Units (knts; 1knt=0.51 m/s)**

An analysis of the local wind resource @50m associated with the Atlantic sea breeze and DE Bay breeze circulations revealed the following results:

- Horizontal wind intensities become less (<3m/sec) at the convergence zone delineated by the inland sea breeze front and at the area of divergence that occurs at the offshore boundary of the sea breeze or Bay breeze circulations. Wind intensities become minimal (<1m/sec) when the sea breeze and Bay breeze interact to form an enhanced area of convergence at the leading edges of both circulations located inland near the coast.

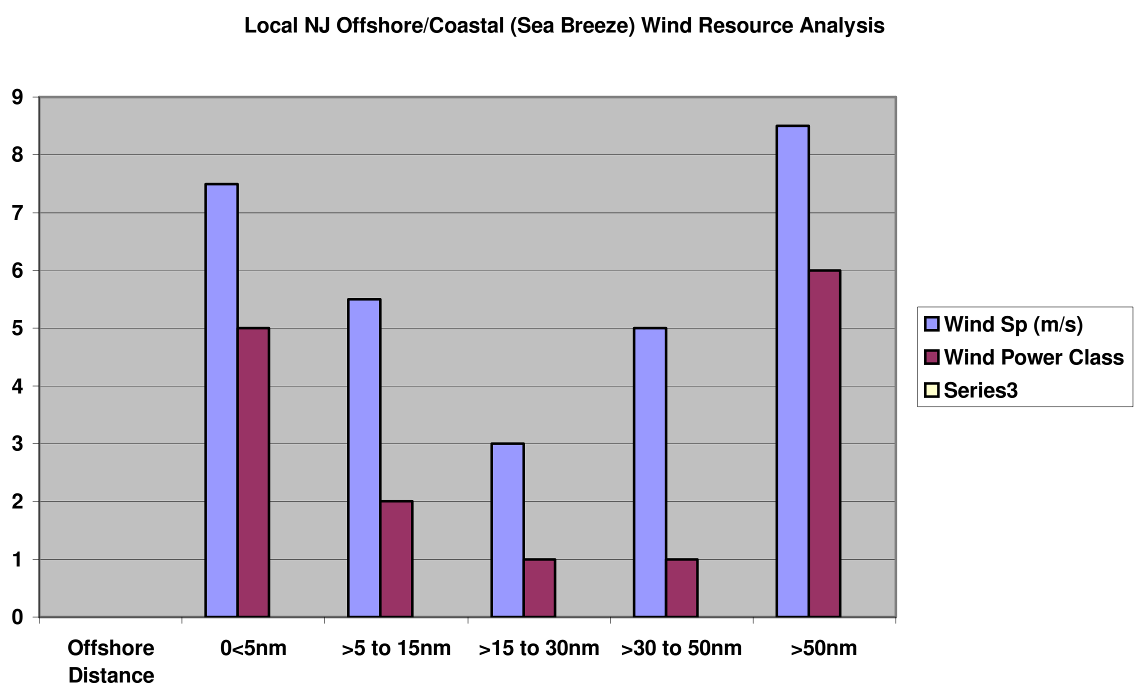
- Wind intensities decrease from the coast to offshore areas out to ~ 25nm (≥7m/sec to <2m/sec) and then increase past ~30nm (6m/sec to ≥9m/sec). Maximum wind intensities occur along and adjacent to the coast and far offshore.

- The NREL map shows wind speed intensities are directly proportional to distance offshore. The WRF model sea breeze simulations indicate that wind speed intensities are inversely proportional to distance offshore. This comparison is assumed valid for offshore distances out to ~25nm.

The results of the local NJ offshore/coastal wind resource analysis are summarized in **Table 3** and **Chart 3**:

| Table 3: **Sea Breeze Wind Resource** (<1km to ~100km) | | | |
|---|---|---|---|
| **Sea Breeze Wind Field Location** | **Wind Speed (m/s)** | **Wind Power Class** | **Wind Resource Potential** |
| Coastline and Adjacent Offshore Waters (0 <5nm) | 8.0 to 7.0 m/s | 6 to 4 | Outstanding to Good |
| ≥5nm to 15nm | 7.0 to 4.0 m/s | 4 to 1 | Good to Poor |
| ≥15nm to 25nm | 4.0 to 2.0 m/s | 1 | Poor |
| ≥25nm to 50nm | 2.0 to 7.0 m/s | 1 to 4 | Poor to Good |
| ≥50nm | 7.0 to ≥9.0 m/s | 4 to 7 | Good to Superb |

**Chart 3**



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